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The Environmental Kuznets Curve: A Primer

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Abstract

The environmental Kuznets curve (EKC) is a hypothesized relationship between various indicators of environmental degradation and income per capita. As economies get richer environmental impacts first rise but eventually fall. In reality, though some types of environmental degradation have been reduced in developed countries others have not. Furthermore, the statistical evidence for the EKC is not robust and the mechanisms that might drive such patterns are still contested.

Keywords
Carbon dioxide emissions, climate change, cointegration, econometrics, economic development, economic growth, environmental economics, environmental policy, pollution, sulfur emissions

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I. Introduction

This paper provides an introduction to the environmental Kuznets curve (EKC) that updates my previous introductory articles in the *Encyclopedia of Energy* (Stern, 2004a) and the now defunct *ISEE Encyclopedia of Ecological Economics*. The environmental Kuznets curve (EKC) is a hypothesized relationship between various indicators of environmental degradation and income per capita. In the early stages of economic growth, pollution emissions increase and environmental quality declines, but beyond some level of income per capita (which will vary for different indicators) the trend reverses, so that at high income levels economic growth leads to environmental improvement. This implies that environmental impacts or emissions per capita are an inverted U-shaped function of income per capita. Figure 1 shows an example of an estimated EKC. The EKC is named after Simon Kuznets who proposed that income inequality first rises and then falls as economic development proceeds.

The EKC is an essentially empirical phenomenon, but most estimates of EKC models are not statistically robust. Concentrations of some local pollutants have clearly declined in developed countries but there is much less clarity about emissions of pollutants. Studies of the relationship between per capita emissions and income that attempt to avoid various statistical pitfalls find that per capita emissions of pollutants rise with increasing income per capita when other factors are held constant. However, changes in these other factors may be sufficient to reduce pollution. In rapidly growing middle-income countries the effect of growth overwhelms these other effects. In wealthy countries, growth is slower, and pollution reduction efforts can overcome the growth effect. This appears to be the origin of the apparent EKC effect. These econometric results are supported by evidence that, in fact, pollution problems are being addressed in developing economies. However, there is still no consensus on the drivers of changes in pollution.

The next two sections of this article review the history of the EKC and the theories that have been developed to explain the observed changes in pollution with income. The fourth section reviews the econometric methods that have been applied to studying the EKC and the pitfalls associated with them. The fifth section reviews some of the extensive empirical evidence. The final three sections review the critique of the EKC on policy grounds, examine alternative approaches, and summarize the findings and discuss future research directions.

II. Background

Until the 1980s, mainstream environmental thought held that environmental impact increased with the scale of economic activity, though either more or less environmentally friendly technology could be chosen. This approach is represented by the IPAT model proposed by Ehrlich and Holdren (1971). IPAT is an identity given by impact = population*affluence*technology. If affluence is income per capita, then the technology term is impact or emissions per dollar of income. The 1980s saw the introduction of the sustainable development concept, which argued that, in fact, development was not necessarily damaging to the environment and that poverty reduction was essential to protect the environment (WCED, 1987). In line with this sustainable development idea, Grossman and Krueger (1991) introduced the EKC concept in their path-breaking study of the potential impacts of the North American Free Trade Agreement (NAFTA). Environmentalist ritics of NAFTA claimed that the economic growth that would result from introducing free trade would damage the environment in Mexico. Grossman and Krueger (1991) argued instead that increased growth actually improve environmental quality in Mexico rather than reduce. To support this argument they carried out an empirical analysis of the relationship between ambient pollution levels in many cities around the world from the GEMS database and income per capita. This analysis found that the concentrations of various pollutants peaked when a country reached roughly the level of Mexico's per capita income at the time.

The EKC was popularized by the World Bank's 1992 *World Development Report*, which relied on research by Shafik (1994). The report argued that: "The view that greater economic activity inevitably hurts the environment is based on static assumptions about technology, tastes and environmental investments" (p38) and that "As incomes rise, the demand for improvements in environmental quality will increase, as will the resources available for investment" (p39). Others have expounded this position even more forcefully with Beckerman (1992) claiming that "there is clear evidence that, although economic growth usually leads to environmental degradation in the early stages of the process, in the end the best – and probably the only – way to attain a decent environment in most countries is to become rich" (p482). However, Shafik's research showed that both urban waste and carbon emissions did not seem to follow an inverted U-shaped curve. Subsequent research confirmed these findings and has cast doubt on the validity of the EKC hypothesis for emissions of other pollutants too.

III. Theory

Panayotou (1993) provided an early rationale for the existence of an EKC:

If there were no change in the structure or technology of the economy, pure growth in the scale of the economy would result in a proportional growth in pollution and other environmental impacts. This is called the scale effect. The traditional view that economic development and environmental quality are conflicting goals reflects the scale effect alone. Proponents of the EKC hypothesis argue that "at higher levels of development, structural change towards information-intensive industries and services, coupled with increased environmental awareness, enforcement of environmental regulations, better technology and higher environmental expenditures, result in leveling off and gradual decline of environmental degradation." (Panayotou, 1993).

Therefore, at the EKC can be explained by the following 'proximate factors':

1. **Scale** of production implies expanding production with the mix of products produced, the mix of production inputs used, and the state of technology all held constant.

2. Different industries have different pollution intensities and typically, over the course of economic development the **output mix** changes. This is often referred to as the **composition effect** (e.g. Copeland and Taylor, 2004).

3. Changes in **input mix** involve the substitution of less environmentally damaging inputs to production for more damaging inputs and vice versa.

4. Improvements in the **state of technology** involve changes in both:

a. **Production efficiency** in terms of using less, *ceteris paribus*, of the polluting inputs per unit of output.

b. **Emissions specific changes in process** result in less pollutant being emitted per unit of input.

The third and fourth factors are together often referred to as the technique effect (e.g. Copeland and Taylor, 2004).

These proximate variables may in turn be driven by changes in underlying variables such as environmental regulation, awareness, and education, which themselves may be driven by other more fundamental variables. A number of articles have developed theoretical models that explain how preferences and technology might interact to result in different time paths of environmental quality. There are two main approaches in this literature – static models that treat economic growth as simply shifts in the level of output and dynamic models that model the economic growth process as well as the evolution of emissions or environmental quality (Kijima *et al*., 2010).

The typical static model assumes that there is a representative consumer who maximizes a utility function that depends on consumption and the level of pollution. Pollution is also treated as an input to the production of consumer goods. These models assume that there are no un-internalized externalities or equivalently that there is a socially efficient price for pollution. Pasten and Figueroa (2012) show that under the simplifying assumption of additive preferences:

$$\frac{dP}{dK} > 0 \text{ if and only if } \frac{1}{\sigma} > \eta \text{ and } \textit{vice versa} \qquad (1)$$

where P is pollution, K is "capital" – all other inputs to production apart from pollution - σ is the elasticity of substitution between K and P in production, and η is the (absolute value of the) elasticity of the marginal utility of consumption with respect to consumption. The smaller σ is, the harder it is to reduce pollution by substituting other inputs for pollution. The larger η is, the harder it is to increase utility with more consumption. So, in other words, pollution is more likely to increase as the economy expands, the harder it is to substitute other inputs for pollution and the easier it is to increase utility with more consumption. This result also implies that if either of these parameters is constant then there cannot be an EKC where first pollution increases and then decreases. The various theoretical models can be classified as ones where the EKC is driven by changes in the elasticity of substitution as the economy grows or models where the EKC is primarily driven by changes in the elasticity of marginal utility (Figueroa and Pasten, 2012).

Dynamic models of the EKC vary in their assumptions about how institutions govern environmental quality and there is no simple way to summarize the results. The nature of collective decision-making influences the income–pollution path chosen, and, hence, societal utility. For example, in Jones and Manuelli's (2001) model the young can choose to tax the pollution that will exist when they are older. By contrast, Brock and Taylor's (2010) green Solow model makes no explicit assumption about either consumer preferences or the pricing of pollution. Rather it is assumed, on the basis of the stylized facts, that a constant share of economic output is spent on abating pollution. Brock and Taylor's work is notable for taking into account more features of the data, such as abatement costs and the decline over time in emissions intensity, than previous research had. Their model builds on Solow's (1956) economic growth model by adding the assumptions that production generates pollution but that the pollution can be reduced by allocating some final production to that pollution abatement. The resulting model implies that countries' level of emissions will converge over time though emissions may rise initially in poorer countries due to rapid economic growth before falling.

While the predictions of the Green Solow model seem plausible given the recent empirical evidence, discussed below, it is not a very satisfying model of the evolution of the economy and emissions. First, it leaves the assumption that the share of abatement in the costs of production is constant as well as other assumptions of the model unexplained. Second, there is actually little correlation between countries' initial levels of income per capita and their subsequent growth rates that drives convergence of income in the Solow model (Durlauf *et al.*, 2005). On the other hand, the assumption of the static models that pollution externalities are optimally internalized over the course of economic does not seem very plausible. Therefore, there is plenty of scope for future research on theoretical models of economic growth and environmental quality.

IV. Econometric Methods

Grossman and Krueger's original EKC estimates used a simple cubic function of the levels of income per capita while Shafik (1994) regressed levels of the environmental indicators on quadratic or cubic functions of the log of income per capita. Neither of these approaches constrains the dependent variable to be non-zero. But economic activity inevitably implies the use of resources and, by the laws of thermodynamics, use of resources inevitably implies the production of waste. Regressions that allow levels of indicators to become zero or negative are inappropriate except in the case of the net rates of change of the stock of renewable resources, where, for example, afforestation can occur. The non-zero restriction can be applied by using a logarithmic dependent variable. The standard EKC regression model is then:

$$\ln E_{it} = \alpha_i + \gamma_t + \beta_1 \ln Y_{it} + \beta_2 \left(\ln Y_{it}\right)^2 + \varepsilon_{it} \qquad (2)$$

where E is either ambient environmental quality or emissions per person, Y is gross domestic product per capita, ε is a random error term, and ln indicates natural logarithms. The first two terms on the right-hand side of the equation are intercept parameters which vary across countries or regions *i* and years *t* and are called country effects and time effects respectively. The assumption is that though the level of emissions per capita may differ over countries at any particular income level, the elasticity of emissions with respect to income is the same in all countries at a given income level. The time specific intercepts are intended to account for time-varying omitted variables and stochastic shocks that are common to all countries.

The "turning point" level of income, where emissions or concentrations are at a maximum, can be found using the following formula:

$$\tau = \exp\left(-0.5\beta_1 / \beta_2\right) \quad (3)$$

Usually the model is estimated with panel data – i.e. observations for many countries or states over a number of years – most commonly using the fixed effects estimator. But time-series and cross-section data have also been used and a very large number of estimations methods have been tried.

There are several econometric problems that may call into question whether estimates of equation (2) can be treated as a valid model. The most important of these are: omitted variables bias, integrated variables and the problem of spurious regression, and the identification of time effects.

There is plenty of evidence that equation (2) is too simple a model and that other omitted variables are important in explaining the level of emissions. For example, Harbaugh *et al.* (2002) re-examined an updated version of Grossman and Krueger's data. They found that the locations of the turning points for the various pollutants, as well as even their existence, were sensitive both to variations in the data sampled and to reasonable changes in the econometric specification. Stern and Common (2001) also showed that estimates of the EKC for sulfur emissions were very sensitive to the choice of sample. Both Harbaugh *et al.* and Stern and Common found using Hausman test statistics that there is a significant difference in the regression parameter estimates when equation (2) is estimated using the random effects estimator and the fixed effects estimator. This indicates that the regressors are correlated with the country effects and time effects, which indicates that the regressors are likely correlated with omitted variables and the regression coefficients are biased.

Tests for integrated variables designed for use with panel data find that sulfur and carbon emissions and GDP per capita are integrated variables. This means that we can only rely on regression estimates of (2) using panel (or time series) data if the regression exhibits cointegration. Otherwise, the model must be estimated using another approach such as first differences or the between estimator, which first averages the data over time (Stern, 2010). Otherwise, the EKC estimate will be a spurious regression. As an illustration of this point, Verbeke and De Clerq (2006) carried out a Monte Carlo analysis where they generated large numbers of artificial integrated time series and then tested for an inverted U-shape relationship between the series. They found an "EKC" in 40% of cases despite using entirely arbitrary and unrelated data series.

Using real data, Perman and Stern (2003) found that for sulfur emissions in 74 countries from 1960 to 1990 around half the individual country EKC regressions cointegrate using standard panel data cointegration tests but many of these had parameters with "incorrect signs". Some panel cointegration tests indicated cointegration in all countries and some accept the non-cointegration hypothesis. But even when cointegration was found, the form of the EKC relationship varies radically across countries with many countries having U-shaped EKCs. A common cointegrating vector in all countries was strongly rejected. These results suggest too that important factors are omitted from the simple EKC model.

Wagner (2008) noted that standard panel cointegration methods do not take into account the presence of powers of unit root variables in EKC regressions and cross-sectional dependence in the data. Conventional panel cointegration methods are not intended for use with non-linear functions of unit-roots. First-generation panel unit root tests and cointegration procedures are also designed for cross-sectionally independent panels, which is a somewhat implausible assumption. Wagner uses de-factored regressions and so-called second-generation panel unit root tests to address these two issues.

Vollebergh *et al.* (2009) pointed out that time, income, or other effects are not uniquely identified in reduced form models such as the EKC and that existing EKC regression results depend on the specific identifying assumptions implicitly imposed. Equation (2) assumes that the time effect is common to all countries. A natural definition of the time effect would be the effects of the passage of time on pollution when there is no economic growth. But this effect might vary across countries. Vollebergh *et al.* solve the problem by assuming that there is a common time effect in each pair of most similar countries. They argue that this imposes the minimum restrictions on the nature of the time effect. Stern (2010) takes a different approach using the between estimator – a regression using the cross-section of time-averaged variables

– to estimate the effect of income. This model is then used to predict the effect of income on emissions using the time series of income in each country. The difference between the prediction and reality is the individual time effect for that country. This latter approach is, though, particularly vulnerable to omitted variables bias. Learning from this previous literature, Anjum *et al*. (2014) reformulate the EKC in terms of long-run growth rates, which avoids unit root issues, reduces omitted variables bias, and, they argue, more clearly identifies the time effect.

This econometric literature has shown that at best the EKC model is only a partial explanation of the evolution of pollution over time. As we will see in the next section, the recent more sophisticated methods also show that the effect of income on pollution is quite different to that shown in the early literature on the EKC.

V. Empirical Evidence

The empirical literature on the EKC is huge and so it is only possible to survey a small fraction of the results. I focus on some of the early studies that established the foundations of the EKC literature as well as some more recent studies that use more sophisticated estimation techniques. I also concentrate in particular on studies of sulfur dioxide emissions and compare and contrast those results to results for carbon dioxide.

Grossman and Krueger (1991) produced the first EKC study as part of a study of the potential environmental impacts of NAFTA. They estimated EKCs for SO_2, dark matter (fine smoke), and suspended particles (SPM) using the GEMS dataset. This dataset is a panel of ambient measurements from a number of locations in cities around the world. Each regression involved a cubic function in levels (not logarithms) of PPP (Purchasing Power Parity adjusted) per capita GDP and various site-related variables, a time trend, and a trade intensity variable. The turning points for SO_2 and dark matter are at around $4,000-5,000 while the concentration of suspended particles appeared to decline even at low income levels.

Shafik's (1994) study was particularly influential as the results were used in the 1992 *World Development Report*. Shafik estimated EKCs for ten different indicators using three different functional forms. Lack of clean water and lack of urban sanitation were found to decline uniformly with increasing income, and over time. Deforestation regressions showed no relation between income and deforestation. River quality tended to worsen with increasing income. Local air pollutant concentrations, however, conformed to the EKC hypothesis with turning points between \$3,000 and \$4,000. Finally, both municipal waste and carbon dioxide emissions per capita increased unambiguously with rising income. This result for carbon dioxide was confirmed by Holtz-Eakin and Selden (1995) and has stood the test of time despite a minority of contrary findings (e.g. Schmalensee *et al.*, 1998).

Selden and Song (1994) estimated EKCs for four emissions series: SO_2, NO_x, SPM, and CO. The data were primarily from developed countries. The estimated turning points were all very high compared to the two earlier studies. For the fixed effects version of their model they are (Converted to 1990 US dollars using the U.S. GDP implicit price deflator): SO_2, \$10,391; NO_x, \$13,383; SPM, \$12,275; and CO, \$7,114. This study showed that the turning point for emissions was likely to be higher than that for ambient concentrations. In the initial stages of economic development urban and industrial development tends to become more concentrated in a smaller number of cities, which also have rising central population densities with the reverse happening in the later stages of development. So it is possible for peak ambient pollution concentrations to fall as income rises even if total national emissions are rising (Stern *et al.*, 1996).

Table 1 summarizes several studies of sulfur emissions and concentrations from the first decade of EKC research, listed in order of estimated income turning point. On the whole the emissions-based studies have higher turning points than the concentrations-based studies. Among the emissions-based estimates, both Selden and Song (1994) and Cole *et al.* (1997) used databases that are dominated by, or consist solely of, emissions from OECD countries. Their estimated turning points are \$10,391 and \$8,232 respectively. List and Gallet (1998) used data for 1929 to 1994 for the fifty U.S. states. Their estimated turning point is the second highest in the table. Income per capita in their sample ranged from \$1,296 to \$25,049 in 1990 US dollars. This is a greater range of income levels than is found in the OECD-based panels for recent decades. This suggests that including more low-income data points in the sample might yield a higher turning point. Stern and Common (2001) estimated the turning point at over \$100,000. They used an emissions database produced for the US Department of Energy by ASL (Lefohn *et al.*, 1999) that covers a greater range of income levels and includes more data points than any of the other sulfur EKC studies. In conclusion, the studies that used more globally representative samples of data find that there is a monotonic relation between sulfur emissions and income just as there is between carbon dioxide and income.

Recent papers using more sophisticated econometrics also find that the relationship between the levels of both sulfur and carbon dioxide 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; Anjum *et al*., 2014). Both Vollebergh *et al*. (2009) and Stern (2010) find very large negative time effects for sulfur and smaller negative time effects for carbon since the mid-1970s. Anjum *et al*. (2014) find a zero or positive time effect for carbon and a negative effect for sulfur. On the other hand, using a set of simple cross-section carbon dioxide EKC regressions, Chow and Jie (2014) find a highly significant coefficient on the square of the log of GDP per capita (t = -22.9) in a standard EKC regression, claiming that this is conclusive econometric evidence for the carbon EKC. However, the mean turning point in their sample is in fact $378,000. The difference in significance level is a function of the large number of degrees of freedom compared to that in Stern's (2010) analysis.

Many studies extended on the basic EKC model by introducing additional explanatory variables intended to model underlying or proximate factors such as "political freedom" (e.g. Torras and Boyce, 1998), output structure (e.g. Panayotou, 1997), or trade (e.g. Suri and Chapman, 1998). On the whole, the included variables turn out to be significant at traditional significance levels (Stern, 1998). However, testing different variables individually is subject to the problem of potential omitted variables bias and there do not appear to be robust conclusions that can be drawn (Carson, 2010). The only robust conclusions from the EKC literature appear to be that concentrations of pollutants may decline from middle-income levels while emissions tend to be monotonic in income. As we will see below, emissions may decline over time in countries at many different levels of development.

VI. Critique of the EKC as a Policy Prescription

The presumed policy implication of the EKC as presented in the *1992 World Development Report* and elsewhere is that development is the best cure for environmental problems. Arrow *et al*. (1995) criticized this approach because it assumes that there is no feedback from environmental damage to economic production as income is assumed to be an exogenous variable. The assumption is that environmental damage does not reduce economic activity sufficiently to stop the growth process and that any irreversibility is not too severe to reduce the level of income in the future. In other words, there is an assumption that the economy is sustainable. But, if higher levels of economic activity are not sustainable, attempting to grow fast in the early stages of development when environmental degradation is rising may prove counterproductive.

It is clear that the levels of many pollutants per unit of output in specific processes have declined in developed countries over time with increasingly stringent environmental regulations and technological innovations. However, the mix of effluent has shifted from sulfur and nitrogen oxides to carbon dioxide and solid waste so that aggregate waste is still high and per capita waste may not have declined. Economic activity is inevitably environmentally disruptive in some way. Satisfying the material needs of people requires the use and disturbance of energy flows and materials. Therefore, an effort to reduce some environmental impacts may just aggravate other problems.

Both Arrow *et al*. (1995) and Stern *et al* (1996) argued that if there was an EKC type relationship it might be partly or largely a result of the effects of trade on the distribution of polluting industries. The Hecksher-Ohlin trade theory - the central theory of trade in modern economics - suggests that, under free trade, developing countries would specialize in the production of goods that are intensive in the production inputs that they are endowed with in relative abundance: labor and natural resources. The developed countries would specialize in human capital and manufactured capital-intensive activities. Part of the reduction in environmental degradation levels in the developed countries and increases in environmental degradation in middle-income countries might reflect this specialization. Environmental regulation in developed countries might further encourage polluting activities to gravitate towards the developing countries. These effects would exaggerate any apparent decline in pollution intensity with rising income along the EKC. In our finite world, the poor countries of today would be unable to find further countries from which to import resource intensive products as they themselves become wealthy. When the poorer countries apply similar levels of environmental regulation they would face the more difficult task of abating these activities rather than outsourcing them to other countries. Subsequent research has, however, found a weak role if any for offshoring of production in reducing emissions in developed countries (Cole, 2004; Stern, 2007; Levinson, 2010) though trade in electricity among U.S. states might have allowed a reduction in carbon emissions in the richer states (Aldy, 2005).

Some early EKC studies showed that a number of indicators: SO_2 emissions, NO_x, and deforestation, peak at income levels around the current world mean per capita income. A cursory glance at the available econometric estimates might have lead one to believe that, given likely future levels of mean income per capita, environmental degradation should decline from now on. This interpretation is evident in the 1992 *World Bank Development Report* (World Bank, 1992). However, income is not normally distributed but very skewed, with much larger numbers of people below mean income per capita than above it. Therefore, it is median rather than mean income that is the relevant variable. Selden and Song (1994) and Stern *et al*. (1996) performed simulations that, assuming that the EKC relationship is valid, showed that global environmental degradation was set to rise for a long time to come. More recent estimates show that the emissions turning point is higher and therefore there should not be room for confusion on this issue.

Another possible interpretation of the EKC is that there are no environmental policies in developed countries and that only when a certain income threshold is passed are policies introduced (Stokey, 1998). This does not actually seem to be the case. Dasgupta *et al*. (2002) presented evidence that environmental improvements are possible in developing countries and they argued that peak levels of environmental degradation will be lower than in countries that developed earlier. Some developing countries have also pledged quite ambitious climate policies (Stern and Jotzo, 2010) and China and other countries have taken extensive action to reduce emissions of air pollutants (Zhao *et al*., 2013). However, the high rate of economic growth in some middle-income countries has in many cases outweighed their efforts at environmental improvement. Instead of arguing that growth is the only way to reduce environmental impacts existing environmental institutions in developing countries need to be encouraged in order to further offset the effects of that growth.

VII. Alternative Approaches

There are several alternative approaches to modeling the income-emissions relationship. The most prominent of these in the economics literature are decomposition analysis and convergence analysis.

An increasing number of studies carry out decompositions of emissions into the proximate sources of emissions changes described in section III. The usual approach is to utilize index numbers and detailed sectoral information on fuel use, production, emissions etc. that unfortunately is unavailable for most countries. Stern (2002) and Antweiler *et al*. (2001) develop econometric decomposition models that require less detailed data and cruder decompositions that ignore structural change can employ the Kaya identity (e.g. Raupach *et al.*, 2007).

The conclusion from the studies conducted so far is that the main means by which emissions of pollutants can be reduced is by time-related technique effects and in particular those directed specifically at emissions reduction, though productivity growth or declining energy intensity has a role to play particularly in the case of carbon emissions where specific emissions reduction technologies do not yet exist (Stern, 2004b).

Though the contributions of structural change in the output mix of the economy and shifts in fuel composition may be important in some countries at some times, their average effect seems less important quantitatively. Those studies that include developing countries, find that changes in technology are occurring in both developing and developed countries. Innovations may first be adopted preferentially in higher income countries but seem to be adopted in developing countries with relatively short lags (Stern, 2004b). This is seen for example for lead in gasoline where most developed countries had substantially reduced the average lead content of gasoline by the early 1990s but many poorer countries also had low lead contents (Hilton and Levinson, 1998). Lead content was much more variable at low-income levels than at high income levels.

The convergence approach is the second major alternative approach to modeling the evolution of emissions. There are three main approaches to testing for convergence: sigma convergence, which tests whether the variance of the variable in question declines over time; 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 of the variable. Using beta and stochastic convergence tests, Strazicich and List (2003) found convergence among the developed economies. Using sigma convergence approaches, Aldy (2006) also found convergence for the developed economies but not for 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, but recent research using stochastic convergence finds evidence of club convergence rather than global convergence (Herrerias, 2013). By contrast, using the beta convergence approach Brock and Taylor (2010) find statistically significant convergence across 165 countries between 1960 and 1998.

VIII. Conclusions and Future Research Directions

The evidence presented in this article shows that the statistical analysis on which the environmental Kuznets curve is based is not robust. There is little evidence for a common inverted U-shaped pathway that countries follow as their income rises. There may be an inverted U-shaped relation between urban ambient concentrations of some pollutants and income though this should be tested with the more newly developed econometric approaches. It seems unlikely that the EKC is a complete model of emissions or concentrations.

The true form of the emissions-income relationship is likely to be monotonic but the curve shifts down over time. Some evidence shows that a particular innovation is likely to be adopted preferentially in high-income countries first with a short lag before it is adopted in the majority of poorer countries. However, emissions may be declining simultaneously in low- and high-income countries over time, *ceteris paribus*, though the particular innovations typically adopted at any one time could be different in different countries. It seems that structural factors on both the input and output sides do play a role in modifying the gross scale effect though they are less influential on the whole than time related effects. In slower-growing economies, emissions-reducing technological change can overcome the scale effect of rising income per capita on emissions. As a result, substantial reductions in sulfur emissions per capita have been observed in many developed countries in the last few decades. In faster growing middle-income economies the effects of rising income overwhelmed the contribution of technological change in reducing emissions.

On the theoretical front, there is still scope for developing more complete dynamic models of the evolution of the economy and pollution emissions. On the empirical front, there has still been little explicit testing of alternative theories. Recently developed econometric methods have also only been applied to analyze a couple of well-known pollutants. Therefore, I expect that in coming years this will continue to be an active area of research interest. New related topics also continue to emerge. One that has emerged in the wake of the great recession in North America and Europe is what happens to emissions in the short run over the course of the business cycle. York (2012) found that carbon emissions rise faster with economic growth than they fall in recessions but this result is contradicted by other recent studies (Doda, 2013; Sheldon, 2013).

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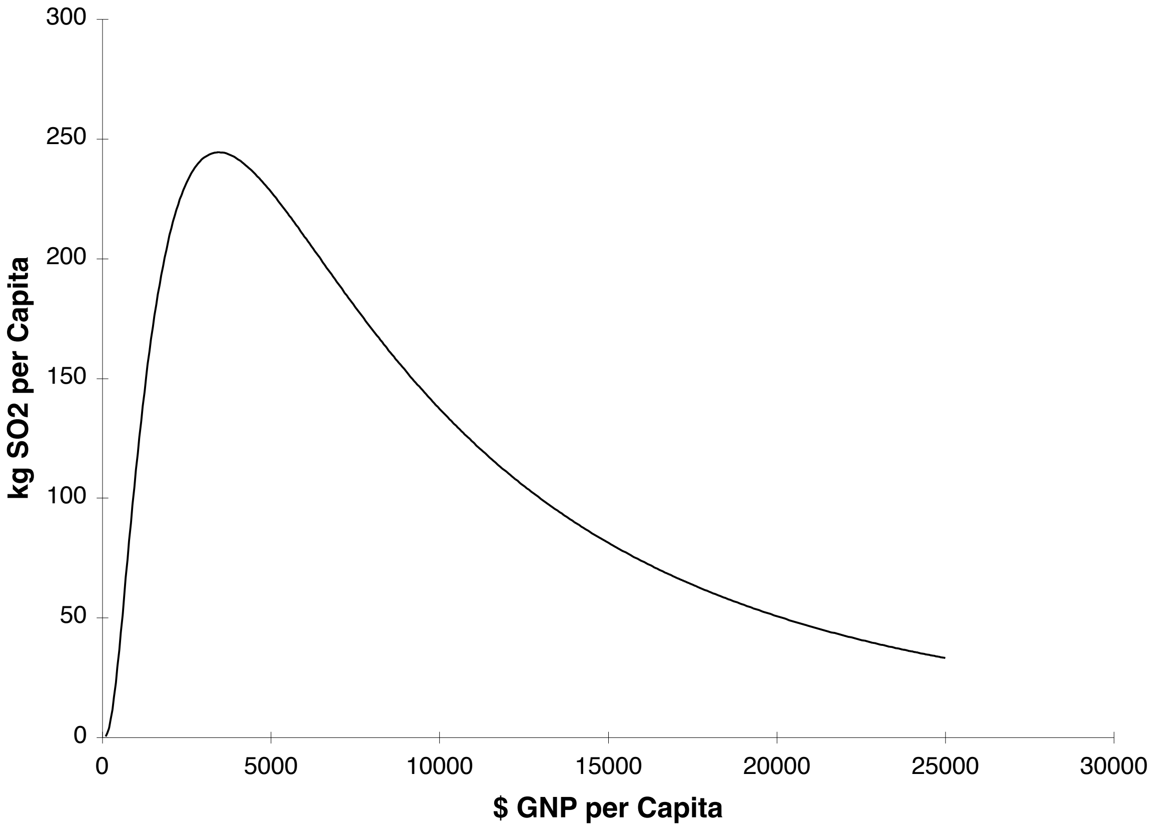
Table 1. Sulfur EKC Studies from the First Decade

Authors	Turning Point 1990 USD	Emis. or Concs.	PPP	Additional Variables	Data Source for Sulfur	Time Period	Countries/cities
Panayotou, 1993	$3,137	Emis	No	-	Own estimates	1987-88	55 developed and developing countries
Shafik, 1994	$4,379	Concs.	Yes	Time trend, locational dummies	GEMS	1972-88	47 Cities in 31 Countries
Torras and Boyce, 1998	$4,641	Concs.	Yes	Income inequality, literacy, political and civil rights, urbanisation, locational dummies	GEMS	1977-91	Unknown number of cities in 42 countries
Grossman and Krueger, 1991	$4,772-5,965	Concs.	No	Locational dummies, population density, trend	GEMS	1977, ‘82, ‘88	Up to 52 cities in up to 32 countries
Panayotou, 1997	$5,965	Concs.	No	Population density, policy variables	GEMS	1982-84	Cities in 30 developed and developing countries
Cole *et al*., 1997	$8,232	Emis.	Yes	Country dummy, technology level	OECD	1970-92	11 OECD countries
Selden and Song, 1994	$10,391-10,620	Emis.	Yes	Population density	WRI - primarily OECD source	1979--87	22 OECD and 8 developing countries
Kaufmann *et al*., 1998	$14,730	Concs.	Yes	GDP/Area, steel exports/GDP	UN	1974-89	13 developed and 10 developing countries
List and Gallet, 1999	$22,675	Emis.	N/A	-	US EPA	1929-1994	US States
Stern and Common, 2001	$101,166	Emis.	Yes	Time and country effects	ASL	1960-90	73 developed and developing countries

Figure 1. Environmental Kuznets Curve for Sulfur Emissions



Source: Panayotou (1993), Stern *et al*. (1996).