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The Environmental Kuznets Curve: Exploring a Fresh Specification

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Abstract

The objective of this paper is primarily methodological. Using a new specification, we reanalyze the data on worldwide environmental quality investigated by Gene Grossman and Alan Krueger in their well-known paper on the environmental Kuznets curve (which postulates an inverse U-shaped relationship between income level and pollution). This new specification avoids using nonlinear transformations of potentially nonstationary regressors in panel estimation, which is a major unresolved econometric problem plaguing much of the existing literature. We furthermore draw conclusions from fixed effects estimation, which had eluded Grossman and Krueger. Our estimation results indicate the presence of an EKC for only six of the fourteen pollutants, whereas Grossman and Krueger find support for all but one pollutant.

KEYWORDS: Environmental Kuznets Curve, Specification, Panel Data

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1. Introduction

Most phenomena generally considered as pollution tend to be related either to industrial production or consumption. Both increase with rising levels of material prosperity. One might therefore expect a generally positive link between a country's income level and measures of environmental pollution. This would hold true even if environmental externalities were optimally taken into account in the usual economist's sense of equating the marginal benefits of regulation with the marginal cost in non-environmental benefits foregone.

However, nations face at least two potentially offsetting effects on the demand side as they get richer. First, they may be prepared to pay more for environmental quality (assuming that environmental amenity is a normal good). Second, the composition of the consumption bundle might shift in the direction of less pollution-intensive goods. Furthermore, important offsetting effects also arise on the supply-side of the economy. Development gives rise to a structural transformation in what an economy produces. High-income countries with high technology standards often produce relatively less pollution-intensive goods with less pollution-intensive production technologies. The technological transformation is often spurred, at least partly, by tighter environmental legislation in more advanced countries. General equilibrium effects in the world trading system might also give rise to systematic effects on the location of pollution-intensive production activities across countries of different stages of development (see Copeland and Taylor, 2003). In principle, the forces leading to changes in the production and consumption activities might be sufficient to offset the adverse effects of economic activity on the environment. Hence, at increasing levels of economic development, pollution may be decreasing.

Thus, theory does not give clear predictions concerning the relationship between pollution and economic activity.[1] Based on the potentially offsetting effects discussed above, the idea that pollution may first increase with rising income before it starts to fall again with even higher income is a hypothesis known as the environmental Kuznets curve (EKC). The term refers by analogy to the inverted U-shaped relationship between the level of economic development and the degree of income inequality, postulated by Simon Kuznets (1955) in his 1954 presidential address to the American Economic Association. Starting with the pioneering work of Grossman and Krueger (1991, 1993, 1995), a large body

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[1] One interesting exception in this respect is the "Green Solow" model developed in Brock and Taylor (2004a), which derives an EKC from a Solow growth model augmented by an abatement technology that experiences technological progress over time. They also investigate the empirical implications of their model-based EKC.

of theoretical and empirical EKC literature has been produced.[2] Examples include Andreoni and Levinson (2001), Antweiler, Copeland and Taylor (2001), Arrow et al. (1995), Beckerman (1992), Cropper and Griffiths (1994), Ekins (1997), Harbaugh, Levinson, and Wilson (2002), Hilton and Levinson (1998), Kahn (1998), Selden and Song (1994, 1995), Shafik and Bandyopadhyay (1992), Stern, Common, and Barbier (1996) or Torras and Boyce (1998). Overview papers like Stern (2004) or Yandle, Bjattarai, and Vijayaraghavan (2004) find more than 100 refereed publications of this type. Brock and Taylor (2004b) is an excellent survey paper on economic growth and the environment.

Ongoing discussion in the empirical EKC literature concerns appropriate specification and estimation strategies (for a comparative discussion of the econometric techniques applied, see Dijkgraaf and Vollebergh, 2001). We restrict our focus to the parametric approach and do not discuss nonparametric EKC approaches (see Millimet, List, and Stengos, 2003), semi-parametric approaches (see Bertinelli and Stroble, 2004) or specifications based on spline interpolations (see Schmalensee, Stoker, and Judson, 1998). Suffice it here to note that all these approaches are fundamentally affected by the econometric problems arising in the presence of nonstationary variables discussed below.

The main contribution of this paper is to present an alternative parametric specification that avoids using nonlinear transformations (e.g., squares and cubes) of potentially nonstationary variables like per capita GDP. Our specification is based on average per capita GDP over the period considered and the average growth rate of per capita GDP over the period considered and hence is not subject to the potential problems pointed out for the first time in Wagner and Müller-Fürstenberger (2004): If per capita GDP (or its log) is unit root nonstationary, as is often conjectured, then the EKC regressions involve nonlinear transformations of nonstationary processes (squares and cubes of per capita GDP). The asymptotic theory for such regressions is fundamentally different from the *linear* unit root case and is not yet developed in the panel context (see Chang, Park and Phillips, 2001, Park and Phillips, 1999, 2001). Our new formulation avoids using these nonlinear transformations and is consequently robust with respect to this fundamental problem.[3] A second potentially severe econometric problem in case of unit root nonstationarity of the variables is the cross-sectional dependence that

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[2] To be precise, Grossman and Krueger use a third order polynomial in GDP, whereas the quadratic formulation (i.e., a proper U-shape) seems to have been initiated by Holtz-Eakin and Selden (1995).

[3] If per capita GDP series are stationary, our alternative specification is also valid and thus it constitutes in our opinion an interesting alternative in both the stationary and the nonstationary case. Wagner and Müller-Fürstenberger (2004) do not reject unit root nonstationarity of log per capita GDP and per capita CO_2 emissions in a large panel comprising 107 countries and present panel estimates of the carbon Kuznets curve based on stationary de-factored observations.

is likely to be present. The panel unit root and cointegration methods applied so far (see e.g., Perman and Stern, 2003), all assume cross-sectional independence.[4] Also these potential problems are avoided with our approach. Harbaugh, Levinson, and Wilson (2002) find strong sensitivity of EKC results with respect to functional form and sample. Also, however, their study neglects the above-mentioned econometric critique concerning the use of nonlinear transformations of nonstationary processes in panel regressions. It is likely that sensitivity, with respect to sample composition and covariates, is present for our formulation as well. A detailed analysis of these issues is left for future research. In this paper, we are merely focusing on reinvestigating the Grossman and Krueger (1995) results with our new specification.

Our empirical analysis is performed with exactly the same data set as used by Grossman and Krueger (1995). As described in Section 3, the data contain concentration measurements for three air and eleven water pollutants for at most 12 years from multiple locations in up to 51 countries. Furthermore, per capita GDP in these countries as well as several covariates are contained in the data set. Contrary to the results of Grossman and Krueger (1995), fixed effects are preferred for most pollutants with our specification. We see this as another advantage of our specification since we believe that, for the problem at hand, fixed effects may be more appropriate than random effects. To see this, one only has to recall the basic condition for applicability of random effects estimation, namely the lack of correlation between the unobserved individual characteristics and the explanatory variables. This, however, is highly unlikely in the present context.

The results obtained using our approach differ in various ways from the Grossman and Krueger results. First, the set of pollutants for which we obtain a significant inverse U-shape differs. Using our basic specification in equation (4) below, we obtain a statistically significant EKC only for the following six pollutants: sulfur dioxide, dissolved oxygen, smoke, chemical oxygen demand, lead, and arsenic. This compares with the Grossman and Krueger results, which find an inverse U-shape for all pollutants except for suspended particles (using their cubic formulation). However, some of their curves rise again for high in-sample income levels. We thus find weaker evidence for the prevalence of environmental Kuznets curves with our fresh specification.

The paper is organized as follows. Section 2 derives and presents the alternative specification; Section 3 briefly discusses the data; Section 4 discusses the results; Section 5 contains a brief summary and conclusions. Two appendices

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[4] A first application of so-called second generation panel unit root and cointegration methods that allow for cross-sectional dependence is contained in Wagner and Müller-Fürstenberger (2004). It might be an interesting research question to analyze the data used in this paper with these methods as well.

follow the main text: Appendix A presents some data characteristics; Appendix B contains the estimated effects, already graphically presented in Section 4, in table format.

2. Methodology

To set the stage, this section presents our alternative specifications and briefly recalls the Grossman and Krueger set-up. The Grossman and Krueger regression is as follows:

$$(1) \qquad P_{it} = \mu_i + \beta_1 Y_{it} + \beta_2 Y_{it}^2 + \beta_3 Y_{it}^3 + \beta_4 \overline{Y}_{it} + \beta_5 \overline{Y}_{it}^2 + \beta_6 \overline{Y}_{it}^3 + \overline{\beta}' Z_{it} + \lambda t + \varepsilon_{it}$$

where P_{it} is the concentration level of pollution, Y_{it} is per capita GDP in station i and in period t, and $\overline{Y}_{it}$ is the average income over the three years prior to t. For all stations in the same country, per capita GDP is identical, as the income data are national averages. The Z_{it} denote other included covariates, as discussed in the following section. Further, λ is the slope of a linear time trend (identical across all stations), and μ_i are individual specific effects. In Grossman and Krueger's (1995) work, these are modeled as random effects.[5]

Our approach differs fundamentally from the above by starting from the idea that a Kuznets curve effect might be related more to long-term developments than to year-to-year fluctuations in income, even if smoothed income $\overline{Y}_{it}$ is also included in Grossman and Krueger's work. We thus start from the following schematic relationship between the rate of change of pollution and income and the growth rate of income at a given point of time, omitting the station subscript i and other explanatory variables for simplicity of presentation:

$$(2) \qquad \frac{\partial P_t}{\partial t} = \alpha (y - y^*) g$$

In equation (2), the change of pollution is a function of the growth rate g and the distance of income to the *turning point* y^*. If the coefficient α is negative and the growth rate g is positive, then pollution increases until income level y^* is reached and decreases thereafter. We include the growth rate g to allow for pollution dynamics that depend upon the growth regime. This allows for rapid pollution growth in fast growing developing countries. Thus, the above formulation can

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[5] In their work on air pollution, Grossman and Krueger (1993) used both fixed and random effects specifications. The coefficients relevant for the EKC were significant only for the random effects estimation.

describe an (inverse) U-shaped relationship between pollution and income. For the empirical application, we use for y an *average income level* over the sample period and for g the average growth rate, both country specific but time invariant (see the details in the following section).[6] Integrating the above equation (2) with respect to time – taking the average income measure and the growth rate to be constant – leads to

$$P_t = \mu + \alpha(y - y^*)gt \tag{3}$$

where μ is a constant of integration. The equation we estimate is derived by adding the individual-specific effects, the covariates, the linear trend, and errors (including again the station index i):

$$\begin{aligned} P_{it} &= \mu_i + \alpha(y_i - y^*)g_i t + \bar{\beta}' Z_{it} + \lambda t + \varepsilon_{it} \\ &= \mu_i + \alpha(y_i g_i t) + \alpha y^*(g_i t) + \bar{\beta}' Z_{it} + \lambda t + \varepsilon_{it} \\ &= \mu_i + \beta_0(y_i g_i t) + \beta_1(g_i t) + \bar{\beta}' Z_{it} + \lambda t + \varepsilon_{it} \end{aligned} \tag{4}$$

Hence $\alpha = \beta_0$ and $y^* = \beta_1 / \beta_0$. Note that the hypothesis of an inverse U-shape can be tested in equation (4) by testing the hypothesis $\alpha < 0$. Estimation of equation (4) includes only a country-specific measure of average per capita GDP over the period considered, y_i, and the country-specific growth rate of per capita GDP, g_i. This formulation is thus not subject to the unresolved problems arising in panel regression with nonlinear transformations of potentially nonstationary regressors noted above, which we see as a major advantage of our alternative approach.

Despite the fact that the above formulation already allows us to study the potential inverse U-shaped relationship between pollution and economic development, we also investigate a more flexible "cubic" version of the relationship, based on:

$$P_t = \mu + \alpha(y - y^*)(y - y^{**})gt \tag{5}$$

The above formulation allows for pollution to pick up again (as a function of t) for income larger than y^{**}, if $\alpha > 0$. From equation (5) the following equation is derived for estimation (by adding again the individual-specific effects, the Z_{it}, the time trend, and errors):

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[6] Thus, in effect we propose a cross-sectional interpretation of the relationship here. Equivalently we can interpret our results as being based on estimation using only two statistics of the income time series (the mean and the average growth rate), rather than the time series itself.

$$\begin{aligned} P_{it} &= \mu_i + \alpha(y_i - y^*)(y_i - y^{**})g_i t + \bar{\beta}' Z_{it} + \lambda t + \varepsilon_{it} \\ &= \mu_i + \alpha(y_i^2 g_i t) - \alpha\left[y^* + y^{**}\right](y_i g_i t) + \alpha y^* y^{**}(g_i t) + \bar{\beta}' Z_{it} + \lambda t + \varepsilon_{it} \\ &= \mu_i + \beta_0 (y_i^2 g_i t) + \beta_1 (y_i g_i t) + \beta_2 (g_i t) + \bar{\beta}' Z_{it} + \lambda t + \varepsilon_{it} \end{aligned} \tag{6}$$

from which one sees $\alpha = \beta_0$, $\beta_1 = -\alpha[y^*+y^{**}]$ and $\beta_2 = \alpha y^* y^{**}$. From these relationships, one can directly compute α, y^*, and y^{**}. Note that y^* and y^{**} are essentially a quadratic function of the β's, and hence complex solutions are possible and also occur for several pollutants for the random effects estimation of equation (6).

The fact that the sample includes countries at rather different levels of development is the key dimension of interest to our study, and it gives rise to the possibility of uncontrolled heterogeneity across countries (even when adding covariates). The two basic possibilities to account for this unobserved heterogeneity are fixed or random effects. As already mentioned in the introduction, we prefer fixed effects, as they allow for correlation between the station-specific unobserved effects and the explanatory variables. Besides the differences in specification, a second important difference from Grossman and Krueger is that with our specification for most pollutants the random effects specification is rejected by the Hausman test (see the details in Section 4).

As in all empirical EKC studies, the question of misspecification of the functional form arises. On this we have nothing more to add except that the specified equations appear to describe the data sufficiently well, i.e. standard specification tests do not lead to rejections. Misspecification is, however, as much an issue in the "standard" formulations as in our specifications. One advantage of our specification in this respect is that due to our formulation that avoids the use of nonlinear transformations of integrated regressors, standard misspecification tests are actually applicable, which is not necessarily the case in the standard specifications.

A second important question with respect to EKC estimation is whether the estimated relationship is time invariant, or whether over time the EKC tends to shift downwards due to global technological progress or upwards due to a race-to-the-bottom in global environmental standards. See Dasgupta et al. (2002) for a discussion. This problem is shared by our specifications and the standard GK-type specification, which are *all* based on constant coefficients. Given some knowledge on the direction and extent of the shift, it is straightforward to use our specifications for scenario analysis by changing the values of e.g. y^* accordingly.

Our reading of the literature is that up to now no consensus has emerged concerning potential shifts of the EKC over time.[7]

Before turning to the data and results, it is important to note that the EKC is a reduced form relationship that should not be used – without further analysis – for policy purposes. Even when adding further covariates to the equation, it is not clear from the reduced form approach that the correlation between pollution and GDP is not in fact caused by some further unobserved variables that are potentially correlated with the regressors (see Müller-Fürstenberger, Wagner and Müller (2004) for a discussion of these issues).

3. Data

The description of the data is kept at a minimum level, since we use exactly the same data as Grossman and Krueger (1995), which are described in detail in their paper. They also include a description of the potential environment and health damages originating from the pollutants.

The data set contains concentration measures of fourteen different pollutants, three air pollutants and eleven water pollutants, collected via the GEMS Air and Water projects of the World Health Organization and the United Nations Environment Programme. The list of countries reporting measurements for the various pollutants can be obtained from the authors upon request. The data reveal substantial variability across pollutants, ranging from 10 countries for nickel to 51 countries for dissolved oxygen. Typically, each country has several monitoring stations. The panels are generally unbalanced, as participation varies over time. For sulfur dioxide, for example, 47 cities in 28 countries reported in 1977, 52 cities in 32 countries reported in 1982, and 27 cities in 14 countries reported in 1988. Following Grossman and Krueger and to facilitate comparison of the magnitude of effects across different pollutants, all concentration measures are scaled by the pollutant-specific standard deviation of the observations in the sample.

The three air pollutants are sulfur dioxide, smoke, and suspended particles in cities. The median annual concentrations are reported for these pollutants and used in the econometric analysis.[8] The time span for the air pollutants is 1977 to 1988. Mean and standard deviation of each pollutant are provided in Table 6 in Appendix A. The GEMS air data include additional characteristics of the measurement station and the measurement instrument used.

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[7] Since the regressions include a linear time trend, they make some allowance for a change of the EKC over time.

[8] The annual concentrations are computed from higher frequency measurements, up to daily measurements for air pollutants.

The eleven water pollutants, measured at stations located at rivers, are grouped in three categories. The annual mean concentrations for the period 1979 to 1990 are used. By 1990, the GEMS programme included 287 measurement stations. The first category describes the oxygen regime, the second category is pathogenic contamination, and the third comprises heavy metals. The first category shows dissolved oxygen, the biological oxygen demand (BOD), the chemical oxygen demand (COD), and nitrates. Dissolved oxygen is a direct measure of water quality and as such is a "good" instead of a "bad". BOD and COD are inverse measures that indicate the presence of contaminants that will eventually lead to oxygen loss. Nitrates are related to excess growth of plants (eutrophication), in particular algae, that after dying will lead to reduced oxygen available for animals.

Two indicators that measure pathogenic contamination are total and fecal coliform. Fecal coliform, which are harmless bacteria present in large numbers in human and animal feces, is seen as the better of the two indicators of potentially very harmful pathogens reaching water reservoirs due to non-treatment of waste. Total coliform, which additionally includes naturally present coliform, is also measured. We perform computations for both, as do Grossman and Krueger (1995). Total coliform is measured in rivers located in 22 countries, and fecal coliform is measured in rivers in 42 different countries. For a coliform variable with concentration P, we follow Grossman and Krueger and use the logarithm of 1 plus the concentration, i.e. $log(1+P)$.

The third group comprises five heavy metals. These are lead, cadmium, arsenic, mercury, and nickel. At least 10 countries are contained in the samples for heavy metals. Metals are discharged by a variety of human activities and accumulate in the bottom sediment, from which they are slowly released to show up, e.g., in drinking water or fish.

Despite the efforts by the GEMS projects to produce a high quality representative data set, several concerns should be kept in mind. First, several important pollutants are not included, e.g., CFCs or carbon dioxide emissions. Second, the panel could have systematic biases in its composition. If countries that report more promptly are those with stricter environmental laws and less pollution, then pollution in these years may be downward biased. On the contrary, if countries with more severe environmental problems inform GEMS sooner, then pollution could have an upward bias. It could also be the case that the selection of the stations induces a bias (with respect to average country conditions), if stations are located first where environmental problems are already observed. The GEMS Water project tries to mitigate station-specific biases by including stations located at baseline locations that are supposed to be unpolluted and at major water supply sources.

As indicated, several additional control variables are also reported by the GEMS databases. For all air pollutants, these are dummy variables indicating the location of the station within the city (suburban or central), nature of land-use nearby, population density, and a dummy to indicate whether the city is located at a coastline. For smoke and suspended particles, the data include a dummy indicating whether the city is located within 100 miles of a desert.

Fewer covariates are available for the water pollutants, but one very important included variable is the mean annual water temperature. The mean temperature is important because warmer water dissolves a greater quantity and variety of chemicals. Where available, a dummy indicating the type of measurement instrument is also included.

Finally, the income data are provided by the Summers and Heston (1991) Penn World Tables Mark 5.6. The Penn World Table contains real per capita GDP in 1985 constant dollars up to 1992. As visible in equations (1), (4), and (6), a linear time trend is included in the regressions as well. Time trends are often included in EKC regressions to allow for "autonomous" changes in the pollution pattern that are not directly related to income.[9]

For the estimation of equations (4) and (6), we need to construct country average values of per capita GDP, y_i, and the country-specific average growth rates of per capita GDP, g_i. These are constructed as follows: Denote by Y_i^1 the average of per capita GDP in country i over the period 1979 to 1982 and by Y_i^2 the average over the period 1989 to 1992.[10] We then compute the average growth rate g_i from $Y_i^2 = Y_i^1 \exp(10 g_i)$ and our measure of average GDP over the period as $y_i = Y_i^1 \exp(5 g_i)$, i.e., interpolated income at the sample mid-point. The average incomes and growth rates computed this way are available from the authors upon request. For illustration, the lowest income value is computed for Zaire with \$460 and the highest value for the United States with \$16,577.

4. Results

In the first subsection of this section, we report the estimation results for equations (4) and (6). Both equations have been estimated with either fixed or random effects included. At the cost of being repetitive, note again that we believe that the fixed effects specification is more appropriate than a random effects specification for the problem at hand, as it is unlikely that the station-specific unobserved

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[9] One empirically well documented example is the so-called autonomous energy efficiency improvement (AEEI).

[10] Since we study more water pollutants than air pollutants, we take 1979 instead of 1977 as the initial year for computed the GDP averages and growth rates. For some countries, the data do not range until 1992; for these the latest available 4-year period is chosen.

effects are uncorrelated with the station-specific income and control variables. The strong econometric support in favor of the fixed effects results (see below) is, thus, a second advantage of our approach compared to the random effects results presented in Grossman and Krueger (1995). In the second subsection, we display the estimated effects derived from equations (4) and (6) and from the Grossman and Krueger specification in equation (1).

4.1 Estimation Results

In Table 1 we present the coefficients β_0, β_1 and λ and the implied turning point y^* for the fixed effects estimation of equation (4). Note for completeness that all time-invariant control variables fall out in fixed effects estimation. For five of the pollutants, the coefficient β_0 is negative and significant at least at the 10% significance level, confirming an inverse U-shape. These are sulfur dioxide, smoke, COD, lead, and arsenic. A significant U-shape is obtained for dissolved oxygen, nitrates, total coliform, and nickel. Since dissolved oxygen is a good, the U-shape for it is a positive finding. Our findings are quite different from Grossman and Krueger's results, which find an inverse U-shape (in a cubic formulation) for all pollutants except suspended particles. Note furthermore that the slope of the linear time trend is significant for several pollutants as well.

Table 1: Estimation Results for Equation (4) with Fixed Effects

	β_0	β_1	λ	y^*
Sulfur Dioxide	**-0.031**	***94.606***	0.057	3055.08
Smoke	**-0.035**	**415.637**	**-3.896**	11972.69
Suspended Particles	-0.004	**103.029**	**-2.307**	28287.20
Dissolved Oxygen	**0.010**	-12.041	***-1.202***	1192.85
BOD	-0.007	7.559	0.426	1137.84
COD	*-0.012*	***-114.558***	**4.425**	-9427.75
Nitrates	***0.013***	**-137.147**	-0.043	10572.03
Fecal Coliform	0.000	0.000	**0.000**	-1263.26
Total Coliform	**0.037**	**-336.483**	**11.687**	8999.78
Lead	**-0.011**	**109.054**	0.298	10290.76
Cadmium	0.000	-4.145	3.666	-15497.33
Arsenic	**-0.027**	**363.072**	-1.082	13247.16
Mercury	0.012	83.184	***-8.026***	-7083.50
Nickel	***0.160***	***-2019.789***	-4.895	12635.04

Notes: Bold indicates significance at 1%, bold and italic indicate significance at 5%, and italic indicates significance at 10%.

Besides the shape of the curve, the turning point is also interesting. Considering only the pollutants with significant shape coefficient β_0, the turning point is negative for COD and very low for dissolved oxygen. For the other pollutants, the turning point is in the middle to high country income range.

We have also estimated equation (4) using random effects; the results are contained in Table 2. With respect to significance of the shape coefficient β_0, very similar results are obtained with random effects as with fixed effects. One difference is that for nickel, a significant inverse U-shape now emerges. Also, COD and smoke have non-significant shape coefficients. In the final column of Table 2, labeled *Hausman*, we report rejection probabilities of the Hausman test, which is loosely speaking a test to determine whether the fixed or random effects specification is appropriate. Considering again only the pollutants with significant shape coefficient β_0, the table shows that the random effects specification is rejected for all except arsenic (i.e., entries in the Hausman column larger than 0.05 or 0.10). Thus, we find that with our specification – contrary to Grossman and Krueger's results – fixed effects estimation appears to be more appropriate.

Let us next turn to the estimation of equation (6). The results for the fixed effects estimation are contained in Table 3, and the random effects results are given in Table 4. These results are comparable to the earlier results obtained with equation (4). The β_0 coefficient is significant for six pollutants in the fixed effects specification and for five pollutants in the random effects specification. The set of pollutants with significance differs, however, and overlaps only for sulfur dioxide, dissolved oxygen, and fecal coliform. At least one of the turning points, y^* or y^{**}, is generally in the sample range of income in the fixed effects estimation.

Table 2: Estimation Results for Equation (4) with Random Effects

	β_0 (10^5)	β_1	λ	y^*	*Hausman*
Sulfur Dioxide	***-45.543***	**0.688**	**-3.683**	15096.60	0.000
Smoke	-120.687	0.728	**-2.459**	6036.26	0.000
Suspended Particles	-209.789	1.789	***-0.820***	8526.60	0.000
Dissolved Oxygen	**132.960**	-0.672	***-0.599***	5053.08	0.000
BOD	20.630	-0.231	-0.180	11212.44	0.445
COD	27.437	*-0.386*	0.924	14059.92	0.010
Nitrates	***78.693***	-0.105	***-1.885***	1333.99	0.000
Fecal Coliform	0.000	0.000	**0.000**	6794.36	0.001
Total Coliform	*83.899*	-0.191	**8.291**	2281.57	0.000
Lead	**-33.200**	0.042	0.090	1253.35	0.001
Cadmium	-13.642	0.292	*1.928*	21406.11	0.014
Arsenic	**-164.445**	0.785	0.816	4771.93	0.081
Mercury	-11.730	-0.603	***-2.565***	-51427.91	0.376
Nickel	*-155.315*	0.778	**-4.797**	5011.70	0.003

Notes: Bold indicates significance at 1%, bold and italic indicate significance at 5%, and italic indicates significance at 10%.

With equation (6), as with equation (4), the random effects specification is rejected by the Hausman test for a vast majority of pollutants. For the pollutants with significant shape coefficient, the random effects specification is again rejected for all except arsenic. Note also that the turning points y^* and y^{**} are found to be complex for four pollutants when estimation is performed with random effects.

Table 3: Estimation Results for Equation (6) with Fixed Effects

	$\beta_0(10^8)$	β_1	β_2	λ	y^*	y^{**}
Sulfur Dioxide	**36.537**	**-0.056**	**105.793**	1.092	1890.95	1531249.90
Smoke	-8.929	*-0.025*	**371.280**	**-4.136**	-2831987.51	14682.25
Suspended Particles	-0.289	-0.003	**102.840**	**-2.309**	-11999006.87	29652.03
Dissolved Oxygen	***16.954***	0.007	-8.594	***-1.206***	-416067.53	1218.35
BOD	***31.493***	**-0.025**	*82.217*	-1.171	3285.89	794498.92
COD	*44.726*	**-0.034**	**-154.741**	**6.904**	-4469.29	774122.66
Nitrates	-8.506	*0.018*	**-159.349**	0.081	8875.49	2110825.26
Fecal Coliform (10^5)	**-290.726**	0.190	-4.134	10.160	21.77	653289.49
Total Coliform	-18.869	**0.056**	***-207.819***	***6.173***	3725.37	2956410.92
Lead	*4.780*	0.004	**-89.753**	0.009	-949998.11	19765.55
Cadmium	31.096	-0.035	166.061	*7.257*	4728.58	1129371.04
Arsenic	7.905	*-0.031*	197.605	3.710	6442.04	3880419.28
Mercury	31.780	-0.013	134.828	-6.074	10341.23	410259.62
Nickel	33.879	***0.156***	**-2180.077**	-3.728	-4625172.98	13912.92

Notes: Bold indicates significance at 1%, bold and italic indicate significance at 5%, and italic indicates significance at 10%. The coefficient β_0 is scaled by the factor 10^8 and the coefficients for fecal coliform are furthermore all scaled by the factor 10^5.

4.2 Graphical Analysis of the Estimated Effects

A more intuitive way of analyzing the results is to show graphically the implied effects of income on pollution, as defined below, at several income levels. This is done in Figures 1 to 4 for the fixed effects results for equations (4) and (6). In these figures, we also show the effects obtained from the Grossman and Krueger (1995) specification of equation (1). Despite the lack of significance of coefficients for some pollutants, we present the results for all fourteen pollutants.

In these graphs, we plot the estimated effects of income on pollution obtained from our basic and cubic specification, but neglecting the effect of all other explanatory variables. Due to estimation with fixed effects all time invariant explanatory variables drop out, but the values of the estimated coefficients do depend on the time-varying regressors included in the fixed effect estimation. In the graphs we also plot the effects as calculated by Grossman and Krueger (1995); see their description in equation (2) on p. 364. The two sets of effects are not directly comparable, since Grossman and Krueger include the effect of all additional explanatory variables in their computation, which in their case do not drop out since they use random effects estimation. Nevertheless we want to compare the effects obtained from the two different approaches despite these methodological differences.

Due to the nonlinear form of the relationships, the effects must be assessed locally. We do so by choosing four income values ranging from low to very high on the horizontal axis. Here *L* indicates low income taken to be \$1,000, *M* indicates middle income taken to be \$5,000, *H* indicates high income taken to be \$10,000, and *VH* indicates very high income taken to be \$15,000. Of course these four income values are chosen somewhat arbitrarily, but they span the observed sample range in the data quite well. For the growth rate, *g*, which we need to compute the effects for our specifications, we choose 3% annual growth of per capita GDP. This number is partly for illustrative purposes, but it is also often seen as a good estimate of the average long-run growth rate. In our sample, the mean growth rate over countries is at about 1.5% (not population weighted); however, this result is influenced by the negative growth performance of various African and Latin American countries.

Table 4: Estimation Results for Equation (6) with Random Effects

	$\beta_0(10^8)$	$\beta_1(10^5)$	β_2	λ	y^*	y^{**}	*Hausman*
Sulfur Dioxide	**-13.225**	**127.365**	0.272	**-2.539**	-1798.60	11428.95	0.000
Smoke	-6.937	-34.213	0.484	**-2.121**	-11178.48	6246.24	0.000
Suspended Particles	0.963	**-224.008**	**1.815**	*-0.906*	8406.15	224093.85	0.000
Dissolved Oxygen	**27.261**	**-198.260**	-0.056	**-1.125**	-272.08	7544.81	0.000
BOD	-2.337	53.319	-0.286	-0.781	8597.17	14217.33	0.143
COD	-3.345	63.894	-0.450	*1.268*	complex	complex	0.000
Nitrates	**-14.614**	**269.379**	*-0.499*	*-1.578*	2087.40	16345.12	0.004
Fecal Coliform (10^4)	**-12.207**	**140.357**	-0.233	***2.325***	2007.26	9491.16	0.000
Total Coliform	14.626	-109.615	0.206	**6.052**	complex	complex	0.000
Lead	0.760	*-41.129*	0.020	-0.370	494.61	53651.73	0.003
Cadmium	-8.578	123.906	-0.143	**4.164**	1266.30	13178.14	0.019
Arsenic	**-16.445**	82.800	-0.117	***2.899***	complex	complex	0.478
Mercury	8.484	-141.848	-0.106	***-3.604***	-717.57	17437.83	0.546
Nickel	-15.077	163.489	-1.082	-3.530	complex	complex	0.049

Notes: Bold indicates significance at 1%, bold and italic indicate significance at 5%, and italic indicates significance at 10%. The coefficient β_0 is scaled by the factor 10^8, the coefficient β_1 is scaled by the factor 10^5, and the coefficients for fecal coliform are furthermore all scaled by the factor 10^4.

In the graphs throughout, the left bars correspond to our basic formulation (4), the central bars correspond to equation (6), and the right bars correspond to the Grossman and Krueger specification (1). The vertical intervals display 95% confidence intervals around the point estimates. These have been computed using the Delta method and robust estimates of the standard errors.

Also, in our choice of the unit for the vertical axis, we follow Grossman and Krueger (1995) by normalizing the computed pollution levels by the standard deviation for that pollutant across all stations in the sample. That is, we choose the pollutant-specific standard deviation as the unit.[11] This scale provides a common metric with which the effects can be compared across pollutants.

Suppose for any given specification that an EKC prevails, that the low income level is below the peak of the inverted-U, and that the high income level is beyond the peak. Then the bars on the left of the graphs should be positive and those on the right negative, marching down from left to right.[12] The information displayed in the graphs is in a sense equivalent to the information contained in the tables, since we just display the functional form implied by the estimates as a function of income (and income growth). However, the graphical information is more informative in visualizing the shape of the pollution-income relationship.

The graphical analysis visualizes the strong evidence found by Grossman and Krueger (1995) in favor of the EKC hypothesis: for all pollutants except total coliform, the effect computed from the Grossman and Krueger specification decreases as income rises from low (*L*) to high (*H*). For seven of the thirteen supportive cases, however, the effects are rising again at the very high income level of $15,000.

Consistent with the weaker evidence shown in the tables, our specification also provides weaker evidence as shown in the figures. For ten of the fourteen pollutants, the effects decrease (increase for dissolved oxygen). This seemingly stronger support compared to the evidence based on the equations is due to the fact that we do not distinguish here between significant and non-significant results.

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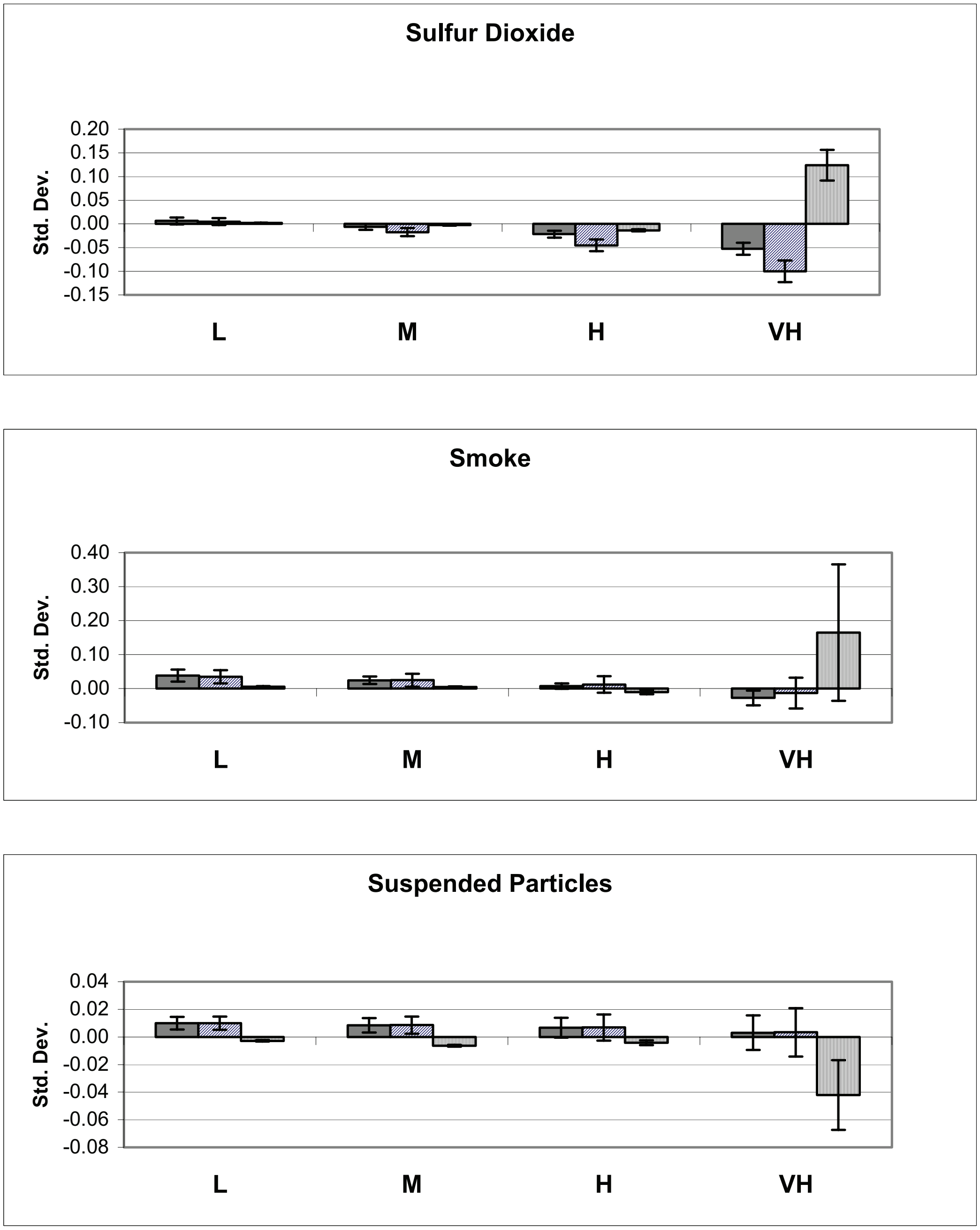
[11] Thus, our scaling corresponds to the scale on the right hand side of Figures I to IV in Grossman and Krueger (1995). Note, however, that the vertical range in the figures differ.

[12] For simplicity we ignore in this argument that the cubic formulation, even with the inverse U-shape in the relevant region, allows for pollution to pick up again for sufficiently large values of income. Note here also that for dissolved oxygen the bars should march up from left to right.

Figure 1: Estimated Effects for Air Pollutants



Sulfur Dioxide

Smoke

Suspended Particles

Notes: L, M, H and VH denote the effects at Low, Medium, High and Very High incomes. Within the blocks, the left bars correspond to the estimates based on equation (4), the central bars correspond to equation (6), and the right bars display the GK results (equation 1). The bars give the point estimates and the intervals display the 95% confidence intervals around the point estimates.

Figure 2: Estimated Effects for Oxygen and Nitrates

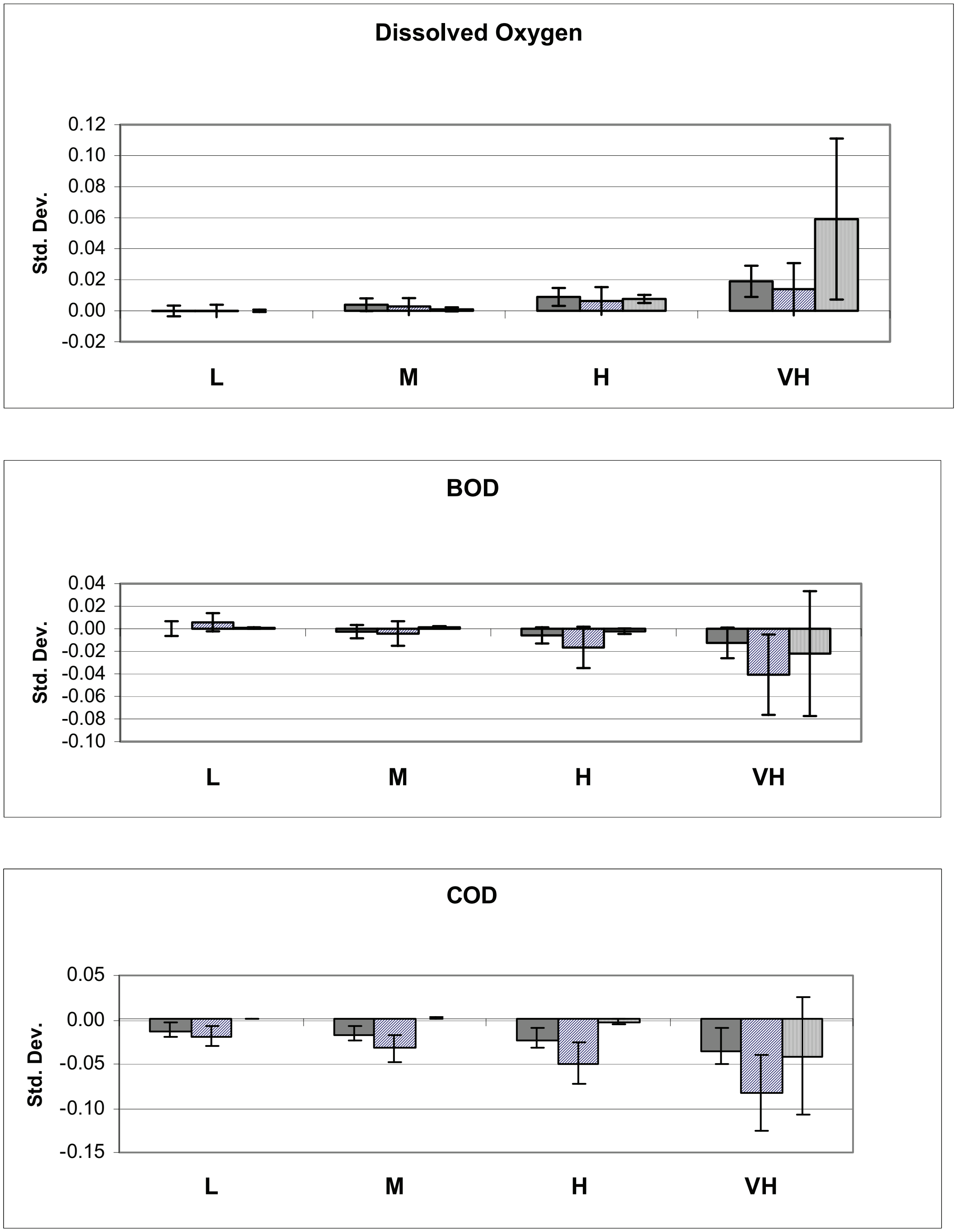
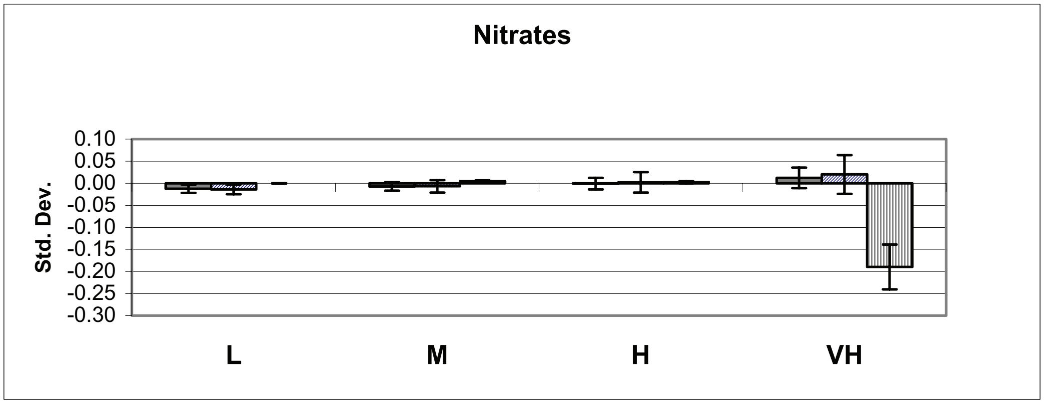
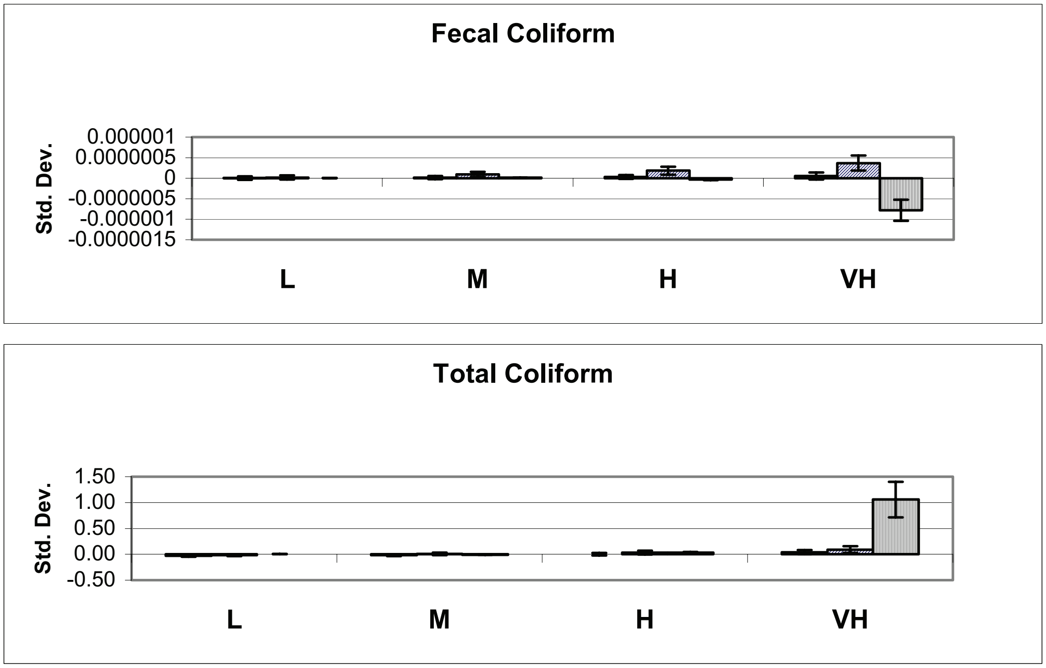


Figure 2: Estimated Effects for Oxygen and Nitrates (cont'd)



Notes: L, M, H and VH denote the effects at Low, Medium, High and Very High incomes. Within the blocks, the left bars correspond to the estimates based on equation (4), the central bars correspond to equation (6), and the right bars display the GK results (equation 1). The bars give the point estimates and the intervals display the 95% confidence intervals around the point estimates.

Figure 3: Estimated Effects for Coliform



Notes: L, M, H and VH denote the effects at Low, Medium, High and Very High incomes. Within the blocks, the left bars correspond to the estimates based on equation (4), the central bars correspond to equation (6), and the right bars display the GK results (equation 1). The bars give the point estimates and the intervals display the 95% confidence intervals around the point estimates.

Figure 4: Estimated Effects for Heavy Metals

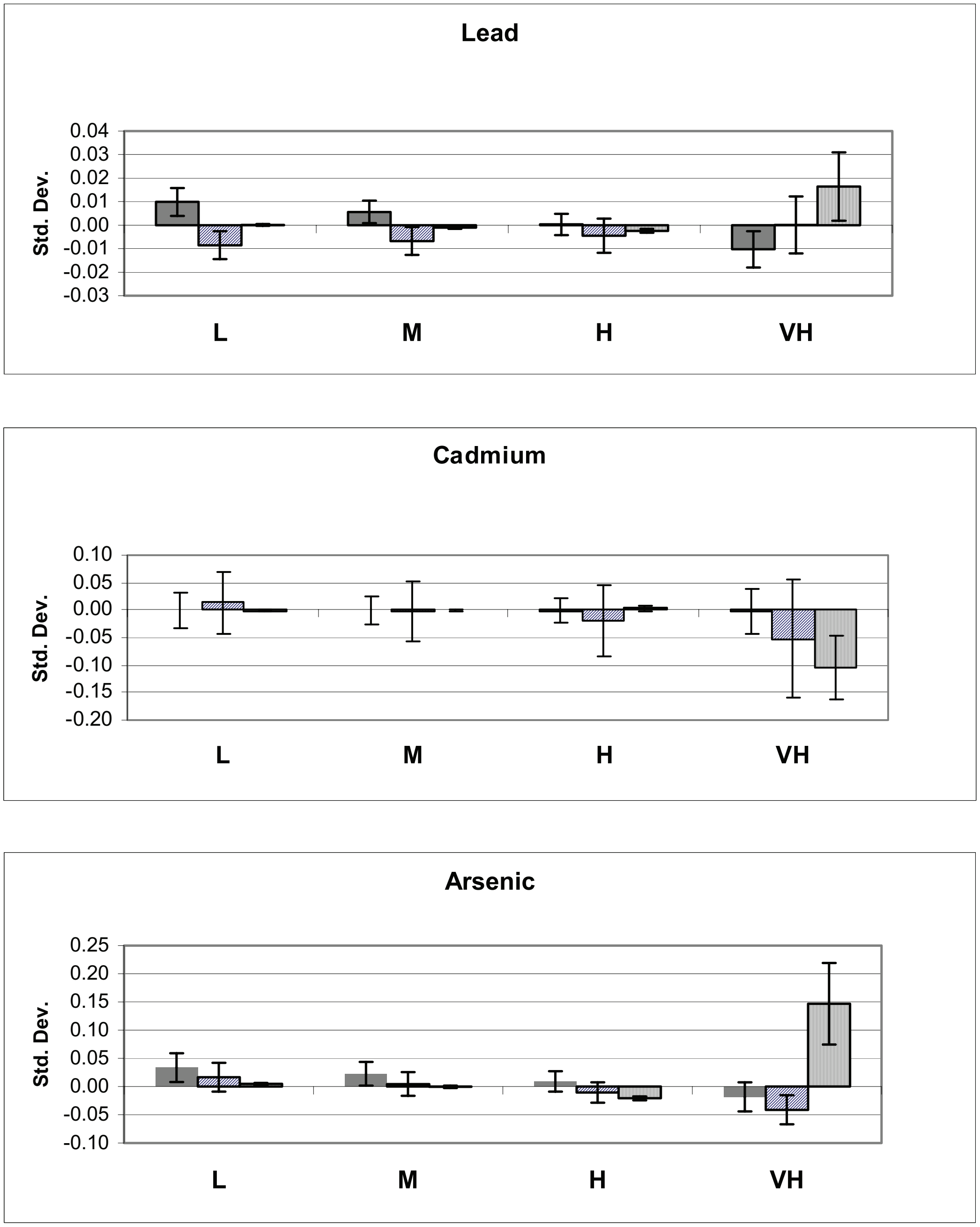
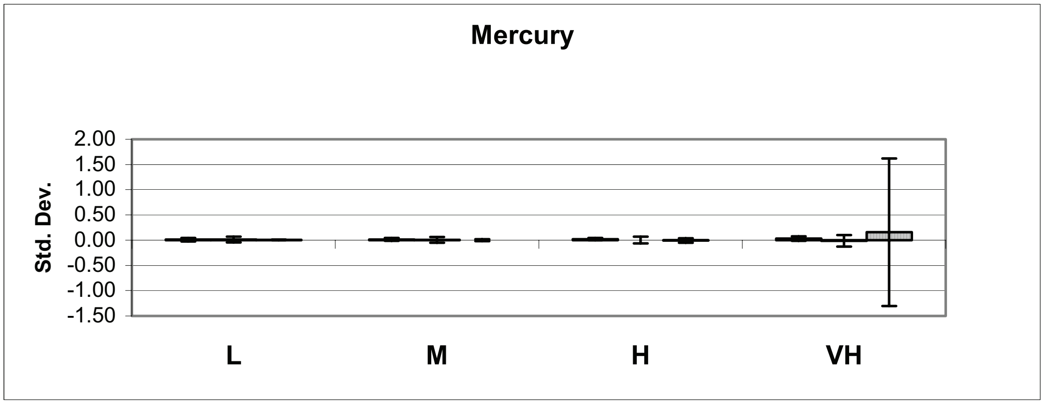
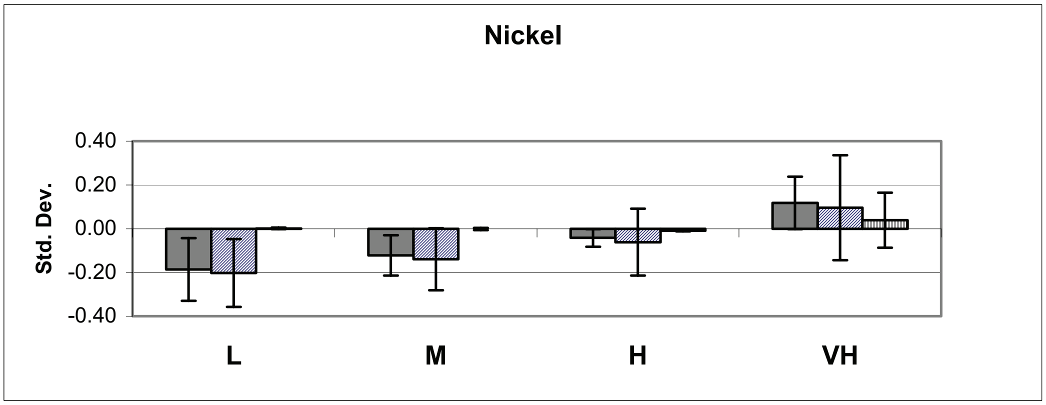


Figure 4: Estimated Effects for Heavy Metals (cont'd)





Notes: L, M, H and VH denote the effects at Low, Medium, High and Very High incomes. Within the blocks, the left bars correspond to the estimates based on equation (4), the central bars correspond to equation (6), and the right bars display the GK results (equation 1). The bars give the point estimates and the intervals display the 95% confidence intervals around the point estimates.

5. Summary and Conclusions

In this paper we have reinvestigated the environmental Kuznets curve hypothesis on the Grossman and Krueger (1995) data with two new specifications. Our new specifications have the advantage that they avoid using nonlinear transformations of possibly nonstationary regressors (i.e., the squares and cubes of per capita GDP). The asymptotic theory for panel regressions with nonlinear transformations of nonstationary processes is not yet developed. Hence, our new specifications are robust to a major source of potential problems plaguing much of the existing literature.[13] A second difference from Grossman and Krueger is that with our specifications, fixed effects are for most pollutants preferred over random effects. For the problem at hand, we believe that the fixed effects specification is preferable as it allows for correlation between the station-specific unobserved characteristics and the explanatory variables.

As shown in the summary in Table 5, our results lead to only limited support for the EKC hypothesis. Whereas Grossman and Krueger find support for the EKC hypothesis for thirteen out of the fourteen pollutants (the exception being total coliform), our analysis supports the hypothesis only for six pollutants. In the first two columns of Table 5, for the shape coefficient estimate, the letter *Y* indicates "yes" regarding significance with correct sign, and *N* indicates "no" (either insignificance or incorrect sign). We find support – with the preferred parsimonious specification of equation (4) – for sulfur dioxide, smoke, dissolved oxygen, COD, lead, and arsenic. With the extended formulation of equation (6), support is found only for sulfur dioxide, BOD, COD, and lead.

Table 5: Summary of Evidence for Kuznets Curve

Pollutant	**Estimates eq.(4)**	**Estimates eq.(6)**	**Graph eq.(4)**	**Graph eq.(6)**	**Graph eq.(1)**	**Score**
Sulfur Dioxide	Y	Y	Y	Y	Y(+)	4.5
Smoke	Y	N	Y	Y	Y(+)	3.5
Suspended Particles	N	N	Y	Y	Y	3
Dissolved Oxygen	Y	N	Y	Y	Y	4
BOD	N	Y	Y	Y	Y	4
COD	Y	Y	Y	Y	Y	5
Nitrates	N	N	Y	Y	Y(+)	2.5
Fecal Coliform	N	N	N	N	Y	1
Total Coliform	N	N	N	N	N	0
Lead	Y	Y	Y	N	Y(+)	3.5
Cadmium	N	N	Y	Y	Y	3
Arsenic	Y	N	Y	Y	Y(+)	3.5
Mercury	N	N	N	Y	Y(+)	1.5
Nickel	N	N	N	N	Y(+)	0.5

Notes: See explanations in the text.

We have also analyzed the evidence for the EKC hypothesis graphically by computing the effects from our two specifications in equations (4) and (6) as well as the effects based on the Grossman and Krueger specification (1). In particular, we evaluate the effect at four income levels, ranging from $1,000 to $15,000. As discussed, the EKC hypothesis implies that – under the assumption that $1,000 is below the peak and $15,000 is above the peak of the inverted U –

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[13] See Wagner and Müller-Fürstenberger (2004) for a discussion of these issues and a potential alternative solution based on factor models.

the effects should decrease with increasing income level. The graphical evidence for all three specifications is summarized in the next three columns of Table 5. In these columns, *Y* indicates "yes" for the prevalence of this monotonous pattern, *Y(+)* indicates monotonicity before the effect picks up again at the highest income level, and *N* indicates all other cases. With the Grossman and Krueger cubic specification, effects at the highest income level rise again for seven of the fourteen pollutants. For these graphical results in Table 5, we again do not distinguish between significant and insignificant effects.

In the final column of Table 5 we compute a simple crude *score* measure for the support of the EKC hypothesis for each of the pollutants by combining the evidence from both the coefficients and the graphs: each *Y* gives 1 point, *Y(+)* gives 0.5 point and *N* gives 0 points. Note that with this measure we do not weigh the different specifications. This admittedly simple exploratory device leads to the strongest support of the EKC hypothesis for sulfur dioxide, dissolved oxygen, BOD, and COD, and it leads to the least support for coliform and nickel.

Appendix A: Some Details of the Data Set

Table 6: Mean, Standard Deviation and Units of Pollutants

Pollutant	Mean	Std. Deviation	Unit
Sulfur Dioxide	34.30	38.90	$\mu g/m^3$
Smoke	53.30	53.20	$\mu g/m^3$
Suspended Particles	151.0	129.0	$\mu g/m^3$
Dissolved Oxygen	8.12	3.25	mg/L
BOD	6.63	22.6	mg O_2/L
COD	48.40	119.43	mg O_2/L
Nitrates	1.53	3.88	mg Nitrates/L
Fecal Coliform	103000	599000	No./100mL
Total Coliform	178000	943000	No./100mL
Lead	0.031	0.293	µg/L
Cadmium	0.044	0.165	µg/L
Arsenic	0.006	0.009	µg/L
Mercury	0.285	0.785	µg/L
Nickel	0.009	0.011	µg/L

Notes: For the air pollutants sulfur dioxide, smoke, and suspended particles, the measurements are median concentrations instead of mean concentration. Source: GEMS Air and Water projects. For all computations, the pollutants are expressed in units of standard deviation in the entire sample of observations, i.e., for each pollutant the concentrations are divided by the standard deviation across all measurements of that pollutant.

Appendix B: Numerical Presentation of Estimated Effects

In Tables 7 to 10 the numbers in black indicate the estimated effects in units of standard deviations for each pollutant, as described in Section 4.2, and the grey numbers below the estimated effects are 1.96 times the standard errors computed from the respective equations using the Delta method (i.e., they display the length of the error bars). Numbers smaller than 0.0001 are rounded to 0.0001.

Table 7: Estimated Effects for Air Pollutants

	L	M	H	VH
Sulphur Dioxide				
eq.(4)	0.0064	-0.0060	-0.0215	-0.0525
	0.0073	0.0065	0.0073	0.0128
eq.(6)	0.0050	-0.0173	-0.0451	-0.1000
	0.0075	0.0086	0.0125	0.0227
GK, eq.(1)	-0.0082	0.0336	0.0364	0.0397
	0.0013	0.0208	0.0226	0.0244
Smoke				
eq.(4)	0.0381	0.0242	0.0068	-0.0279
	0.0175	0.0113	0.0081	0.0217
eq.(6)	0.0346	0.0245	0.0119	-0.0135
	0.0197	0.0189	0.0246	0.0452
GK, eq.(1)	-0.0026	0.0112	0.0108	0.0109
	0.0025	0.0357	0.0396	0.0439
Suspended Particles				
eq.(4)	0.0099	0.0085	0.0067	0.0030
	0.0046	0.0053	0.0072	0.0125
eq.(6)	0.0099	0.0086	0.0068	0.0034
	0.0047	0.0061	0.0095	0.0175
GK, eq.(1)	-0.0057	-0.0448	-0.0477	-0.0508
	0.0011	0.0148	0.0161	0.0174

Table 8: Estimated Effects for Oxygen and Nitrates

	L	M	H	VH
Dissolved Oxygen				
eq.(4)	-0.0002	0.0038	0.0089	0.0190
	0.0035	0.0041	0.0058	0.0101
eq.(6)	-0.0002	0.0027	0.0063	0.0139
	0.0040	0.0055	0.0089	0.0169
GK, eq.(1)	0.0024	0.0047	0.0059	0.0074
	0.0020	0.0026	0.0027	0.0027

Table 8: Estimated Effects for Oxygen and Nitrates (cont'd)

BOD				
eq.(4)	0.0001	-0.0026	-0.0059	-0.0125
	0.0065	0.0058	0.0072	0.0137
eq.(6)	0.0057	-0.0043	-0.0166	-0.0408
	0.0081	0.0109	0.0184	0.0357
GK, eq.(1)	0.0004	-0.0008	-0.0015	-0.0022
	0.0018	0.0022	0.0023	0.0024
COD				
eq.(4)	-0.0127	-0.0175	-0.0236	-0.0358
	0.0094	0.0105	0.0147	0.0262
eq.(6)	-0.0189	-0.0326	-0.0495	-0.0825
	0.0108	0.0144	0.0230	0.0430
GK, eq.(1)	0.0010	-0.0006	-0.0016	-0.0027
	0.0021	0.0027	0.0029	0.0031
Nitrates				
eq.(4)	-0.0124	-0.0072	-0.0007	0.0122
	0.0097	0.0098	0.0130	0.0233
eq.(6)	-0.0141	-0.0069	0.0020	0.0198
	0.0109	0.0143	0.0232	0.0441
GK, eq.(1)	0.0072	0.0196	0.0193	0.0182
	0.0020	0.0247	0.0268	0.0289

Table 9: Estimated Effects for Coliform

	L	**M**	**H**	**VH**
Fecal Coliform (x10^5)				
eq.(4)	0.0058	0.0159	0.0286	0.0541
	0.0443	0.0394	0.0468	0.0856
eq.(6)	0.0186	0.0938	0.1866	0.3678
	0.0534	0.0640	0.0981	0.1834
GK, eq.(1)	0.0001	0.0119	-0.0297	-0.7800
	0.0001	0.0066	0.0145	0.2550
Total Coliform				
eq.(4)	-0.0299	-0.0150	0.0037	0.0411
	0.0163	0.0191	0.0247	0.0389
eq.(6)	-0.0152	0.0071	0.0349	0.0902
	0.0190	0.0249	0.0367	0.0640
GK, eq.(1)	0.0040	-0.0079	0.0338	1.0593
	0.0014	0.0039	0.0100	0.3446

Table 10: Estimated Effects for Heavy Metals

	L	M	H	VH
Lead				
eq.(4)	0.0098	0.0056	0.0003	-0.0103
	0.0059	0.0048	0.0045	0.0077
eq.(6)	-0.0085	-0.0067	-0.0045	0.0001
	0.0060	0.0059	0.0073	0.0122
GK, eq.(1)	-0.0018	-0.0023	-0.0024	-0.0024
	0.0006	0.0008	0.0008	0.0008
Cadmium				
eq.(4)	-0.0004	-0.0005	-0.0007	-0.0009
	0.0326	0.0258	0.0235	0.0406
eq.(6)	0.0131	-0.0009	-0.0183	-0.0527
	0.0552	0.0542	0.0651	0.1077
GK, eq.(1)	0.0030	0.0037	0.0034	0.0027
	0.0023	0.0032	0.0035	0.0036
Arsenic				
eq.(4)	0.0336	0.0226	0.0089	-0.0185
	0.0256	0.0209	0.0181	0.0258
eq.(6)	0.0167	0.0044	-0.0109	-0.0414
	0.0396	0.0400	0.0475	0.0748
GK, eq.(1)	-0.0096	-0.0165	-0.0200	-0.0225
	0.0023	0.0079	0.0079	0.0078
Mercury				
eq.(4)	0.0095	0.0142	0.0201	0.0318
	0.0360	0.0269	0.0229	0.0429
eq.(6)	0.0121	0.0069	0.0004	-0.0120
	0.0565	0.0557	0.0680	0.1145
GK, eq.(1)	-0.0048	-0.0011	-0.0011	-0.0003
	0.0216	0.2700	0.2976	0.3284
Nickel				
eq.(4)	-0.1860	-0.1221	-0.0421	0.1177
	0.1434	0.0928	0.0404	0.1196
eq.(6)	-0.2024	-0.1398	-0.0614	0.0958
	0.1545	0.1416	0.1531	0.2396
GK, eq.(1)	-0.0044	0.1610	0.1737	0.1867
	0.0030	0.1598	0.1728	0.1860

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