Environment and Development Economics 22: 699–724 © Cambridge University Press 2017
doi:10.1017/S1355770X17000109

Modeling the emissions–income relationship using long-run growth rates

DAVID I. STERN
Crawford School of Public Policy, The Australian National University, Acton, Australia, ACT 2601, Australia.
Email: david.stern@anu.edu.au

REYER GERLAGH
Economics Department, Tilburg University, The Netherlands.
Email: r.gerlagh@uvt.nl

PAUL J. BURKE
Arndt-Corden Department of Economics, Crawford School of Public Policy, The Australian National University, Australia.
Email: paul.j.burke@anu.edu.au

Submitted 13 April 2016; revised 16 January 2017; accepted 10 February 2017; first published online 27 April 2017

ABSTRACT. The authors adopt a new approach to modeling the relationship between emissions and income using long-run per capita growth rates. This approach allows them to test multiple hypotheses about the drivers of per capita emissions in a single framework and avoid several of the econometric issues that have plagued the environmental Kuznets curve literature. They estimate models for carbon and sulfur dioxide emissions. They can reject restricted models that omit either growth or beta convergence effects. Although the term representing the environmental Kuznets effect is statistically significant for per capita carbon and sulfur dioxide emissions, the estimated income per capita turning points are out of the sample for the full data set.

The authors thank Jie Li and Gregory Chow for help with the data used in their paper and Zeba Anjum for very helpful research assistance. They are grateful for useful comments from Zsuzsanna Csereklyei and seminar participants at the Arndt-Corden Department of Economics, ANU, particularly Ari Kokko and Hal Hill; Padjadjaran University, Indonesia; and Beijing Institute of Technology. The authors also thank participants at the 58th Australian Agricultural and Resource Economics Conference in Port Macquarie, NSW; the 6th Atlantic Workshop on Energy and Environmental Economics at A Toxa, Spain, particularly Andreas Löschel and Alberto Ansuategi; and the World Congress of Environmental Economics in Istanbul, in particular David Maddison.

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

1. Introduction

Is economic growth[1] first dirty and then clean once countries become wealthier, as the environmental Kuznets curve (EKC) hypothesis proposes? Are higher emissions intensities associated with slower growth in emissions, or even reductions in emissions? How important are the time effects – changes in pollution not associated with economic growth – emphasized by Vollebergh *et al.* (2009)? The answers to these questions are not only important for understanding the relationship between economic growth and development theoretically, but also for projecting future business-as-usual emissions. In this paper, we present a new approach that combines the EKC model and beta convergence approaches to modeling the evolution of emissions in a single equation. This allows us to test the relative adequacy of these approaches as explanations of the evolution of emissions.

Our econometric approach is inspired by figure 1,[2] which shows a strong positive correlation between the long-run average growth rate of per capita carbon dioxide (CO_2) emissions and the long-run average growth rate of GDP per capita. Fast-growing economies typically see increases in per capita CO_2 emissions while slow-growing or declining economies tend to have declining per capita emissions. Figure 1 shows a fairly strong linear relationship between the rate of growth of per capita GDP and the rate of growth of per capita emissions, with the remaining variation reflecting differences in the rate of change in emissions per dollar of GDP ('emissions intensity'). Emissions intensity declined in slightly more than half of the countries. Some rapidly growing economies, such as China, saw significant declines in emissions intensity, in many cases at a faster rate than in most developed countries.

Figure 1 also shows that a number of slow-growing non-OECD countries have had declining per capita emissions, while some OECD countries have had rising per capita emissions. This suggests that a simple EKC story – that economic growth in poor countries increases per capita emissions while economic growth in rich countries reduces per capita emissions – cannot fully explain the data. The figure suggests a new and simple econometric approach: regressing the long-run average growth rate of per capita emissions on the long-run average growth rate of income per capita, and using additional variables to explain the remaining variation in emissions intensity.

In this paper, we assess the determinants of long-run per capita emissions growth rates using our new econometric approach, making two main contributions. First, our approach has important econometric advantages over the conventional panel data representation used to estimate EKC models. Secondly, our approach allows us to unify the main existing

[1] We use the term economic growth to refer to growth in per capita GDP.

[2] A similar chart, but for total greenhouse gas emissions, is presented by Blanco *et al.* (2014: section 5.3.3).

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

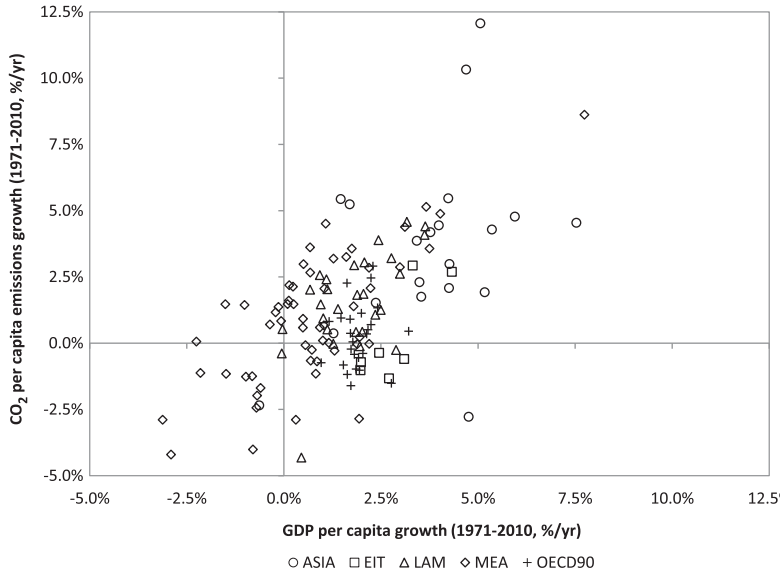


Figure 1. *Growth rates of per capita income and per capita carbon dioxide emissions from fossil fuel combustion and cement production*
Notes: Regional labels: ASIA, developing Asia; EIT, Eastern Europe and the former USSR; LAM, Latin America; MEA, Middle East and Africa; OECD90, OECD members as of 1990.
Source: CDIAC and Penn World Table 8.0.

models – a simple IPAT model,[3] the EKC and the beta convergence approach – and directly test the relative explanatory power of each.

There are four econometric advantages of our long-run growth rates approach. First, we circumvent the unit root problem raised by Wagner (2008), as unit roots are differenced. Secondly, by taking average growth rates over a long period of time, we filter out short-run effects and put more weight on the long-run components of variability.[4] Thirdly, we address the identification of time effects issue raised by Vollebergh *et al*. (2009); our model identifies the mean time effect as the mean long-run emissions

[3] As IPAT (Ehrlich and Holdren, 1971) is an identity, it must hold true. By a simple IPAT model we mean an approach in which IPAT is taken to be a causal model where the affluence and technology terms are separable.

[4] Chirinko *et al*.'s (2011) Interval Difference Estimator to estimating production function parameters similarly emphasizes long-run change and avoids several econometric problems common to panel data estimation. Our approach is also related to the 'fresh specification' for the EKC of Bradford *et al*. (2005), who start by assuming that the derivative of pollution with respect to time is a linear function of the rate of growth of income and the interaction between it and the level of income. This is a continuous-time version of our equation (3) assuming that the time effect is zero. But they then integrate this function with respect to time, deriving an estimation equation in levels.

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

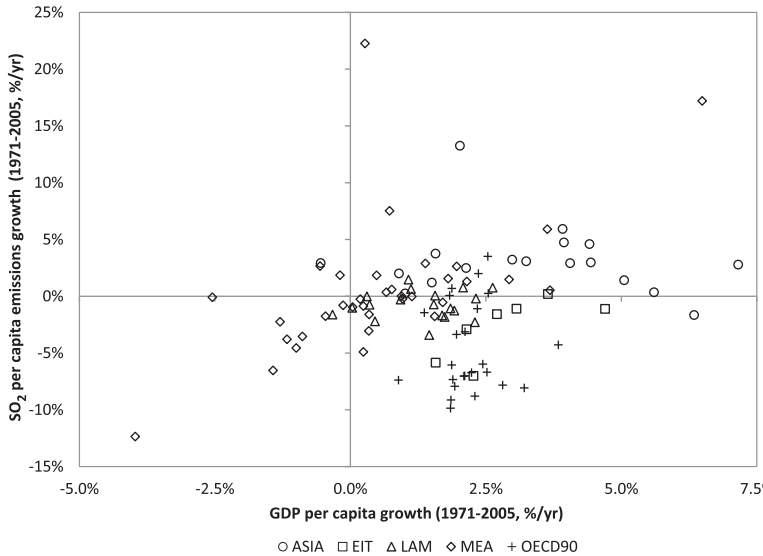


Figure 2. *Growth rates of per capita income and per capita sulfur dioxide emissions*
Notes: Regions as in figure 1.
Source: Smith et al. *(2011) and Penn World Table 8.0.*

growth rate when GDP growth is zero and other variables are at their sample mean. Fourthly, our approach reduces the main problem associated with the between estimator (BE) proposed by Stern (2010) – that omitted variables correlated with the levels of both emissions per capita and income per capita may result in biased estimates. In our new approach, the means of these variables are removed by differencing.

We estimate our model for CO_2 emissions from fossil fuel combustion and cement production, as well as sulfur dioxide (SO_2) emissions estimated by Smith *et al*. (2011). Long-run growth in SO_2 emissions is again positively correlated with economic growth (figure 2), although the entire distribution of per capita emissions growth is shifted downwards, suggesting a strong negative time effect. There is a group of smaller OECD countries with very negative per capita emissions growth clustered toward the bottom of the figure.

Using our simple unified approach, we can reject the restrictions implied by models that exclude the initial levels of emissions and income. We can also easily reject the restrictions implied by Brock and Taylor's (2010) short green Solow model, which excludes the growth rate of per capita GDP. Thus both growth and beta convergence effects are needed to explain emissions, as suggested by Ordás Criado *et al*. (2011). For the full sample period, we do not find significant evidence in favor of the EKC hypothesis for either CO_2 or SO_2 emissions although the elasticity of per capita emissions growth with respect to per capita GDP growth – which we refer to as the 'emissions–income elasticity' – is lower in higher income countries. While we do find an in-sample income turning point for SO_2 in the 1988–2005 period, this turning point is estimated imprecisely. Negative time effects

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

are also important in explaining the reductions in per capita SO_2 emissions experienced in some countries.

The outline of the paper is as follows. In section 2 we lay out prior work and in section 3 we present our research design. We then describe the overall features of the data in section 4, followed by results in section 5 and conclusions in section 6.

2. Prior research

There has been an extensive debate on the drivers of pollution emissions and other environmental impacts. Three main approaches have dominated the literature. Our method allows us to test all three in a single equation model.

Until the 1980s, mainstream environmental thought held that environmental impact increased with the scale of economic activity (i.e., aggregate GDP), although either more or less environmentally friendly technology could be chosen. This approach is represented by Ehrlich and Holdren's (1971) IPAT model. IPAT is an identity given by impact ≡ population ∗ affluence ∗ technology.[5] If affluence is taken to be income per capita, then the technology term is impact or emissions per dollar of income. If technology is independent of income per capita, then IPAT implies that the elasticity of per capita emissions with respect to per capita GDP ('emissions–income elasticity') is 1. We will use our long-run growth rates approach to test whether this is indeed the case.

The 1980s saw the introduction of the sustainable development concept, which argued that development was not necessarily damaging to the environment and that poverty reduction was essential to protect the environment (WCED, 1987). In line with this idea, Grossman and Krueger (1991, 1995) introduced the second main approach to modeling the income–emissions relationship – the EKC – which proposes that environmental impacts first increase and then decrease over the course of economic development.[6] Proponents of the EKC argue that, although economic growth at first increases environmental degradation, in the long run countries must become rich in order to clean up their environment (e.g., Beckerman, 1992). The EKC was popularized by the *1992 World Development Report* (World Bank, 1992), which relied on research by Shafik (1994). However, this showed that per capita CO_2 emissions do not seem to be an inverted U-shape function of GDP per capita, a conclusion also reached by Holtz-Eakin and Selden (1995). Figure 3 uses the same data featured in figure 1 to confirm the lack of a cross-country CO_2 EKC.

[5] Decomposition approaches to modeling emissions (e.g., Rafaj *et al.*, 2014) are ultimately derived from IPAT or the related Kaya Identity (Kaya, 1990). The STIRPAT approach of Dietz and Rosa (1997) and Rosa and Dietz (1998) is also derived from IPAT but allows the elasticities of population and affluence to deviate from unity and estimates technology as a residual.

[6] For recent critical reviews of the EKC literature, see Carson (2010), Pasten and Figueroa (2012) and Kaika and Zervas (2013a, 2013b).

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

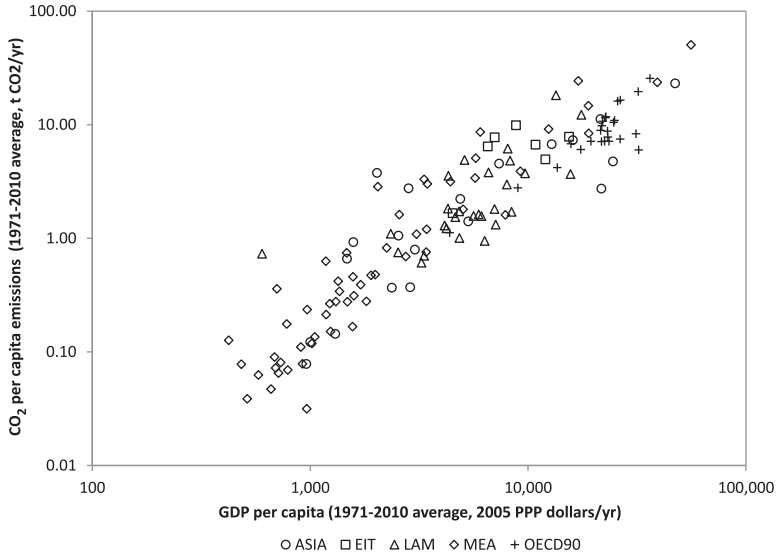


Figure 3. *Levels of per capita income and per capita carbon dioxide emissions from fossil fuel combustion and cement productio*
Notes: Regions and data sources as in figure 1.

Stern and Common (2001) found that in a globally representative sample of countries, even for SO_2 emissions, there was a monotonic relationship between per capita emissions and income per capita when time effects were included in the regression model. Recent papers using more sophisticated econometrics also find that the relationship between the levels of per capita emissions and income per capita is monotonic when the effect of the passage of time is controlled for (Wagner, 2008; Vollebergh *et al.*, 2009; Stern, 2010). On the other hand, using a set of simple cross-sectional CO_2 EKC regressions, Chow and Li (2014) find a highly significant coefficient on the square of the log of GDP per capita ($t = -22.9$), claiming conclusive econometric evidence in favor of the CO_2 EKC. However, their mean turning point is in fact at a GDP per capita level of US$378,000, so this result also supports a monotonic emissions–income trajectory.

Using Bayesian shrinkage estimators, Mazzanti and Musolesi (2013) find an in-sample turning point for per capita CO_2 emissions for Northern European members of the EU but not for other developed countries. Their models do not allow for a time effect and they also removed Austria, Ireland and Norway, where emissions have not fallen, from the sample of Northern European countries. Non-parametric approaches have also been used to estimate the EKC (e.g., Carson *et al.*, 1997; Millimet *et al.*, 2003; Azomahou *et al.*, 2006; Tsurumi and Managi, 2015), although many of these estimates also suffer from the issues raised by Wagner (2008, 2015), Vollebergh *et al.* (2009) and others. These mostly do not produce radically different results from parametric estimates.

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

Even if the relationship between GDP per capita and per capita emissions is monotonic, an EKC-like pattern could emerge from a combination of growth and time effects (Stern, 2004). Growth of per capita emissions in faster growing countries might outpace the efficiency improvements that come with time, so that per capita emissions would rise in fast-growing countries and decline in slow-growing countries. The fastest growing economies have been middle-income countries such as China and the Asian tiger economies that are catching up to the developed countries by adopting existing technologies.

The third main approach to the evolution of per capita emissions is to hypothesize that they are converging. There are three main approaches to testing for convergence: sigma convergence, which tests whether the dispersion of the variable in question declines over time using either just the variance or the full distribution (e.g., Ezcurra, 2007); stochastic convergence, which tests whether the time series for different countries cointegrate; and beta convergence, which tests whether the growth rate of a variable is negatively correlated to the initial level. Pettersson *et al.* (2013) provide a review of the literature on convergence of per capita CO_2 emissions.

Using beta and stochastic convergence tests, Strazicich and List (2003) found convergence among developed economies. Using sigma convergence approaches, Aldy (2006) found convergence for the developed economies but not the world as a whole. Using stochastic convergence, Westerlund and Basher (2008) reported convergence for a panel of 28 developed and developing countries over a very long period. Recent research using stochastic convergence finds evidence of club convergence rather than global convergence, however (Herrerias, 2013; Pettersson *et al.*, 2013). On the other hand, using the beta convergence approach, Brock and Taylor (2010) found convergence among 165 developed and developing countries between 1960 and 1998. Figure 4 shows beta convergence for per capita CO_2 emissions for our sample of countries. There is a clear tendency for emissions to grow in countries with a low initial level of emissions and vice versa.

The beta convergence approach has been criticized (e.g., Quah, 1993; Evans, 1996; Evans and Karras, 1996) because it is clear that dependence of the growth rate on the initial level of the variable is insufficient, though necessary (Pettersson *et al.*, 2013), for actual sigma convergence. Beta convergence could also be purely due to regression to the mean (Friedman, 1992; Quah, 1993). However, we find it hard to believe that, for example, the high levels of emissions intensity in formerly centrally planned economies are simply random fluctuations. In any case, economic theory – including Brock and Taylor's (2010) green Solow model and Ordás Criado *et al.*'s (2011) model – suggests that the initial level of emissions should be a factor in explaining emissions growth. We are not, therefore, so concerned with whether countries' emissions or emissions intensity actually converges in the sigma sense but whether the initial level of emissions or emissions intensity has an effect on future emissions growth.

Brock and Taylor's (2010) theoretical green Solow model is essentially the IPAT decomposition with the addition of economic models to explain *A*

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

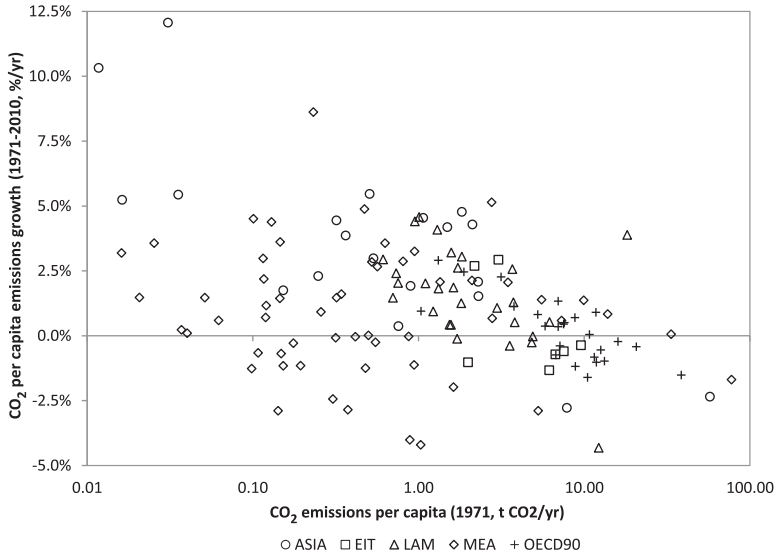


Figure 4. *Convergence in per capita carbon dioxide emissions from fossil fuel combustion and cement production*
Notes: Regions and data sources as in figure 1.

and T (and the treatment of population as exogenous). They explain affluence or income per capita using the Solow (1956) growth model, in which poorer countries grow faster than rich countries. In Brock and Taylor's empirical analysis, they assume a constant rate of technological progress in pollution 'abatement' that is common across countries.[7] As a result, the growth rate of emissions is a function of initial emissions per capita and there is convergence in emissions per capita across countries over time. Depending on the specification chosen, this model explains 14–42 per cent of the variance in average national 1960–1998 per capita CO_2 emissions growth rates.

Stefanski (2013) challenges Brock and Taylor's findings, arguing that GDP growth rates have declined over time at a slower rate than emissions intensity growth rates have. Therefore, it does not make sense to argue that emissions growth has slowed mainly due to Solow-style convergence of GDP per capita growth rates. There is a strong negative relationship between countries' initial level of emissions intensity and their subsequent emissions intensity growth rate (figure 5), which will be captured in our model.

Ordás Criado *et al.* (2011) developed a neoclassical growth model that finds that, along the optimal path, pollution growth rates are positively related to the growth rate of output and negatively related to emission

[7] Abatement is written in inverted commas because emissions intensity might decline for reasons completely unconnected with active abatement effort.

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

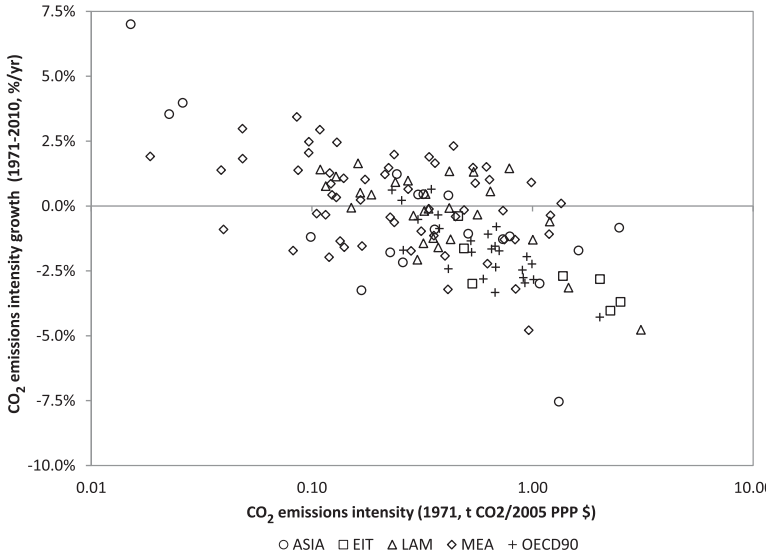


Figure 5. *Convergence in carbon dioxide emissions intensity*
Notes: Regions and data sources as in figure 1.

levels. The origin of the latter is because utility is a function of both consumption of goods and the level of pollution, and defensive expenditures can be used to reduce pollution. Econometrically, this model reduces to a beta convergence equation with the addition of an economic growth effect. They estimate the model for a panel of 25 European countries from 1980 to 2005 using 5-year period averages. Parametric estimates for per capita SO_2 emissions find that the rate of convergence is −0.021, the emissions–income elasticity is 0.653, and there are strong negative time effects, particularly in countries with initially high levels of income. For NO_x the rate of convergence is −0.036 and there are again strong negative time effects, but the initial level of income has only a small and not very significant effect. Non-parametric estimates largely confirm their parametric estimates.

The Ordás Criado *et al*. (2011) model is a more elegant theoretical model than the green Solow model and, due to the significance of the growth and initial income terms, the model explains more of the variation in the data (in their SO_2 model). As we will see in the following section, our model combines the Ordás Criado and EKC models in a single framework. However, the initial level of per capita emissions could explain the growth rate of per capita emissions for reasons besides the defensive expenditures effect, such as the diffusion of technology from low-emissions countries to high-emissions countries. Therefore, we do not interpret our results exclusively in the light of Ordás Criado *et al*.'s (2011) theoretical model.

3. Hypotheses, models and methods

We are agnostic about the data-generating processes for per capita GDP and emissions. It is likely, as shown by Wagner (2008) and others, that

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

both are stochastically trending (I(1)) variables, which may or may not cointegrate. Hence our adoption of the long-run growth rates representation, which should be robust for both stochastically and deterministically trending data (Chirinko *et al.*, 2011). An interaction term between the economic growth rate and the initial level of income allows us to capture heterogeneity in the emissions–income elasticity. Our conceptual model is:

$$\hat{E}_i = \alpha_0 + \alpha_1 \hat{G}_i + \beta' X_i + \varepsilon_i, \tag{1}$$

where hats indicate long-run growth rates, i.e., $\hat{E}_i = (E_{iT} - E_{i0})/T$ and $\hat{G}_i = (G_{iT} - G_{i0})/T$, where T is the final year of the time series in levels, 0 indicates the initial year, and i indexes countries.[8] E is the log of emissions per capita, and G is the log of GDP per capita. X_i is a vector of explanatory and control variables. We deduct the sample mean from each of the continuous levels variables in this vector. α_1 is an estimate of the emissions–income elasticity, which we expect to be positive, and α_0 is an estimate of the mean of $\hat{E}_i$ for countries with zero economic growth, the continuous levels variables at their sample means, and the dummy variables at their default value of zero. This is equivalent to the average time effect in traditional panel data EKC models. If $\alpha_0 < 0$, then in the absence of economic growth (and when the other variables are at their mean or default values), there is on average a reduction in per capita emissions over time, and vice versa.

By carefully choosing the explanatory variables, we can test hypotheses about different mechanisms that drive emissions. In particular, we propose:

$$\hat{E}_i = \alpha_0 + \alpha_1 \hat{G}_i + \beta_1 \hat{G}_i G_{i0} + \beta_2 E_{i0} + \beta_3 G_{i0} + \sum_{j=4}^{k} \beta_j X_{ji} + \varepsilon_i. \tag{2}$$

The third term on the RHS, $\hat{G}_i G_{i0}$, is the interaction between the rate of economic growth and the initial level of log income per capita. This term is intended to test the EKC hypothesis that there is a level of per capita income, a 'turning point', so that, *ceteris paribus*, economic growth is associated with a decline in per capita emissions when per capita income increases above a threshold.[9] We will refer to it as the 'EKC interaction term'.

[8] Growth rates could also be calculated as $r_{yi} = (y_{iT}/y_{i0})^{1/T} - 1$, where $y = \exp(Y)$ and $Y = E, G$. For the growth rate of GDP per capita, the mean, minimum and standard deviation of r_{gi} and $\hat{G}_i$ are identical at three decimal places and the maxima are 0.080 and 0.077, respectively. The growth rates of per capita CO_2 and SO_2 emissions are also similar using either approach.

[9] In an earlier version of this paper (Anjum *et al.*, 2014), we used the average of GDP over the sample period instead. This did not change the results qualitatively.

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

For the EKC hypothesis to hold, β_1 must be significantly less than zero. Assuming that $\alpha_1 > 0$ and $\beta_1 < 0$, we can compute the EKC turning point where $\frac{\partial \hat{E}}{\partial \hat{G}} = 0$ as $\tau = exp\left(-\frac{\alpha_1}{\beta_1} + \mu_G\right)$, where μ_G is the cross-country mean of initial GDP per capita that was deducted from the initial level of the GDP per capita variable prior to estimation. We use the delta method to compute the standard error of τ. If β_1 is significantly less than zero but the EKC turning point is above the maximum per capita income in the sample, we can conclude that, while the emissions–income elasticity is lower for countries with higher GDP per capita, it does not fall to or below zero as would be required for an EKC downturn.

The fourth and fifth terms of (2) are the initial levels of emissions and income, included to test convergence-type theories. If $\beta_2 < 0$, then there is beta convergence in the level of emissions per capita. If $\beta_3 = -\beta_2$ then there is beta convergence in emissions intensity without an additional effect of the initial level of income on the emissions growth rate. The remaining X_j are control variables, discussed below. We include these controls in each of our restricted models, although they do not appear in the original models in the literature. These control variables effectively allow the time effects to vary across countries as in Vollebergh *et al.* (2009).

By applying restrictions to (2) we can test whether simpler specifications are adequate representations of the data. We formally test each of the exclusion restrictions, which define equations (3)–(6), using likelihood ratio (LR) tests. First, we can set $\beta_1 = 0$, which defines the Ordás Criado *et al.* (2011) model:

$$\hat{E}_i = \alpha_0 + \alpha_1 \hat{G}_i + \beta_2 E_{i0} + \beta_3 G_{i0} + \sum_{j=4}^{k} \beta_j X_{ji} + \varepsilon_i. \tag{3}$$

We would expect $\alpha_1 > 0$ and $\beta_2 < 0$. Figure 5 shows that the correlation between the initial emissions intensity and the subsequent growth in emissions intensity is higher than that between initial emissions per capita and its subsequent growth rate illustrated in figure 4. Countries such as China that initially had high emissions intensity (and low per capita emissions) have had large decreases in emissions intensity. This suggests that it is indeed likely to be important to include the initial level of income per capita as well as the initial level of emissions per capita.

To derive the short green Solow model (Brock and Taylor, 2010), we set $\alpha_1 = \beta_1 = \beta_3 = 0$:

$$\hat{E}_i = \alpha_0 + \beta_2 E_{i0} + \sum_{j=4}^{k} \beta_j X_{ji} + \varepsilon_i. \tag{4}$$

We would again expect $\beta_2 < 0$. To derive a basic EKC model in growth rates without the initial per capita emissions and income terms, we set $\beta_2 = \beta_3 = 0$:

$$\hat{E}_i = \alpha_0 + \alpha_1 \hat{G}_i + \beta_1 \hat{G}_i G_{i0} + \sum_{j=4}^{k} \beta_j X_{ji} + \varepsilon_i. \tag{5}$$

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

We would expect $\alpha_1 > 0$ and $\beta_1 < 0$. Finally, we set $\beta_1 = \beta_2 = \beta_3 = 0$ to define a simple IPAT-inspired growth rates model:

$$\hat{E}_i = \alpha_0 + \alpha_1 \hat{G}_i + \sum_{j=4}^{k} \beta_j X_{ji} + \varepsilon_i. \tag{6}$$

Here $\alpha_1 = 1$ for a simple IPAT model if change in 'technology' is independent of the GDP growth rate. If $\alpha_1 < 1$, then the rate of change in the technology term in the IPAT model is correlated with the rate of economic growth.

In the following, we discuss the additional controls. A wide variety of variables have been considered in the EKC literature. Some are genuinely exogenous or predetermined, whereas others might be seen as channels through which the development process drives emissions changes. Examples of the latter are democracy, free press, good governance and lack of corruption, which have been found to both improve economic performance and reduce environmental pressure (Pellegrini and Gerlagh, 2006a, 2006b). Variables such as industrial structure are also clearly driven by income growth or develop alongside GDP as part of the development process. Controlling for these could be a way to test the effect of different channels of the influence of income on emissions growth. However, we are interested in testing the overall effect of per capita income and economic growth on per capita emissions growth and so our main analysis only includes variables that are predetermined or exogenous to the development process.

The exogenous variables included in equation (2) are as follows. We include dummies for non-English legal origin, as there is evidence that legal origin is relevant for per capita emissions of SO_2 (Stern, 2012). We also include a dummy for centrally planned economies in the expectation that their reforms spurred reductions in emissions intensity. We control for the effect of climate, using country averages of temperatures over the three summer months and the three winter months, as emissions may have grown more rapidly in countries with larger cooling or heating requirements. We also include the log of the value of estimated fossil fuel endowments in 1971 (Norman, 2009), as countries that are poor in fossil fuel endowments might exhibit faster transitions to low-emission energy sources such as nuclear power and renewables. Differences in fossil fuel endowments have been found to be an important cause of heterogeneity in emissions–income paths in prior work (Burke, 2012, 2013; Stern, 2012). Finally, we include the average of the log of population density; for a given level of emissions per capita, higher population density implies higher pollution concentrations and so we would expect this variable to affect efforts to reduce SO_2 emissions (*ceteris paribus*). Higher population density may also reduce per capita energy use and thus per capita CO_2 and SO_2 emissions through lower transportation costs and possibly smaller living and workspaces.

We exclusively use a linear modeling approach, where our parameter estimates attempt to capture the average effects in a possibly heterogeneous sample (Angrist and Pischke, 2010). We estimate all the models using

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

OLS with heteroskedasticity-robust standard errors. We also implement three heteroskedasticity tests. First, we use White's (1980) test of general heteroskedasticity. Secondly, because emissions per capita and income per capita are means computed over populations of various sizes, the variance of these variables should be inversely related to the size of the population, which introduces grouping-related heteroskedasticity (Maddala, 1977). Using the delta method, we can see that the variance of the log of these means also should be inversely related to the size of the population. We test whether this is the case, using the Breusch–Pagan test (Breusch and Pagan, 1979), which involves regressing the squared residuals from each regression on the reciprocal of the mean over time of population.[10] Thirdly, it is possible that, due to measurement errors, the variance of the error term is not linearly related to the size of the population, but instead to a power of it. To test this we use the Harvey (1976) test where we regress the log of the squared residuals on the log of population. We also estimate models using weighted least squares (WLS) where the error variance is assumed to be inversely proportional to population.

We assume that the explanatory variables in our regressions are exogenous. Clearly, there can be no reverse causality from growth rates to initial values. There is potentially feedback from the growth rate of emissions to the growth rate of income if either (a) local pollutants affect national economic growth, or (b) as in the case for CO_2 emissions, emissions growth is tied to growth in energy use, which itself likely contributes to economic growth. Omitted variables bias may also be important as there are many variables that may be correlated with GDP or GDP growth, and which may help explain emissions growth. Finally, measurement error is a significant issue in the estimation of both GDP and emissions.[11] Usually, measurement error in GDP would be expected to bias the estimates of the regression coefficients toward zero (Hausman, 2001).

A common way to deal with these issues is to use instrumental variables. However, it is hard to find plausible instrumental variables (Bazzi and Clemens, 2013), especially for long-run growth rates or levels of the variables. Cseresklyei and Stern (2015) suggest that the magnitude of the bias due to reverse causality is likely to be small. The differencing we use to generate growth rates removes country-levels effects and hence one source of unexplained heterogeneity. Using long-run growth rates should reduce the effect of measurement error on the estimates (Hauk and Wacziarg, 2009).

[10] Breusch and Pagan (1979) allow for the residual variance to be related to any variables, not just the regressors.

[11] Blanco *et al.* (2014) discuss the uncertainty in emissions data. For CO_2 emissions from fossil fuels and cement production, the uncertainties are in the order of ±8 per cent. For SO_2, uncertainties for individual countries range from ±5 to ±36 per cent, depending on the country and source of emissions (Smith *et al.*, 2011). Uncertainties in the estimation of GDP are also large. Uncertainties in GDP growth rates are probably lower than in the initial level of GDP, as the former uses countries' own national accounts growth rates, avoiding the uncertainty in PPP exchange rates (Feenstra *et al.*, 2015).

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

Table 1. *Descriptive statistics*

	Country						
	Mean	*SD*	*Min*	*Median*	*Max*	*Global aggregate*	*Population-weighted mean*
Emissions per capita mean annual growth rate 1971–2005 or 1971–2010:							
CO_2 sample	0.013	0.025	−0.043	0.010	0.121	0.005	0.025
SO_2 sample	−0.007	0.050	−0.124	−0.005	0.223	−0.019	0.005
GDP per capita mean annual growth rate 1971–2005 or 1971–2010:							
CO_2 sample	0.017	0.018	−0.031	0.017	0.077	0.020	0.036
SO_2 sample	0.017	0.018	−0.040	0.018	0.072	0.021	0.034

Notes: Growth rates are presented in fractions rather than percentages, as that is the way the data are used in our regression analysis. The first five columns present unweighted statistics for our sample when computing the statistics for each country separately first. In the sixth column (global), we first compute the total emissions, GDP, and population for our sample of countries, and then compute the mean annual growth rate and mean per capita level of this global aggregate. In the final column we compute the growth rates using population-weighted regressions of the country-level growth rates on a constant.

4. Data

The online appendix, available at https://doi.org/10.1017/S1355770X17000109, describes the data sources in detail. Table 1 presents descriptive statistics for the growth rates of income and emissions per capita. The first five columns present statistics for the distribution of the country-level per capita income growth rates and mean (over time) per capita income levels. The sixth presents data for global-aggregate income and emissions per capita.[12] The final column provides population-weighted means of the country-level growth rates.

Per capita CO_2 emissions are rising on average across countries by more than 1 per cent per annum while per capita SO_2 emissions are falling at 0.7 per cent per annum on average. Variations in the rate of change across countries are much larger for SO_2 emissions than for carbon emissions, as the standard deviation of the per capita SO_2 emissions growth rate is twice as large as that for per capita carbon emissions. GDP per capita has on average grown a little faster than per capita CO_2 emissions, with a bit less variation across countries. There do not seem to be important differences between the distributions of the GDP per capita growth rates. Based on these simple statistics, the naïve estimates of the emissions–income elasticity would be 0.75 and −0.39 for the two data sets. As we will see, separating the total effect into time and growth effects greatly modifies the latter estimate.

The growth rates of global-aggregate per capita emissions are much lower than the unweighted country mean, while the population-weighted

[12] These are for the aggregate of the countries in our sample and thus are not truly global as some countries are omitted from each of our samples.

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

means are much higher. This is because, due to convergence, countries with higher initial per capita emissions saw slower growth in per capita emissions, while China and India, which have the largest populations, had rapid economic growth and rapid growth in per capita emissions.

5. Results

Table 2 presents the results for equation (2) for both pollutants, tables 3 and 4 present the results for restricted models, and tables 5–6 present results for (2) where the sample is split into two sub-periods.

Both models in table 2 explain about 70 per cent of the variation in the data. The time effects are negative but not significant for CO_2, and significantly negative (1 per cent per annum) for SO_2. The emissions–income elasticity, which ranges from 0.85 to 0.93, is insignificantly different from unity for both CO_2 and SO_2. The coefficient of the interaction term between growth and the level of GDP per capita is negative and significantly different from zero for both. There is thus some evidence that the emissions–income elasticity is lower for countries at higher per capita income levels. This elasticity does not become negative within the observed range of GDP per capita, however, meaning that any EKC turning point is out of sample.

The coefficients of log initial GDP per capita and log initial emissions per capita are similar, but larger in absolute value for SO_2. Strikingly, the annual rate of conditional convergence for per capita CO_2 and SO_2 is similar to the 'iron-law' rate of conditional convergence in GDP per capita of 2 per cent reported by Barro (2015). If we re-parameterize the model for initial emissions intensity rather than initial emissions per capita, then the remaining effect of initial income per capita is very small.[13] The effects of summer and winter temperature are both statistically significant and similar across the data sets with, again, a larger effect for SO_2. Summer temperature has a positive effect on emissions growth, perhaps because of increasing use of air conditioning in hot countries. The coefficient is largest for per capita SO_2 emissions, which are mostly produced as a result of electricity generation. Higher winter temperatures have a negative effect on per capita emissions growth, but this is smaller in absolute value than the effect of higher summer temperatures.

The coefficients of the remaining variables are very different for CO_2 and SO_2. Legal origin has no significant effect on per capita CO_2 emissions growth, but countries with non-English legal origin saw a much more rapid decline in per capita SO_2 emissions than the English legal origin countries, confirming previous findings (Stern, 2005, 2012). To date SO_2 emissions have received more active policy attention than CO_2 emissions; therefore differences in legal and regulatory regimes are more likely to have resulted in different outcomes. Formerly centrally planned status has a significantly positive effect on per capita SO_2 emissions growth, *ceteris paribus*. As there was a rapid decline in energy intensity in these countries following liberalization, we would expect emissions to decline more rapidly in reforming

[13] The remaining effect of initial income per capita would equal $\beta_2 + \beta_3$.

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

Table 2. *General model (equation (2))*

Data set	*Carbon dioxide*	*Sulfur dioxide*
Constant	−0.0025	−0.0099*
	(0.0023)	(0.0055)
$\hat{G}_i$	0.8901***	0.8543***
	(0.0927)	(0.1553)
	[−1.1859]	[−0.9382]
$G_{i0}\hat{G}_i$	−0.1330**	−0.2668**
	(0.0592)	(0.1217)
G_{i0}	0.0167***	0.0197**
	(0.0031)	(0.0049)
E_{i0}	−0.0154***	−0.0209***
	(0.0019)	(0.0039)
Centrally planned	−0.0054	0.0292**
	(0.0048)	(0.0138)
French legal origin	0.0007	−0.0151****
	(0.0025)	(0.0056)
German legal origin	0.0006	−0.0356***
	(0.0039)	(0.0102)
Scandinavian legal origin	−0.0038	−0.0446***
	(0.0044)	(0.0156)
Summer temperature	0.0008**	0.0028***
	(0.0003)	(0.0008)
Winter temperature	−0.0004*	−0.0010***
	(0.0002)	(0.0004)
Log fossil fuel endowment per capita 1971	0.0011***	−0.0015
	(0.0003)	(0.0009)
Log population density	−0.0003	−0.0093***
	(0.0010)	(0.0022)
EKC income per capita turning point (1000s of US$)	2,649	101
	(9,213)	(178)
$\bar{R}^2$	0.6997	0.7090
White test χ^2 (2k + 0.5($k^2 - k$))	101.83	157.50
	(0.0177)	(0.0000)
BP test: Inverse of population χ^2 (1)	0.2075	4.6676
	(0.6487)	(0.0307)
Harvey test: Log population χ^2 (1)	1.9548	1.7345
	(0.1620)	(0.1878)
Sample size	134	100

Notes: Figures in parentheses are standard errors for the regression coefficients and the EKC turning point and p-values for White, Breusch–Pagan (BP) and Harvey test statistics. Figures in square brackets are the t-statistic for the difference between the coefficient and unity. k is the number of non-constant regressors. Significance levels of regression coefficients: *10%, **%, ***1%. The sample mean is subtracted from all levels variables except dummy variables so that the intercept is an estimate of the mean of $\hat{E}_i$ for countries with zero economic growth, the continuous levels variables at the sample mean and the dummy variables at their default value of zero. See online appendix for further information on variable definitions.

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

Table 3. *Restricted models: carbon emissions 1971–2010*

Variable/ statistic/test	*Eq. (3) Ordás Criado*	*Eq. (4) GSM*	*Eq. (5) EKC*	*Eq. (6) IPAT*
Constant	−0.0039*	0.0142***	−0.0011	−0.0053*
	(0.0023)	(0.0037)	(0.0035)	(0.0032)
$\hat{G}_i$	0.9670***		0.7964***	0.9890***
	(0.0833)		(0.1247)	(0.1181)
	[−0.3959]		[−1.6322]	[−0.0935]
$G_{i0}\hat{G}_i$			−0.2648***	
			(0.0906)	
G_{i0}	0.0156***			
	(0.0031)			
E_{i0}	−0.0157***	−0.0098***		
	(0.0019)	(0.0016)		
EKC income per capita turning point (1000s of US$)			67	
			(85)	
$\bar{R}^2$	0.6922	0.3007	0.4352	0.3895
White test $\chi^2(2k + 0.5(k^2 - k))$	102.9161	40.2828	58.3248	59.5269
	(0.0015)	(0.6317)	(0.3899)	(0.0721)
BP test: Inverse of population χ^2 (1)	5.0572	2.8250	4.9279	5.2683
	(0.0245)	(0.0928)	(0.0264)	(0.0217)
Harvey test: Log population χ^2 (1)	3.4163	7.1537	11.3998	4.1382
	(0.0656)	(0.0075)	(0.0007)	(0.0419)
LR test against the general model	5.0572	226.6954	86.9089	111.3925
	(0.0245)	(0.0000)	(0.0000)	(0.0000)

Notes: 134 data points. Control variables are also included but their coefficients are not reported. Figures in parentheses are standard errors for the regression coefficients and the EKC turning point and *p*-values for the White, Breusch–Pagan, Harvey and LR test statistics. Figures in square brackets are the *t*-statistic for the difference between the coefficient and unity. *k* is the number of non-constant regressors. Significance levels of regression coefficients: *10%, ***1%. The sample mean is subtracted from all continuous levels variables.

economies. However, as we see in table 5, they grew much more rapidly in the centrally planned economies prior to reform and this effect dominates the full sample results.

A larger fossil fuel endowment increases the rate of growth of per capita CO_2 emissions, as we would expect (Burke, 2010, 2012; Stern, 2012), but does not have a significant effect on per capita SO_2 emissions.[14] Population

[14] We also tested adding an interaction between fossil fuel endowments and the economic growth variable. For CO_2, the coefficient of the interaction term was significant and the coefficient of the levels term of fossil fuel endowment was insignificant. For SO_2 the interaction term was not significant. Other coefficients did not change much and so we chose to just present the model as in equation (2).

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

Table 4. *Restricted models: sulfur dioxide 1971–2005*

Variable/ statistic/test	*Eq. (3) Ordás Criado*	*Eq. (4) GSM*	*Eq. (5) EKC*	*Eq. (6) IPAT*
Constant	−0.0129**	0.0082	−0.0030	−0.0106
	(0.0058)	(0.0060)	(0.0097)	(0.0104)
$\hat{G}_i$	0.9723***		0.8795***	1.2176***
	(0.1605)		(0.2213)	(0.2622)
	[−0.1726]		[−0.5446]	[0.8298]
$G_{i0}\hat{G}_i$			−0.5578***	
			(0.1565)	
$\hat{G}_{i0}$	0.0179***			
	(0.0051)			
$\hat{E}_{i0}$	−0.0220***	−0.0176***		
	(0.0037)	(0.0028)		
EKC income per capita turning point (1000s of US$)			19.8	
			(13.5)	
$\bar{R}^2$	0.7024	0.5650	0.4762	0.4264
White test $\chi^2(2k + 0.5(k^2 - k))$	80.4522	63.0256	63.9335	61.3183
	(0.0483)	(0.0313)	(0.1445)	(0.0345)
BP test: Inverse of population χ^2 (1)	3.5380	2.5784	2.9834	2.9050
	(0.0600)	(0.1083)	(0.0841)	(0.0883)
Harvey test: Log population χ^2 (1)	4.0969	2.5609	8.0448	1.6450
	(0.0430)	(0.1095)	(0.0046)	(0.1990)
LR test against the general model	4.8051	80.0797	28.6406	70.8570
	(0.0284)	(0.0000)	(0.0000)	(0.0000)

Notes: 100 data points. Control variables are also included but their coefficients are not reported. Figures in parentheses are standard errors for the regression coefficients and the EKC turning point and *p*-values for the White, Breusch–Pagan, Harvey and LR test statistics. Figures in square brackets are the *t*-statistic for the difference between the coefficient and unity. k is the number of non-constant regressors. Significance levels of regression coefficients: **5%, ***1%. The sample mean is subtracted from all continuous levels variables.

density has a strong negative effect on SO_2 as expected and a smaller and insignificant effect on CO_2.

Looking at the diagnostic statistics, the Breusch–Pagan test statistic for a specific theory-based heteroskedasticity structure is statistically significant at the 5 per cent level for SO_2 but the Harvey test does not find that there is significant heteroskedasticity for either of these models. Population weighted WLS estimates (not reported) are, therefore, close or qualitatively similar to the OLS estimates, which means that countries with small populations that are potential outliers do not affect the results substantially. White test statistics for heteroskedasticity of an unknown form are highly significant, which justifies the use of heteroscedasticity-robust standard errors.

We also tested for the effects of some other variables that are not reported in these main results. Although energy prices are not exogenous, there is

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

Table 5. *Equation (2) period 1*

Data set	*Carbon dioxide*	*Sulfur dioxide*
Constant	−0.0014	0.0076
	(0.0042)	(0.0094)
$\hat{G}_i$	0.8177***	0.8340***
	(0.0990)	(0.1907)
	[−1.84]	[−0.87]
$G_{i0}\hat{G}_i$	−0.0448	−0.1498
	(0.0652)	(0.1413)
$\hat{G}_{i0}$	0.0245***	0.0246**
	(0.0056)	(0.0117)
$\hat{E}_{i0}$	−0.0234***	−0.0304***
	(0.0036)	(0.0094)
Centrally planned	−0.0093	0.0728***
	(0.0117)	(0.0244)
French legal origin	0.0049	−0.0226***
	(0.0046)	(0.0092)
German legal origin	0.0074	−0.0573***
	(0.0104)	(0.0217)
Scandinavian legal origin	−0.0101	−0.0714***
	(0.0091)	(0.0227)
Summer temperature	0.0017**	0.0031**
	(0.0007)	(0.0012)
Winter temperature	−0.0010***	−0.0022***
	(0.0003)	(0.0006)
Log fossil fuel endowment per capita 1971	0.0020***	−0.0017
	(0.0007)	(0.0012)
Log population density	0.0017	−0.0120***
	(0.0018)	(0.0041)
EKC income per capita turning point (1000s of US$)	2.7*E*08	1,073
	(7.2*E*09)	(5,340)
$\bar{R}^2$	0.5455	0.5849
White test $\chi^2(2k + 0.5(k^2 - k))$	106.15	99.10
	(0.0044)	(0.0126)
BP test: Inverse of population χ^2 (1)	0.5943	0.1922
	(0.4408)	(0.6610)
Harvey test: Log population χ^2 (1)	6.1083	2.1077
	(0.0135)	(0.1466)
Sample	1971–1990	1971–1988

Notes: Figures in parentheses are standard errors for the regression coefficients and the EKC turning point and *p*-values for heteroskedasticity test statistics. Figures in square brackets are the *t*-statistic for the difference between the coefficient and unity. *k* is the number of non-constant regressors. Significance levels of regression coefficients: **5%, ***1%. The sample mean is subtracted from all continuous levels variables. See online appendix for further information on variable definitions.

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

interest in their effect on the growth of emissions. In the absence of data for other fuel prices for our large international sample, we use the log of the retail price of road-sector gasoline as a proxy of country-by-country fossil fuel prices. Adding this variable to equation (2) for the CO_2 data, the coefficient is −0.0099 (0.0026). The main changes in the other parameters are as follows. The coefficient on the EKC interaction term becomes insignificant. The coefficient on the fossil fuel endowment becomes much smaller and only significant at the 10 per cent level. Therefore, greater fossil fuel endowments are correlated with lower gasoline prices (Burke and Nishitateno, 2013) and the slightly lower emissions–income elasticity that was present for countries at higher initial GDP per capita levels appears to be partly related to higher fuel prices in these countries. The gasoline price has a negative but insignificant coefficient for the SO_2 data set. Due to the large literature on the relationship between trade and the environment, which also inspired the first study of the EKC (Grossman and Krueger, 1991), we also tested for the effect of trade openness. When added to (2) its coefficient is positive. This effect is not statistically significant at the 5 per cent level for CO_2 but it is for SO_2 (with a coefficient of 0.0159 (0.0047)). We also added dummies for the five regions shown in the figures. These had statistically significant effects for SO_2 but generally not for CO_2, and did not change the results qualitatively. We also considered the potential effects of hydroelectric power (Burke, 2010, 2013) by controlling for freshwater resources per capita. This variable was statistically insignificant.

Looking at tables 3 and 4, the restricted models can be rejected at the 5 per cent significance level. We thus conclude that our general specification is preferable. In both cases, the Ordás Criado *et al*. (2011) model (3) has a much higher adjusted R-squared than the other restricted models and cannot be rejected at the 1 per cent level. Both the growth and beta convergence effects are thus important in explaining emissions. Models including convergence effects explain much more of the variation in the dependent variable than does the basic EKC model (5). The green Solow model (4) explains the least for CO_2, although it is a better fit than the EKC model for SO_2. The time effect for the green Solow model is positive and statistically significant for CO_2, because of the elimination of the growth effect. For the EKC model, the turning points are smaller than in equation (2). For SO_2 the income turning point is at US$20,000, although this estimate has a large standard error ($p = 0.142$).

To explore whether effects varied over time, we split the sample period in half and re-estimated equation (2) for the two sub-periods 1971–1990 and 1990–2010 for CO_2 and 1971–1988 and 1988–2005 for SO_2 separately. Tables 5 and 6 report these results. The findings that economic growth and emissions convergence are significant drivers of emissions growth and that there is either no meaningful EKC turning point or a high EKC turning point are robust across the separate sample periods. But this sub-period analysis reveals some interesting stories. The EKC interaction term is insignificant in the first period for both pollutants and becomes more negative and highly significant for SO_2 in the second period. The income turning point for SO_2 also moves into the sample range (US$21,000), but

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

Table 6. *Equation (2) period 2*

Data set	*Carbon dioxide*	*Sulfur dioxide*
Constant	−0.0036	−0.0223***
	(0.0030)	(0.0077)
$\hat{G}_i$	0.9279***	0.7678***
	(0.1355)	(0.1900)
	[−0.53]	[−1.22]
$G_{i0}\hat{G}_i$	−0.1095*	−0.5484***
	(0.0597)	(0.1890)
G_{i0}	0.0137***	−0.0210***
	(0.0041)	(0.0054)
E_{i0}	−0.0133***	−0.0135***
	(0.0035)	(0.0041)
Centrally planned	−0.0043	−0.0062
	(0.0095)	(0.0229)
French legal origin	−0.0027	−0.0099
	(0.0036)	(0.0078)
German legal origin	−0.0031	−0.0264
	(0.0066)	(0.0167)
Scandinavian legal origin	0.0007	−0.0733***
	(0.0059)	(0.0170)
Summer temperature	0.0009	0.0045***
	(0.0005)	(0.0010)
Winter temperature	−0.0001	−0.0007
	(0.0004)	(0.0013)
Log fossil fuel endowment per capita 1971	0.0010*	−0.0094
	(0.0005)	(0.0013)
Log population density	−0.0013	−0.0092***
	(0.0017)	(0.0029)
EKC income per capita turning point (1000s of US$)	20,005	21.2
	(114,836)	(14.6)
$\bar{R}^2$	0.5383	0.5619
White test $\chi^2(2k + 0.5(k^2 - k))$	105.95	69.86
	(0.0088)	(0.4824)
BP test: Inverse of population χ^2 (1)	0.0006	0.0027
	(0.9798)	(0.9584)
Harvey test: Log population χ^2 (1)	0.1117	1.0018
	(0.7382)	(0.3169)
Sample	1990–2010	1988–2005

Notes: Figures in parentheses are standard errors for the regression coefficients and the EKC turning point and p-values for heteroskedasticity test statistics. Figures in square brackets are the t-statistic for the difference between the coefficient and unity. k is the number of non-constant regressors. Significance levels of regression coefficients: *10%, ***1%. The sample mean is subtracted from all continuous levels variables. See online appendix for further information on variable definitions.

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

remains statistically insignificant. For SO_2, the time effect becomes significant and negative only in the second period. As might be expected, the coefficient for centrally planned economies is very positive and significant in the first period and becomes negative, though insignificant, in the second. Initial income has a strong negative effect for SO_2 in this second period, but only Scandinavian legal origin has a significantly negative coefficient in the second period. So, after 1988 when efforts to reduce acid rain intensified (Stern, 2005), per capita SO_2 emissions began to fall everywhere in the absence of growth, particularly in high-income countries and especially in Scandinavia. The effect of winter temperatures disappears for both pollutants in the second period.

6. Discussion and conclusions

We have pursued a new long-run growth rates approach to emissions modeling that allows tests of competing explanations for emissions trajectories and nests the prior models of Ordás Criado *et al.* (2011), Brock and Taylor (2010) and the EKC. We find that the effect of income growth on emissions is strongly positive, with a mean elasticity slightly below unity for both per capita CO_2 and SO_2 emissions. However, a simple per capita GDP growth rates model is not sufficient to explain changes in per capita emissions. Beta convergence effects, in particular, add considerable explanatory power for country-level emissions.

Interaction terms between income growth and the initial level of log per capita income are negative and statistically significantly for both CO_2 and SO_2. While this provides some evidence that the emissions–income elasticity is lower in higher income countries, any EKC per capita income turning point is well out of sample and statistically insignificant for both pollutants for the full period. We thus conclude that there is no practically important EKC in the full sample for either CO_2 or SO_2. For SO_2, this supports conclusions first drawn by List and Gallet (1999) and Stern and Common (2001), although they used formulations in levels rather than growth rates. In the post-1988 period there is an in-sample turning point for SO_2, but it is imprecisely estimated.

There is a strong negative time effect for SO_2 ranging from -1.0 to -2.2 per cent p.a. Time effects for CO_2 are not statistically significant. We find strong evidence of convergence across countries in either emissions per capita or emissions intensity. Our estimates of the green Solow model for per capita CO_2 emissions have lower adjusted R-squared values than any of our models that include the growth rate of GDP. We therefore conclude that, although both are important, economic growth explains more of the variation in per capita CO_2 emissions growth rates than convergence does. However, for SO_2 we find the reverse: convergence has greater explanatory power than GDP growth or the EKC interaction term.

Our results provide smaller elasticities of emissions with respect to income and smaller time effects for CO_2 than Stern (2010). This suggests that Stern's (2010) results are biased by omitted variables. Perhaps this is also the case for the results of Wagner (2008) and Vollebergh *et al.* (2009), who also use models in levels.

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

In summary, both growth and convergence effects are important, as proposed by Ordás Criado *et al*. (2011). The implication is that observed cases of per capita CO_2 emissions flattening in some high-income countries are not due to a natural tendency of per capita emissions to come down with time or at higher per capita income levels, but more likely are outlier countries returning to the mean, despite a robust underlying income-driven upward trend. For SO_2, the data are suggestive of a more optimistic perspective, with a strong downward trend driven by technology, and per capita emissions leveling off and perhaps falling at higher per capita income levels in more recent decades. Of course, decline in per capita emissions is not a guarantee of a decline in total emissions, as the latter depends on the rate of population growth as well.

Although we find that beta convergence is important for both SO_2 and CO_2 per capita emissions, our analysis does not explain why. Convergence could be due to globalization leading to economic structures and the technologies used across countries becoming more similar over time, or due to countries with high emissions intensities taking policy action to improve their environments (Ordás Criado *et al*., 2011) and/or reduce their dependence on imported energy. We also found evidence on the effect of economic scarcity: countries with more abundant fossil fuel endowments have faster emissions growth. For SO_2, the evidence provides more support for a policy-induced effect, visible through lower emissions in densely populated areas and strong effects of legal origin variables.

No method can address all potential issues. The fact that long-run GDP growth rates filter out non-stationary dynamics, short-run relations, time varying time-effects, and variables that might explain variation in the initial level of emissions across countries means that we cannot use our approach to assess these important issues. For example, variation in countries' initial levels of emissions is left unexplained. This omission is shared with the panel data approach with country fixed effects. Also, we do not consider the effect of the business cycle on emissions (see Burke *et al*., 2015). The approach we follow focuses on identifying the long-term effects of economic growth on emissions.

Supplementary material and methods

To view supplementary material for this article, please visit https://doi.org/10.1017/S1355770X17000109.

References

Aldy, J.E. (2006), 'Per capita carbon dioxide emissions: convergence or divergence?', *Environmental and Resource Economics* **33**(4): 533–555.

Angrist, J.D. and J.-S. Pischke (2010), 'The credibility revolution in empirical economics: how better research design is taking the con out of econometrics', *Journal of Economic Perspectives* **24**(2): 3–30.

Anjum, Z., P.J., Burke, R. Gerlagh, and D.I. Stern (2014), 'Modeling the emissions–income relationship using long-run growth rates', CCEP Working Paper No.

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

1403, Centre for Climate and Economic Policy, Australian National University, Canberra.
Azomahou, T., F. Laisney, and P. Nguyen-Van (2006), 'Economic development and CO_2 emissions: a nonparametric panel approach', *Journal of Public Economics* **90**(6–7): 1347–1363.
Barro, R.J. (2015), 'Convergence and modernisation', *Economic Journal* **125**(585): 911–942.
Bazzi, S. and M.A. Clemens (2013), 'Blunt instruments: avoiding common pitfalls in identifying the causes of economic growth', *American Economic Journal: Macroeconomics* **5**(2): 152–186.
Beckerman, W. (1992), 'Economic growth and the environment: whose growth? Whose environment?', *World Development* **20**: 481–496.
Blanco, G., R. Gerlagh, S. Suh, *et al.* (2014), 'Drivers, trends and mitigation', in O. Edenhofer *et al*. (eds), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Reportof the Intergovernmental Panel on Climate Change*, Cambridge: Cambridge University Press.
Bradford, D.F., R.A. Fender, S.H. Shore, and M. Wagner (2005), 'The environmental Kuznets curve: exploring a fresh specification', *B.E. Journal of Economic Analysis & Policy* **4**(1): art. 5.
Breusch, T.S. and A.R. Pagan (1979), 'A simple test for heteroscedasticity and random coefficient variation', *Econometrica* **47**: 1287–1294.
Brock, W.A. and M.S. Taylor (2010), 'The green Solow model', *Journal of Economic Growth* **15**: 127–153.
Burke, P.J. (2010), 'Income, resources, and electricity mix', *Energy Economics* **32**(3): 616–626.
Burke, P.J. (2012), 'Climbing the electricity ladder generates carbon Kuznets curve downturns', *Australian Journal of Agricultural and Resource Economics* **56**(2): 260–279.
Burke, P.J. (2013), 'The national-level energy ladder and its carbon implications', *Environment and Development Economics* **18**(4): 484–503.
Burke, P.J. and S. Nishitateno (2013), 'Gasoline prices, gasoline consumption, and new-vehicle fuel economy: evidence for a large sample of countries', *Energy Economics* **36**: 363–370.
Burke, P.J., M. Shahiduzzaman, and D.I. Stern (2015), 'Carbon dioxide emissions in the short run: the rate and sources of economic growth matter', *Global Environmental Change* **33**: 109–121.
Carson, R.T. (2010), 'The environmental Kuznets curve: seeking empirical regularity and theoretical structure', *Review of Environmental Economics and Policy* **4**(1): 3–23.
Carson, R.T., Y. Jeon, and D.R. McCubbin (1997), 'The relationship between air pollution and emissions: U.S. data', *Environment and Development Economics* **2**: 433–450.
Chirinko, R.S., S.M. Fazzari, and A.P. Meyer (2011), 'A new approach to estimating production function parameters: the elusive capital–labor substitution elasticity', *Journal of Business & Economic Statistics* **29**(4): 587–594.
Chow, G.C. and J. Li (2014), 'Environmental Kuznets curve: conclusive econometric evidence for CO_2', *Pacific Economic Review* **19**(1): 1–7.
Csereklyei, Z. and D.I. Stern (2015), 'Global energy use: decoupling or convergence?', *Energy Economics* **51**: 633–641.
Dietz, T. and E.A. Rosa (1997), 'Effects of population and affluence on CO_2 emissions', *Proceedings of the National Academy of Sciences* **94**: 175–179.
Ehrlich, P.R. and J.P. Holdren (1971), 'Impact of population growth', *Science* **171**(3977): 1212–1217.

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

Evans, P. (1996), 'Using cross-country variances to evaluate growth theories', *Journal of Economic Dynamics and Control* **20**(6–7): 1027–1049.
Evans, P. and G. Karras (1996), 'Convergence revisited', *Journal of Monetary Economics* **37**(2): 249–265.
Ezcurra, R. (2007), 'Is there cross-country convergence in carbon dioxide emissions?', *Energy Policy* **35**: 1363–1372.
Feenstra, R.C., R. Inklaar, and M.P. Timmer (2015), 'The next generation of the Penn World Table', *American Economic Review* **105**(10): 3150–3182.
Friedman, M. (1992), 'Do old fallacies ever die?', *Journal of Economic Literature* **30**(4): 2129–2132.
Grossman, G.M. and A.B. Krueger (1991), 'Environmental impacts of a North American Free Trade Agreement', Working Paper No. 3914, National Bureau of Economic Research, Cambridge, MA.
Grossman, G.M. and A.B. Krueger (1995), 'Economic growth and the environment', *Quarterly Journal of Economics* **110**: 353–377.
Harvey, A.C. (1976), 'Estimating regression models with multiplicative heteroskedasticity', *Econometrica* **44**: 461–466.
Hauk, W.R. and R. Wacziarg (2009), 'A Monte Carlo study of growth regressions', *Journal of Economic Growth* **14**: 103–147.
Hausman, J.A. (2001), 'Mismeasured variables in econometric analysis: problems from the right and problems from the left', *Journal of Economic Perspectives* **15**(4): 57–67.
Herrerias, M.J. (2013), 'The environmental convergence hypothesis: carbon dioxide emissions according to the source of energy', *Energy Policy* **61**: 1140–1150.
Holtz-Eakin, D. and T.M. Selden (1995), 'Stoking the fires? CO_2 emissions and economic growth', *Journal of Public Economics* **57**(1): 85–101.
Kaika, D. and E. Zervas (2013a), 'The Environmental Kuznets Curve (EKC) theory – Part A: concept, causes and the CO_2 emissions case', *Energy Policy* **62**: 1392–1402.
Kaika, D. and E. Zervas (2013b), 'The environmental Kuznets curve (EKC) theory – Part B: critical issues', *Energy Policy* **62**: 1403–1411.
Kaya, Y. (1990), 'Impact of carbon dioxide emission control on GNP growth: interpretation of proposed scenarios', Paper presented to the IPCC Energy and Industry Subgroup, Response Strategies Working Group, Paris.
List, J.A. and C.A. Gallet (1999), 'The environmental Kuznets curve: does one size fit all?', *Ecological Economics* **31**(3): 409–423.
Maddala, G.S. (1977), *Econometrics*, Singapore: McGraw-Hill.
Mazzanti, M. and A. Musolesi (2013), 'The heterogeneity of carbon Kuznets curves for advanced countries: comparing homogeneous, heterogeneous and shrinkage/Bayesian estimators', *Applied Economics* **45**(27): 3827–3842.
Millimet, D.L., J.A. List, and T. Stengos (2003), 'The environmental Kuznets curve: real progress or misspecified models?', *Review of Economics and Statistics* **85**: 1038–1047.
Norman, C.S. (2009), 'Rule of law and the resource curse: abundance versus intensity', *Environmental and Resource Economics* **43**: 183–207.
Ordás Criado, C., S. Valente, and T. Stengos (2011), 'Growth and pollution convergence: theory and evidence', *Journal of Environmental Economics and Management* **62**: 199–214.
Pasten, R. and E. Figueroa (2012), 'The environmental Kuznets curve: a survey of the theoretical literature', *International Review of Environmental and Resource Economics* **6**: 195–224.
Pellegrini, L. and R. Gerlagh (2006a), 'Corruption, democracy, and environmental policy: an empirical contribution to the debate', *Journal of Environment & Development* **15**(3): 332–354.

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press

Pellegrini, L. and R. Gerlagh (2006b), 'Corruption and environmental policies: what are the implications for the enlarged EU?', *European Environment* **16**(3): 139–154.
Pettersson, F., D. Maddison, S. Acar, and P. Söderholm (2013), 'Convergence of carbon dioxide emissions: a review of the literature', *International Review of Environmental and Resource Economics* **7**: 141–178.
Quah, D. (1993), 'Galton's fallacy and the tests of the convergence hypothesis', *Scandinavian Journal of Economics* **95**(4): 427–443.
Rafaj, P., M. Amann, J. Siri, and H. Wuester (2014), 'Changes in European greenhouse gas and air pollutant emissions 1960–2010: decomposition of determining factors', *Climatic Change* **124**(3): 477–504.
Rosa, E.A. and T. Dietz (1998), 'Climate change and society: speculation, construction and scientific investigation', *International Sociology* **13**(4): 421–455.
Shafik, N. (1994), 'Economic development and environmental quality: an econometric analysis', *Oxford Economic Papers* **46**: 757–773.
Smith, S.J., J. van Ardenne, Z. Klimont, R.J. Andres, A. Volke, and S.D. Arias (2011), 'Anthropogenic sulfur dioxide emissions: 1850–2005', *Atmospheric Chemistry and Physics* **11**: 1101–1116.
Solow, R.M. (1956), 'A contribution to the theory of economic growth', *Quarterly Journal of Economics* **70**(1): 65–94.
Stefanski, R. (2013), 'On the mechanics of the "Green Solow Model"', OxCarre Research Paper No. 47, University of Oxford.
Stern, D.I. (2004), 'The rise and fall of the environmental Kuznets curve', *World Development* **32**(8): 1419–1439.
Stern, D.I. (2005), 'Beyond the environmental Kuznets curve: diffusion of sulfur-emissions-abating technology', *Journal of Environment and Development* **14**(1): 101–124.
Stern, D.I. (2010), 'Between estimates of the emissions-income elasticity', *Ecological Economics* **69**: 2173–2182.
Stern, D.I. (2012), 'Modeling international trends in energy efficiency', *Energy Economics* **34**: 2200–2208.
Stern, D.I. and M.S. Common (2001), 'Is there an environmental Kuznets curve for sulfur?', *Journal of Environmental Economics and Management* **41**: 162–178.
Strazicich, M.C. and J.A. List (2003), 'Are CO_2 emission levels converging among industrial countries?', *Environmental and Resource Economics* **24**(3): 263–271.
Tsurumi, T. and S. Managi (2015), 'Environmental Kuznets curve: economic growth and emission reduction', in S. Managi (ed.), *The Economics of Green Growth: New Indicators for Sustainable Societies*, Abingdon: Routledge, pp. 49–70.
Vollebergh, H.R.J., B. Melenberg, and E. Dijkgraaf (2009), 'Identifying reduced-form relations with panel data: the case of pollution and income', *Journal of Environmental Economics and Management* **58**(1): 27–42.
Wagner, M. (2008), 'The carbon Kuznets curve: a cloudy picture emitted by bad econometrics', *Resource and Energy Economics* **30**: 388–408.
Wagner, M. (2015), 'The environmental Kuznets curve, cointegration and nonlinearity', *Journal of Applied Econometrics* **30**(6): 948–967.
WCED (World Commission on Environment and Development) (1987), *Our Common Future*, Oxford: Oxford University Press.
Westerlund, J. and S.A. Basher (2008), 'Testing for convergence in carbon dioxide emissions using a century of panel data', *Environmental and Resource Economics* **40**: 109–120.
White, H.A. (1980), 'A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity', *Econometrica* **48**: 817–838.
World Bank (1992), *World Development Report 1992: Development and the Environment*, New York: Oxford University Press.

https://doi.org/10.1017/S1355770X17000109 Published online by Cambridge University Press