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ANALYSIS

The environmental Kuznets curve: does one size fit all?

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Abstract

This paper uses a new panel data set on state-level sulfur dioxide and nitrogen oxide emissions from 1929–1994 to test the appropriateness of the 'one size fits all' reduced-form regression approach commonly used in the environmental Kuznets curve literature. Empirical results provide initial evidence that an inverted-U shape characterizes the relationship between per capita emissions and per capita incomes at the state level. Parameter estimates suggest, however, that previous studies, which restrict cross-sections to undergo identical experiences over time, may be presenting statistically biased results. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Studies of the environmental Kuznets curve (EKC), which posit that an inverted-U relationship exists between a measure of wealth and environmental degradation, have attracted increasing attention in the literature.[1] Numerous studies have examined the issue (e.g. Hettige et al., 1992; Shafik and Bandyopadhyay, 1992; Panayatou, 1993; Cropper and Griffiths, 1994; Selden and Song, 1994; Antle and Heidebrink, 1995; Grossman, 1995; Grossman and Krueger, 1995; Holtz-Eakin and Selden, 1995; and the special issue of Ecological Economics, 1998), but perhaps the most convincing sign of the EKC's significance is that interest has extended well beyond academic circles (see, e.g. Arrow et al., 1995).

A plethora of the academic studies find that some pollutants adhere to the inverted-U hypothesis. With this evidence in mind, it may be tempting to generalize such results and argue that the 'way to attain a decent environment in most

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[1] Selden and Song (1994) suggest that the eventual improvement in environmental quality, associated with the negatively sloped region of the EKC, may be due to one or more of the following: a positive income elasticity for environmental quality, a shift in production and consumption towards less-polluting industries, increased education and concern for the environment, and a more open political process.

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countries is to become rich' (Beckerman, 1992). Although this premise is appealing, the EKC model has noteworthy limitations. First, the inverted-U relationship appears to hold for some pollutants, but it has not been found to be a particularly accurate depiction for all pollutants. For example, Shafik (1994), Holtz-Eakin and Selden (1995), and Roberts and Grimes (1997) find that carbon emissions fail to follow an inverted-U path. Second, if the estimated turning points occur at exceedingly high levels of wealth, the environmental benefits of economic growth may be unachievable for many countries. Third, some studies find that when alternative variables are included in the EKC specification, the estimated coefficients of the EKC equation either diminish in significance or no longer adhere to an inverted-U (Kaufmann et al., 1998; Rothman, 1998; Torras and Boyce 1998).

Another limitation of the existing EKC literature rests with the nature of the data under examination. Due to the lack of available data, studies have traditionally estimated EKCs with cross-country panel data. Given that the quality of such data is often questionable, the empirical results obtained may be suspect. Furthermore, since the common method of estimation with panel data assumes that all cross-sections adhere to the same EKC, if cross-sections vary in terms of resource endowments, infrastructure, etc., it may be unreasonable to impose isomorphic EKCs (see Unruh and Moomaw, 1998). We address these and other issues using a new panel data set on state-level sulfur dioxide (SO_2) and nitrogen oxide (NO_x) emissions from 1929–1994. Our analysis focuses on two hypotheses. First, do emissions at the state-level follow the inverted-U shape proposed by the previously cited cross-country studies? Yes, we find that US states have undergone the familiar environmental degradation followed by environmental amelioration found in many recent cross-country studies. Second, is it appropriate to restrict states to follow isomorphic EKCs? No, empirical results suggest parameter estimates will be miscalculated if the modeler assumes interstate slope homogeneity.

The remainder of the paper is organized as follows: Section 2 describes the data and econometric techniques employed. Section 3 presents empirical results, and Section 4 concludes.

2. Data and econometric techniques

2.1. Data

Data for emissions of the two criteria air pollutants, SO_2 and NO_x, come from the US Environmental Protection Agency (EPA) in their National Air Pollutant Emission Trends, 1900–1994, and encompass the fiscal years 1929–1994. Emission estimating methodologies for this time period fall into two major categories: 1929–1984 and 1985–1994. Emission estimates from 1929–1984 are calculated using a 'top-down' approach where national information is used to create a national emission estimate based on activity indicators, material flows, control efficiencies, and fuel property values. National estimates are then allocated to states based on state production activities. A variety of factors account for state production activities. For example, to estimate emissions from motor vehicles, a primary emitter of both SO_2 and NO_x, a typical estimation process relies on fuel type, vehicle type, technology, and extent of travel. Given that vehicle activity levels are related to changes in economic conditions, fuel prices, cost of regulations, and population characteristics, emissions from motor vehicles are a function of vehicle activity levels and emission rates per unit activity. Emissions for the years 1985–1994 are estimated using a 'bottom-up' methodology where emissions are derived at the plant or county level and aggregated to the state-level.

Use of US emission data has both advantages and disadvantages. In light of comments by Grossman (1995) and Stern et al. (1996), a major advantage of using US data is that they are probably much more reliable than the Global Environmental Monitoring System (GEMS) data used in many cross-country studies. Another advantage in using these data is tied to the length of the sampling period. Since they encompass a reasonably long time period (1929–1994), there is a greater chance that they will capture both the upward and downward sloping portions of the estimated EKC, alleviating some of the concerns about out-of-sample turning points. One possible shortcoming of these data is that emission estimates for 1985–1994 are direct measurements, whereas estimates prior to 1985 are indirect measurements, leading to the potential introduction of bias in the data. Empirical methods described below control for this potential aggregation problem.

2.2. Econometric model

Maintaining consistency with previous studies, we model state-level emissions as a quadratic and a cubic function of state per capita income:

$$P_{jit} = \sum_{k=1}^{K} \beta_{jki} X_{jkit} + \Phi_{ji} T + \varepsilon_{jit} \quad i = 1, 2, \ldots, 48 \quad t = 1, 2, \ldots, 66 \tag{1}$$

where P_{jit} represents per capita emissions of pollutant j ($j = SO_2$, NO_x) in state i at time t, β_{jki} is the unknown vector of potentially heterogeneous intercept and slope coefficients, X_{jkit} is the vector of K exogenous parameters for state i at time t, where $K = 3$ in the quadratic case and $K = 4$ in the cubic specification ($X_{j1it} = 1$, representing the constant term), Φ_{ji} is the vector of potentially heterogeneous coefficient estimates on time, $T =$ 1929, 1930, . . ., 1994; and ε_{jit} is the contemporaneous error term.[2] Table 1 contains descriptive statistics for all variables.

A few noteworthy aspects of equation (1) warrant further discussion. First, equation (1) is in its familiar reduced-form to allow direct and indirect measures of the relationship between income and emissions. Thus, inclusion of endogenous characteristics of income growth, such as composition of output, education, and regulatory intensities, would undermine the objective (see, e.g. Holtz-Eakin and Selden, 1995). Because equation (1) is in reduced-form, one must refrain from making causality conjectures; hence we cannot directly infer why the relationship between income and pollution exists. Second, equation (1) explicitly allows states to have heterogeneous slope and intercept parameters. Since the general premise underlying the EKC is that a single cross-sectional unit undergoes the inverted-U relationship over time, this estimation procedure not only allows this process to occur, but potentially avoids heterogeneity bias, which leads to inconsistent and biased parameter estimates. Previous EKC studies have allowed intercept heterogeneity, but have ignored the possibility of slope heterogeneity due to data limitations, i.e. pre-World War II pollution data are unavailable for most countries. As a consequence, these studies run a higher risk of omitted variable bias since countries may not have isomorphic EKCs. Nevertheless, akin to previous EKC studies that use panel data models, efficiency gains from joint parameter estimation are still obtained in our regression model since we estimate equation (1) as a system. Third, equation (1) allows for state-specific time trends, which reduce the unexplained variation in the dependent variable by accounting for factors such as pollution abatement technologies, temporal population fluctuations, institutional particulars regarding environmental regulation, and nuances in the data set such as emission estimating methodologies.

Another concern in estimation of equation (1) is whether the response coefficients (β_{jki}, Φ_{ji}) should be considered fixed or random parameters. If they are assumed fixed, equation (1) is the seemingly unrelated regressions (SUR) model, and if they are assumed random, the Swamy

Table 1
Descriptive statistics[a,b]

Variable	Mean (SD)	Minimum	Maximum
Per Capita Nitrogen oxide	0.092 (0.073)	0.023	1.14
Per capita Sulfur dioxide	0.16 (0.21)	0.002	1.62
Per capita Income (1987$)	$9089 ($4241)	$1162	$22 462

[a] Descriptive statistics are for the 48 contiguous states for the period 1929–1994 ($n = 3168$).

[b] Emission levels are measured in one thousand short tons.

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[2] Emission data are measured in one thousand short tons and are in per capita terms. Income and population data are from the State Annual Summary Tables constructed by the US Department of Commerce, 1929-1994.

Table 2
Summary estimates of environmental Kuznets curves[a]

Estimation Technique	Traditional model[b]				General model[c]			
	NO$_x$		SO$_2$		NO$_x$		SO$_2$	
	Quadratic	Cubic	Quadratic	Cubic	Quadratic	Cubic	Quadratic	Cubic
Income	1.8E-5	3.0E-5	8.6E-5	1.1E-4	–	–	–	–
	(7.9)	(9.5)	(14.1)	(13.3)	–	–	–	–
Income^2	−8.5E-10	−2.4E-9	−2.1E-9	−5.6E-9	–	–	–	–
	(−13.6)	(−8.2)	(−13.0)	(7.3)				
Income^3	–	4.8E-14	–	1.1E-13	–	–	–	–
		(5.5)		(4.6)				
Estimated turning point of peak (1987$)[d]	$10 778	$8656	$20 138	$22 553	–	–	–	–
	(655)	(589)	(1140)	(2076)				
Unweighted mean turning point of peak[d]	–	–	–	–	$17 577	$12 731	$19 480	$15 502
					(2573)	(489)	(1984)	(2552)
Median turning point of peak (1987$)[d]	–	–	–	–	$14 977	$12 923	$16 826	$13 192
F[e] (DF)	–	–	–	–	3.63	2.68	12.62	13.56
					(94 3072)	(141 3024)	(94 3072)	(141 3024)
State effects	YES	YES	YES	YES	YES	YES	YES	YES

[a] Dependent variable is per capita emissions of nitrogen oxide or sulfur dioxide. t-ratios in parentheses under coefficient estimates.

[b] Traditional model allows heterogeneous intercepts but assumes slope homogeneity.

[c] General model allows both intercept and slope heterogeneity.

[d] Standard errors in parentheses under turning point estimates.

[e] F-test is for slope heterogeneity; H$_o$: $\beta_{ki}=\beta_{k1}$ for all i states.

(1970) random coefficient model results. The important consideration is whether the variable coefficients are correlated with per capita income. If they are, the Swamy model returns inconsistent and biased estimates. If the coefficients are orthogonal to income levels, the Swamy model is appropriate since the interstate variation in emissions is taken into account and, therefore, coefficient estimates are more efficient than the alternative SUR model. Equation (1) suggests a fixed effects formulation, in that the β_{j1i} (state-specific intercept terms), which partially determine the location of the EKC, are most likely correlated with state income levels. Indeed, in all cases a Hausman (1978) test rejects the random effects formulation in favor of the fixed effects model. Therefore, only the fixed coefficient estimates are provided below.[3]

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[3] Nevertheless, parameter estimates across models are highly similar. This is not unusual, as it is well known that fixed and random effects estimates converge when the number of cross-sections and the length of the time-series both expand.

3. Empirical results

Table 2 contains summary estimation results for the 'traditional' and more general empirical models.[4] Columns 1–4 of Table 2 include response coefficient estimates for the empirical models that assume homogeneous slopes but allow intercept heterogeneity. Jointly, parameter estimates in each of the traditional specifications are consistent with an inverted-U EKC and are significant at the 1% level. Hence, estimated parameters suggest that, after a critical level of income is reached, per capita income and per capita emissions are negatively related. The estimated turning points of the quadratic and cubic models indicate that per capita emissions of nitrogen oxides reached a peak at an income level close to \$9000, while per capita sulfur emissions began to decline at an income level around \$21 000 (in 1987 US dollars).[5] Given that 1929–1994 real income levels ranged from \$1162 to \$22 462, the data capture both the upward and downward sloping portions of the estimated EKC for NO_x, but the SO_2 turning point is on the boundary of our sample.[6]

Table 2 also contains summary estimates from the more general specifications, which allow both slope and intercept heterogeneity. A first issue is whether the general model is necessary. Homogeneity tests of identical slopes across states are presented in columns 5–8 of Table 2 (NO_x: quadratic, $F(94, 3072) = 3.63$; cubic, $F(141, 3024) = 2.68$; SO_2: quadratic, $F(94, 3072) = 12.62$; cubic, $F(141, 3024) = 13.56$). Given that the magnitudes of these F-statistics are sufficient to reject the null of slope homogeneity at conventional levels of significance, we reject the traditional econometric specification for all estimated models, implying that states have not undergone identical EKC experiences. This finding indicates that slope heterogeneity should be controlled in the econometric equation to mitigate the possibility of biased and inconsistent parameter estimates.

Besides parameter estimates, we also include the unweighted mean and median turning points for the peak of the general EKCs in columns 5–8 of Table 2. An interesting result is that in the general models the estimated turning points are much different from comparable turning point estimates in the traditional models. Allowing for state-specific EKCs, we find that the median turning points for NO_x (SO_2) occur at higher (lower) per capita incomes than the traditional model predicts. Although turning points in both the quadratic and cubic SO_2 specifications remain at higher income levels than comparable turning point estimates in the NO_x models, 95% confidence intervals around the mean peaks overlap for each model type. As such, turning points are identical in a statistical sense, which is more in line with the empirical findings of Selden and Song (1994) and Grossman (1995).

Tables 3 and 4 provide estimates of state-specific EKCs for NO_x and SO_2. In each table, we also present state-specific peaks, inflection points, and troughs for each pollutant type. To provide a more thorough presentation, we use these estimates to construct Tables 5 and 6, which contain states that follow an inverted-U EKC. In Tables 5 and 6, we split states into three groups according to their estimated peak in each model type (quadratic and cubic). The three groups are constructed based on whether the state's estimated

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[4] In all specifications the null hypothesis of homogenous intercept terms is rejected. Fixed state effects and estimated coefficients on time are available upon request.

[5] These estimated turning points are reasonably close to those obtained by Selden and Song (1994) and Grossman (1995). In particular, Selden and Song estimate cross-country turning points for NO_x and SO_2 to be \$12 041–\$21 773 and \$8916–\$10 681, respectively; whereas Grossman, using US pollution concentration data, estimates turning points for NO_x and SO_2 to be \$18 453 and \$13 379, respectively. Although our estimated turning points for NO_x occur prior to SO_2, contrary to Selden and Song and Grossman, attention will soon be given to the more appropriate specification which allows EKCs to vary across states.

[6] Since per capita income may depend on the 'environmental resource base' of the economy, following Arrow et al. (1995) and Stern et al. (1996), we suspect simultaneity bias may be an issue in our models. To test for endogeneity of income, similar to Holtz-Eakin (1994), we construct an instrumental variable estimator that uses the mean of bordering states' income levels as the instrument. Estimation results from a Hausman (1978) general specification test for the quadratic model suggest that the null of exogeneity cannot be rejected for either pollutant type (NO_x:$\chi^2(2) = 0.15$; SO_2: $\chi^2(2) = 3.34$).

Table 3
State-level NO_x environmental Kuznets curves[a]

State	Quadratic model Income	 Income^2	 Turning point (peak)	Cubic model Income	 Income^2	 Income^3	 Turning Points (trough; peak)
Alabama	0.81	−5.40E-05	7462	−1.55	3.56E-04	−1.86E-08	2785; 9975
	(1.55)	(−2.02)		(−1.84)	(3.14)	(−3.74)	
Arizona	−0.10	2.74E-05	1770[b]	−3.88	5.42E-04	−2.00E-08	4918; 13 148
	(−0.12)	(0.65)		(−2.12)	(2.4)	(−2.36)	
Arkansas	0.90	−1.71E-05	26 169	0.23	7.00E-05	−5.00E-09	– – –; 10 747
	(2.08)	(−0.71)		(0.29)	(0.62)	(−0.95)	
California	−0.08	4.72E-06	7976[b]	−3.29	3.26E-04	−9.00E-09	7182; 16 966
	(−0.05)	(0.08)		(−0.81)	(0.85)	(−0.82)	
Colorado	1.10	−3.65E-05	15 068	−0.29	1.33E-04	−6.00E-09	1185; 13 601
	(2.98)	(−2.12)		(−0.37)	(1.55)	(−1.97)	
Connecticut	0.46	−1.52E-05	15 131	1.01	−6.12E-05	1.00E-09	29 316; 11 484
	(2.2)	(−2.31)		(1.86)	(1.41)	(1.00)	
Delaware	1.54	−9.78E-05	7873	−1.44	2.22E-04	−1.00E-08	4800; 10 000
	(1.74)	(−2.19)		(−0.45)	(0.72)	(−1.21)	
Florida	−2.23	1.10E-04	10 136[b]	−10.50	1.07E-03	−3.20E-08	7292; 15 000
	(−3.09)	(3 49)		(−8.18)	(7.9)	(−7.00)	
Georgia	0.76	−2.46E-05	15 406	−1.97	3.67E-04	−1.50E-08	3387; 12 923
	(2.26)	(−1.73)		(−4.21)	(6.8)	(−7.45)	
Idaho	0.27	−3.35E-06	40 298	−1.90	3.48E-04	−1.50E-08	3540; 11 926
	(0.30)	(−0.06)		(−0.98)	(1.27)	(−1.35)	
Illinois	1.36	−4.44E-05	15 315	0.51	5.23E-05	−3.00E-09	– – –; 15 338
	(6.80)	(−4.86)		(0.96)	(0.97)	(−2.02)	
Indiana	0.93	−2.02E-05	22 945	−0.70	1.75E-04	−7.00E-09	2324; 14 326
	(2.08)	(−0.84)		(−0.70)	(1.42)	(−1.48)	
Iowa	0.53	−2.25E-05	11 733	−0.26	9.96E-05	−5.00E-09	1467; 11 819
	(2.56)	(−2 09)		(−0.53)	(1.62)	(−2.16)	
Kansas	0.84	−3.22E-05	12 981	−1.29	2.80E-04	−1.20E-08	2812; 12 743
	(1.71)	(−1.18)		(−1.20)	2.09	(−2.39)	
Kentucky	1.36	−4.54E-05	14 977	−1.93	5.21E-04	−2.50E-08	2201; 11 692
	(2.03)	(−1.27)		(−1.67)	(3.33)	(−3.74)	
Louisiana	2.61	−1.79E-04	7290	−3.46	8.36E-04	−4.60E-08	2648; 9467
	(1.11)	(−1.44)		(−0.78)	(1.32)	(−1.71)	
Maine	0.55	−2.06E-05	13 228	0.15	3.95E-05	−2.00E-09	– – –; 14 870
	(1.61)	(−1.24)		(0.18)	(0.41)	(−0.68)	
Maryland	0.16	−3.80E-06	21 052	−0.56	8.11E-05	−2.58E-09	4359; 16 575
	(0.39)	(−0.25)		(−0.59)	(0.96)	(−1.10)	
Massachusetts	0.28	−8.92E-06	15 863	0.05	1.60E-05	−7.30E-09	– – –; 2457
	(1.03)	(−1.04)		(0.09)	(0.30)	(−0.52)	
Michigan	0.68	−2.56E-05	13 261	−0.05	5.95E-05	−2.89E-09	434; 13 258
	(3.48)	(−2.71)		(−0.10)	(1.03)	(−1.54)	
Minnesota	−1.76	4.75E-05	18 526[b]	−2.61	1.91E-04	−5.56E-O9	–
	(−1.40)	(0.95)		(−1.15)	(0.80)	(−0.71)	
Mississippi	1.20	−4.80E-06	125 000	0.29	1.99E-04	−1.25E-08	– – –; 11 293
	(3.13)	(−0.20)		(0.44)	(1.98)	(−2.46)	
Missouri	0.94	−2.30E-05	20 434	−0.42	1.48E-04	−6.52E-09	1585; 13 539
	(3.06)	(−1.66)		(−0.64)	(1.97)	(−2.47)	
Montana	2.21	−1.63E-04	6779	−3.38	5.48E-04	−2.48E-08	4395; 10 335
	(1.22)	(−1.57)		(−0.73)	(0.90)	(−1.03)	
Nebraska	0.276	8.42E-06	–	−0.61	1.42E-04	−5.71E-09	2536; 14 068
	(1.01)	(0.58)		(−1.0)	(1.89)	(−2.08)	

Table 3 (continued)

	Quadratic model			Cubic model			
State	Income	Income^2	Turning point (peak)	Income	Income^2	Income^3	Turning Points (trough; peak)
Nevada	−1.48	7.40E-05	10 000[b]	−6.53	5.20E-04	−1.07E-08	8519; 23 880
	(−0.30)	(0.31)		(−0.44)	(0.38)	(−0.27)	
New Hampshire	1.01	−2.91E-05	17 353	−0.13	1.08E-04	−4.24E-09	625; 16 381
	(2.15)	(−1.97)		(−0.15)	(1.48)	(−1.97)	
New Jersey	−0.31	1.16E-05	13 189[b]	−1.29	1.28E-04	−3.22E-09	6767; 19 734
	(−0.40)	(0.46)		(−0.70)	(0.84)	(−0.83)	
New Mexico	3.79	−1.71E-04	11 081	−5.14	1.43E-03	−7.45E-08	2163; 10 633
	(3.54)	(−2.52)		(−2.44)	(4.44)	(−5.19)	
New York	0.37	−1.17E-05	15 641	0.38	−1.22E-05	−7.00E-11	– – –; 14 040
	(1.33)	(−1.19)		(0.48)	(0.18)	(−0.04)	
North Carolina	1.48	−6.73E-05	10 995	0.01	1.63E-04	−9.58E-09	– – –; 11 387
	(4.80)	(−5.19)		(0.03)	(2.92)	(−4.38)	
North Dakota	−0.30	1.16E-05	12 801[b]	−1.97	2.01E-04	−6.10E-09	7380; 14 587
	(−0.54)	(0.45)		(−1.75)	(1.32)	(−1.02)	
Ohio	1.48	−4.94E-05	14 979	−0.43	1.83E-04	−8.25E-09	1287; 13 487
	(6.43)	(−3.98)		(−0.68)	(2.51)	(−3.34)	
Oklahoma	0.88	−1.83E-05	24 016	−2.0	4.61E-04	−1.94E-08	2593; 13 248
	(1.56)	(−0.62)		(−1.85)	(2.93)	(−2.96)	
Oregon	−0.73	4.18E-05	8720[b]	−3.28	3.91E-04	−1.27E-08	5877; 14 647
	(−0.69)	(0.74)		(−1.23)	(1.28)	(−1.19)	
Pennsylvania	1.28	−5.22E-05	12 260	−0.12	1.12E-04	−5.58E-09	559; 12 836
	(4.60)	(−4.08)		(−0.17)	(1.62)	(−2.52)	
Rhode Island	0.04	−8.53E-06	2344	0.54	−5.99E-05	1.52E-09	20 494; 5733
	(0.09)	(−0.45)		(0.39)	(−0.45)	(0.38)	
South Carolina	0.92	−3.16E-05	14 509	−1.11	2.87E-04	−1.40E-08	2332; 11 335
	(2.64)	(−1.78)		(−1.90)	(3.79)	(−4.25)	
South Dakota	0.48	−1.37E-05	17 591	−0.83	2.05E-04	−9.42E-09	2432; 12 079
	(1.85)	(0.95)		(−1.59)	(2.83)	(−3.21)	
Tennessee	1.92	−7.46E-05	12 868	0.27	1.87E-04	−1.16E-08	– – –; 11 433
	(3.12)	(−2.60)		(0.26)	(1.44)	(−2.26)	
Texas	2.6	−1.30E-04	10 000	0.70	1.59E-04	−1.22E-08	– – –; 10 510
	(2.32)	(−2.49)		(0.32)	(0.58)	(−1.18)	
Utah	0.51	−1.40E-05	18 285	2.35	−2.69E-04	9.84E-09	10 965; 7260
	(0 93)	(−0.35)		(1.61)	(−1.32)	(1.15)	
Vermont	0.55	−1.38E-05	19 963	0.02	7.52E-05	−3.46E-09	– – –; 14 590
	(1.37)	(−0.81)		(0.02)	(0.84)	(−1.11)	
Virginia	0.61	−3.41E-05	8958	0.50	−2.04E-05	−6.02E-10	– – –; 8815
	(1.90)	(−2.87)		(0.88)	(−0.37)	(−0.33)	
Washington	−0.03	4.90E-07	34 795[b]	−3.28	3.52E-04	−1.12E-08	6993; 13 959
	(−0.07)	(0.02)		(−2.85)	(2.94)	(−2.94)	
West Virginia	2.27	−4.05E-05	28 024	−4.51	1.08E-03	−4.97E-08	2530; 11 957
	(2.08)	(−0.65)		(−2.19)	(3.87)	(−4.11)	
Wisconsin	0.92	−2.81E-05	16 405	−0.81	1.91E-04	−7.86E-09	2509; 13 706
	(3.63)	(−2.24)		(−1.38)	(2.83)	(−3.33)	
Wyoming	3.48	−7.05E-05	24 680	−30.2	4.03E-03	−1.37E-07	5044; 14 566
	(0.43)	(−0.21)		(−1.78)	(2.01)	(−2.0)	

[a] Dependent variable is per capita emissions of sulfur dioxide. Dashed markings indicate either undefined or negative value of per capita income. t-ratios in parentheses.

[b] Corresponds to a minimum.

Table 4
State-level SO_2 environmental Kuznets curves[a]

	Quadratic model			Cubic model			
State	Income	Income^2	Turning point (peak)	Income	Income^2	Income^3	Turning points (trough; peak)
Alabama	2.89	−2.02E-04	7153	−0.88	4.67E-04	−3.01E-08	1049; 9301
	(1.74)	(−2.33)		(−0.28)	(1.02)	(−1.50)	
Arizona	14.60	−9.93E-04	7351	40.0	−4.22E-03	1.15E-07	18 035; 6428
	(2.48)	(−3.21)		(2.39)	(−2.00)	(1.46)	
Arkansas	0.85	5.91E-05	–	1.59	−7.15E-05	6.21E-09	– – –; – – –
	(1.42)	(1.73)		(1.37)	(−0.39)	(0.73)	
California	0.20	1.23E-06	–	0.17	4.61E-06	−3.83E-11	– – –; 95 703
	(0.3)	(0.04)		(0.07)	(0.02)	(−0.01)	
Colorado	0.81	−1.48E-05	27 364	0.75	−1.08E-05	−7.10E-11	– – –; 27 226
	(2.38)	(−0.93)		(0.85)	(−0.11)	(−0.02)	
Connecticut	1.43	−3.84E-05	18 619	5.93	−4.25E-04	9.26E-09	19 836; 10 761
	(2.04)	(−1.72)		(2.79)	(−2.44)	(2.23)	
Delaware	2.75	−2.04E-04	6740	5.37	−4.43E-04	5.89E-09	43 088; 7053
	(1.11)	(−1.62)		(0.55)	(−0.47)	(0.21)	
Florida	0.72	−2.28E-05	15 789	−1.06	1.97E-04	−7.57E-09	3329; 14 019
	(1.08)	(−0.78)		(−0.69)	(1.16)	(−1.32)	
Georgia	2.13	−3.72E-05	28 629	−3.05	7.14E-04	−2.88E-08	2520; 14 007
	(2.18)	(−0.89)		(−1.74)	(3.25)	(−3.46)	
Idaho	1.18	−4.86E-05	12 139	3.74	−4.39E-04	1.58E-08	11 884; 6639
	(1.4)	(−0.90)		(1.79)	(−1.45)	(1.27)	
Illinois	7.88	−1.71E-04	23 040	12.90	−6.98E-04	1.59E-08	– – –; – – –
	(5.93)	(−2.80)		(3.16)	(−1.66)	(1.28)	
Indiana	7.99	−2.35E-04	17 000	6.08	−8.34E-06	−7.25E-09	– – –; 16 340
	(5.41)	(−2.92)		(1.53)	(−0.02)	(−0.41)	
Iowa	1.28	−5.27E-05	12 144	6.0	−6.92E-04	2.38E-08	12 838; 6545
	(1.18)	(−0.92)		(2.28)	(−2.07)	(1.94)	
Kansas	1.50	6.00E-06	–	2.45	−1.26E-04	5.4E-O9	– – –; – – –
	(1.75)	(0.12)		(1.11)	(−0.48)	(0.52)	
Kentucky	6.63	−2.29E-04	14 475	1.82	6.23E-04	−3.83E-08	– – –; 12 148
	(2.91)	(−1.86)		(0.39)	(0.40)	(−1.28)	
Louisiana	0.50	8.22E-06	–	−2.15	4.13E-04	−1.63E-08	3215; 13 676
	(0.24)	(0.07)		(−0.45)	(0.59)	(−0.55)	
Maine	1.65	−3.94E-05	20 939	1.63	−3.17E-05	−1.97E-10	– – –; 21 429
	(1.58)	(−0.76)		(0.53)	(−0.08)	(−0.01)	
Maryland	1.24	−2.86E-05	21 678	4.18	−3.15E-04	8.04E-O9	– – –; – – –
	(1.98)	(−1.24)		(2.37)	(−1.92)	(1.76)	
Massachusetts	1.48	−4.88E-05	15 163	3.79	−2.69E-04	5.9E-09	19 302; 11 093
	(1.49)	(−1.56)		(1.42)	(−1.14)	(0.94)	
Michigan	3.67	−1.25E-04	14 680	4.25	−1.85E-04	1.8E-09	53 923; 14 595
	(6.18)	(−435)		(2.52)	(−1.01)	(0.30)	
Minnesota	2.96	−9.56E-05	15 481	3.97	−2.24E-04	4.5E-O9	– – –; – – –
	(3.11)	(−2.51)		(1.91)	(−0.98)	(0.60)	
Mississippi	2.72	2.80E-07	–	0.90	3.84E-04	−1.96E-08	– – –; 14 143
	(3.05)	(0.01)		(0.57)	(1.42)	(−1.44)	
Missouri	6.07	−9.46E-05	32 082	−3.55	1.15E-03	−4.46E-08	1714; 15 475
	(3.67)	(−1.25)		(−0.89)	(2.43)	(−2.67)	
Montana	7.47	−4.04E-04	9245	9.35	−6.18E-04	7.00E-09	49 942; 8915
	(2.89)	(−2.73)		(1.25)	(−0.64)	(0.18)	
Nebraska	1.21	−2.48E-05	24 395	2.73	−2.43E-04	8.6E-09	– – –; – – –
	(1.44)	(−0.56)		(1 33)	(−0.94)	(−0.91)	

Table 4 (continued)

State	Quadratic model			Cubic model			
	Income	Income^2	Turning point (peak)	Income	Income^2	Income^3	Turning points (trough; peak)
Nevada	0.74	−2.19E-05	16 826	32.60	−3.03E-03	8.66E-08	14 909; 8416
	(0.17)	(−0.10)		(2.19)	(−2.19)	(2.17)	
New Hampshire	−3.76	−1.02E-04	–	2.34	6.55E-05	−5.1E-09	– – –; 17 368
	(2.68)	(−2.29)		(0.82)	(0.24)	(−0.64)	
New Jersey	−1.59	−2.37E-05	–	2.71	−1.20E-04	2.39E-09	– – –; – – –
	(1.86)	(−0.84)		(1.06)	(−0.55)	(0.43)	
New Mexico	−7.38	−4.89E-04	–	4.54	2.40E-05	−2.33E-08	– – –; 8409
	(3.06)	(−3.17)		(0.77)	(0.03)	(−0.57)	
New York	1.73	−4.65E-05	18 602	3.46	−1.99E-04	3.93E-09	– – –; – – –
	(2.81)	(−2.1)		(1.59)	(−1.06)	(0.80)	
North Carolina	2.72	−7.95E-05	17 106	2.33	−8.10E-06	−3.00E-09	– – –; 15 215
	(5.82)	(4.0)		(2.81)	(−0.08)	(−0.74)	
North Dakota	−0.67	4.63E-05	7192[b]	−0.76	3.84E-05	7.0E-10	17 283; – – –
	(0.75)	(1.11)		(−0.39)	(0.15)	(0.08)	
Ohio	6.85	−1.86E-04	18 413	7.0	−2.02E-04	7.0E-10	173 127; 19 254
	(6.66)	(3.34)		(2.22)	(0.56)	(0.06)	
Oklahoma	1.70	−4.06E-05	20 935	5.62	−6.97E-04	2.76E-08	10 146; 6689
	(2.28)	(−1.03)		(3.4)	(−2.85)	(2.8)	
Oregon	0.03	1.22E-05	– – –	0.34	−2.19E-05	1.18E-09	– – –; – – –
	(0.08)	(0.70)		(0.34)	(−0.20)	(0.30)	
Pennsylvania	4.11	−1.40E-04	14 678	4.98	−2.35E-04	2.94E-09	38 697; 14 590
	(6.12)	(−4.49)		(2.60)	(−1.12)	(0.44)	
Rhode Island	0.05	−8.58E-06	2989	8.12	−8.54E-04	2.58E-08	15 136; 6931
	(0.04)	(−0.16)		(1.76)	(−1.85)	(1.85)	
South Carolina	2.01	−3.27E-05	30 733	1.75	1.59E-05	−2.27E-09	– – –; 18 534
	(4.08)	(−1.28)		(1.86)	(0.12)	(−0.39)	
South Dakota	0.76	−4.24E-05	8938	0.26	3.33E-05	−3.00E-09	– – –; 10 208
	(1.89)	(−1.89)		(0.30)	(0.28)	(−0.63)	
Tennessee	6.64	−2.20E-04	15 090	2.60	4.19E-04	−2.67E-08	– – –; 12 965
	(3.23)	(−2.27)		(0.65)	(0.80)	(−1.28)	
Texas	1.45	−1.05E-05	69 047	2.35	−1.32E-04	4.54E-09	– – –; – – –
	(2.19)	(−0.34)		(1.52)	(−0.66)	(0.61)	
Utah	3.16	−1.16E-04	13 620	51.80	−7.06E-03	2.92E-07	10 472; 5646
	(0.69)	(−0.35)		(4.07)	(−3.98)	(3.93)	
Vermont	1.71	−1.96E-05	43 622	1.80	−1.80E-05	−5.66E-11	– – –; 41 770
	(1.75)	(−0.47)		(0.76)	(−0.07)	(−0.01)	
Virginia	1.19	−3.23E-05	18 421	3.91	−3.69E-04	1.12E-08	13 041; 8923
	(1.45)	(−1.05)		(2.44)	(−2.12)	(1.95)	
Washington	0.74	−2.69E-05	13 773	0.66	−1.44E-05	−4.97E-10	– – –; 13 419
	(1.81)	(−1.3)		(0.53)	(−0.11)	(−0.12)	
West Virginia	8.14	−2.03E-04	20 049	−10.0	2.73E-03	−1.29E-07	2164; 11 945
	(1.83)	(−0.79)		(−0.99)	(1.89)	(−2.06)	
Wisconsin	5.34	−1.62E-04	16 481	4.71	−7.58E-05	−2.96E-09	– – –; 16 025
	(4.39)	(−2.68)		(1.48)	(−0.20)	(−0.22)	
Wyoming	4.29	−4.37E-05	49 084	−10.7	1.85E-03	−6.46E-08	3553; 15 538
	(1.61)	(0.4)		(−1.62)	(2.40)	(−2.47)	

[a] Dependent variable is per capita emissions of sulfur dioxide. Dashed markings indicate either undefined or negative value of per capita income. t-ratios in parentheses.

[b] Corresponds to a minimum.

Table 5
Categorization of NO_x turning points for states that follow an inverted-U EKC[a]

Quadratic model			Cubic model		
Below	Within	Above	Below	Within	Above
Alabama	Iowa[b]	Arkansas	Massachusetts	Louisiana	Alabama[b]
Delaware[b]	New Mexico[b]	Colorado[b]	Rhode Island	Virginia	Arizona[b]
Louisiana	North Carolina[b]	Connecticut[b]	Utah		Arkansas
Montana	Texas[b]	Georgia[b]			California
Rhode Island		Idaho[b]			Colorado
Virginia[b]		Illinois[b]			Connecticut
		Indiana			Delaware
		Kansas			Florida[b]
		Kentucky			Georgia[b]
		Maine			Idaho
		Maryland			Illinois
		Massachusetts			Indiana
		Michigan[b]			Iowa
		Mississippi			Kansas
		Missouri[b]			Kentucky[b]
		New Hampshire[b]			Maine
		New York			Maryland
		Ohio[b]			Massachusetts
		Oklahoma			Michigan
		Pennsylvania[b]			Mississippi
		South Carolina[b]			Missouri
		South Dakota			Montana
		Tennessee[b]			Nebraska
		Utah			Nevada
		Vermont			New Hampshire
		West Virginia			New Jersey
		Wisconsin[b]			New Mexico[b]
		Wyoming			New York
					North Carolina
					North Dakota
					Ohio
					Oklahoma[b]
					Oregon
					Pennsylvania
					South Carolina[b]
					South Dakota
					Tennessee
					Vermont
					Washington[b]
					West Virginia[b]
					Wisconsin
					Wyoming[b]

[a] States are categorized according to whether their per capita income turning points fall below, within, or above the 95% confidence interval for the quadratic or cubic turning point of the traditional model.

[b] Indicates a state for which all estimated coefficients are statistically different from zero at the 10% or better level of significance.

turning point falls below, within, or above the 95% confidence interval surrounding the estimated peak of the traditional model. In summary, of the 48 contiguous states, 38 (47) of the states follow an EKC shape for the NO_x quadratic (cubic) model, whereas 38 (37) follow an inverted-

Table 6
Categorization of SO_2 turning points for states that follow an inverted-U EKC[a]

Quadratic model			Cubic model		
Below	Within	Above	Below	Within	Above
Alabama[b]	Connecticut[b]	Colorado	Alabama	Maine	California
Arizona[b]	Maine	Georgia	Arizona	Ohio	Colorado
Delaware	Maryland	Illinois[b]	Connecticut[b]	South Carolina	Vermont
Florida	New York[b]	Missouri	Delaware		
Idaho	Ohio[b]	Nebraska	Florida		
Indiana[b]	Oklahoma	South Carolina	Georgia[b]		
Iowa	Virginia	Texas	Idaho		
Kentucky[b]	West Virginia	Vermont	Indiana		
Massachusetts		Wyoming	Iowa[b]		
Michigan[b]			Kentucky		
Minnesota[b]			Louisiana		
Montana[b]			Massachusetts		
Nevada			Michigan		
North Carolina[b]			Mississippi		
Pennsylvania[b]			Missouri		
Rhode Island			Montana		
South Dakota[b]			Nevada[b]		
Tennessee[b]			New Hampshire		
Utah			New Mexico		
Washington			North Carolina		
Wisconsin[b]			Oklahoma[b]		
			Pennsylvania		
			Rhode Island[b]		
			South Dakota		
			Tennessee		
			Utah[b]		
			Virginia[b]		
			Washington		
			West Virginia		
			Wisconsin		
			Wyoming		

[a] States are categorized according to whether their per capita income turning points fall below, within, or after the 95% confidence interval for the quadratic or cubic turning point of the traditional model.

[b] Indicates a state for which all estimated coefficients are statistically different from zero at the 10% or better level of significance.

U for the SO_2 quadratic (cubic) model.[7] Evidence presented in Table 5 reinforces the empirical estimates in Table 2, and suggests that important differences exist in state EKCs, since the peak turning point for the majority of states falls outside the confidence interval for the peak of the traditional model, imposing an isomorphic EKC on all states leads us to ignore important differences across states. For example, we find that in general the traditional model predicts much earlier turning points for NO_x than what actually occurred. In contrast, the traditional model predicts a much later SO_2 turning point for the majority of states. Coupling these results suggests that the traditional model paints an overly opti-

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[7] As noted in Table 5, however, several state EKCs have one or more estimated coefficients that are insignificantly different from zero. Nonetheless, it is interesting to note that in many of the states for which all estimated coefficients of the cubic EKC are significantly different from zero, the shapes of the curves for NO_x and SO_2 are opposite of each other. In particular, for NO_x the curves fall, then rise, and then fall, inducing the troughs to occur before the peaks. For SO_2, however, the curves rise, then fall, and then rise, leading the troughs to occur after the peaks.

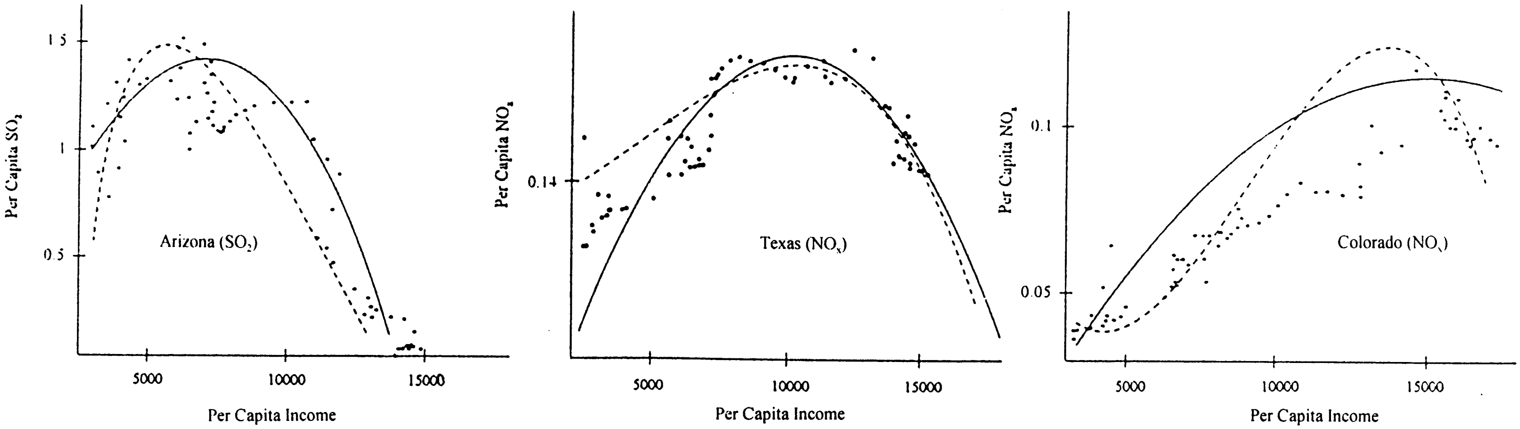

Fig. 1. EKCs for selected states [Quadratic (—), Cubic (- -)].

Table 7
Characteristics of states that follow a quadratic inverted-U[a]

	No_x			SO_2		
Characteristic	Below	Within	Above	Below	Within	Above
Population per square mile	0.29	0.07	0.13[b]	0.18	0.27	0.08
	(0.35)	(0.05)	(0.14)	(0.25)	(0.23)	(0.06)
Percent high school graduate	0.70	0.71	0.77[b]	0.73	0.72	0.74
	(0.05)	(0.05)	(0.07)	(0.07)	(0.04)	(0.06)
Number of heating degree days	1515.00	1651.50	1946.40[b]	1790.52	2004.75	1863.33
	(637.55)	(562.76)	(396.59)	(713.35)	(467.94)	(755.57)
Neighboring state per capita income	8967.90	8258.29	9041.25	9224.46	9410.80	8525.56[b]
	(1940.81)	(862.31)	(1097.78)	(1157.65)	(1113.44)	(1057.47)
Median age	30.20	29.59	30.20	33.94	31.23	29.65[b]
	(1.07)	(1.41)	(1.69)	(1.86)	(0.76)	(0.96)
NO_x level	0.10	0.12	0.09	0.08	0.08	0.11
	(0.04)	(0.0.5)	(0.06)	(0.03)	(0.04)	(0.09)
SO_2 level	0.15	0.16	0.16	0.22	0.14	0.12[b]
	(0.14)	(0.09)	(0.11)	(0.05)	(0.12)	(0.08)

[a] Figures correspond to means (with standard deviations given in parentheses).

[b] Indicates that below and above means are different from one another at the $P<0.10$ or better level of significance.

mistic scenario for reductions of NO_x emissions, whereas it portrays an overly pessimistic picture for emissions of SO_2.

This phenomenon is highlighted at the individual state-level in Fig. 1, which plots data that represent EKCs for three states across the three groupings in Tables 5 and 6. The three panels in Fig. 1 display plots for Arizona, Texas, and Colorado. Since the traditional model predicts that each cross-section should turn at an income per capita of $10 778 (quadratic) or $8656 (cubic) for NO_x and $20 138 (quadratic) or $22 553 (cubic) for SO_2, the plots give an indication of the error associated with an overly pessimistic prediction (Arizona; SO_2), an accurate prediction (Texas; NO_x), and an overly optimistic prediction (Colorado; NO_x). For example, it is quite clear from both the plot of the data and the regression curves that Arizona's EKC peaked at a much lower level of income than the traditional model predicts. In addition, Colorado peaks at much higher levels of income than the traditional model conjectures for both model types.

Given that the state-level turning points are potentially quite heterogeneous, as an initial exploratory probe we attempt to explain the location of the EKC using state-level indicators. Table 7 provides descriptive statistics for a variety of variables that may affect the location of the EKC. Using the same categorization of states that followed a quadratic inverted-U from Tables 5 and 6, we calculate sample means and standard deviations for population density (population per square mile), percent of population with a high school degree, number of heating degree days, median age, per capita levels of NO_x and SO_2, and neighbors' state income (computed as the mean income level of bordering states).[8]

The results in Table 7 are mixed. Comparing states that peak to the left of the traditional peak to those that peak to the right, we find that parametric t-tests of means suggest that mean population density is higher for those states that

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[8] Data on population per square mile, median age, percent of population with a high school degree, and neighbors' state income are from the US Census Bureau. The number of heating degree days is calculated by the US Department of Agriculture as (accumulated days) * (temperature $<65°$), and come from the Weekly Weather and Crop Report, 1990. Note that, among others, Selden and Song (1994), Grossman and Krueger (1995), and Torras and Boyce (1998) include such demographic factors as population density, adjacent country income, and/or literacy rates in specifications of the EKC. We avoid including regressors other than income to allow a more direct test of our hypotheses.

peak at lower income levels, although this result is only significant at the $P < 10$ level for NO_x. This result is intuitively appealing in that states with higher population densities, dominated by large urban areas, may have received attention from policymakers earlier in the pollution process (see Selden and Song, 1994). A further result that is potentially of some interest is that states with a greater number of heating degree days peak at higher levels of income than those states that have warmer climates. Since this result is statistically significant for NO_x, but not for SO_2, it may indicate that states in colder climates relied on less technologically advanced, more pollution-intensive methods of heating, leading them to 'turn the corner' at higher levels of per capita income. Also, at least for SO_2, states adjacent to higher per capita income states tend to have EKCs that peak before those states that neighbor lower income states. This result is sensible as SO_2 has many transboundary effects and wealthy neighbors may have induced polluters to reduce their SO_2 emissions. Evidence of this effect can be seen from the interstate compacts that many northeastern states have made over the past two decades (List and Gerking, 1996).

Another trend in our data is that states whose EKCs peak to the left of the traditional confidence interval tend to have higher per capita emissions of the respective pollutant. With respect to SO_2, for example, the average per capita SO_2 for states to the left (right) of the traditional peak is 0.22 (0.12). An explanation for this finding is that states with higher per capita emission levels react more quickly to adopt policies designed to combat pollution. We should note, however, that each of these findings should be considered preliminary, and stress that a more complete structural model is necessary to make causal statements about the shape and location of the EKC.

4. Concluding remarks

This paper used US state-level sulfur dioxide and nitrogen oxide emission data from 1929–1994 to estimate the reduced-form relationship between per capita emissions and incomes for US states. Results from panel data models provide initial evidence that states' emissions have followed an inverted-U path. Parameter estimates indicate, however, that previous studies, which restrict cross-sections to undergo identical experiences over time, may be presenting statistically biased results. Since sustainable development strategies critically depend on well-informed policymakers, this result highlights the importance of allowing generality in the EKC specification.

Our major finding that state-level EKCs differ from one another does not serve to indict those who have used the isomorphic model to test for a Kuznets (inverted-U) relationship between emissions or ambient pollution levels and a measure of income. Rather, it merely illustrates that past results are potentially biased due to data limitations. Nevertheless, this result is particularly alarming given that one would hypothesize if any cross-sections would follow similar pollution paths it would be US states, which are much more homogenous than the sample of countries used in previous EKC studies.

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