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REEXAMINING THE EMPIRICAL EVIDENCE FOR AN ENVIRONMENTAL KUZNETS CURVE

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ABSTRACT

This paper uses an updated and revised panel data set on ambient air pollution in cities world-wide to examine the robustness of the evidence for the existence of an inverted U-shaped relationship between national income and pollution. We test the sensitivity of the pollution-income relationship to functional forms, to additional covariates, and to changes in the nations, cities, and years sampled. We find that the results are highly sensitive to these changes. We conclude that there is little empirical support for an inverted-U-shaped relationship between several important air pollutants and national income in these data.

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1. Introduction

Several recent and often-cited papers on the relationship between pollution and economic growth find that many forms of air and water pollution "initially worsen but then improve as incomes rise" (World Bank, 1992). Grossman and Krueger (1995), in particular, report that for most pollutants, this turning point in environmental quality typically occurs at incomes below $8000 per capita. Because of its similarity to the pattern of income inequality documented by Kuznets (1955), this inverse-U-shaped pollution-income pattern is sometimes called an "environmental Kuznets curve."

In response to these empirical findings, a number of researchers have sought further evidence for inverse-U-shaped pollution-income relationships (Holtz-Eakin and Selden, 1995; Selden and Song, 1994; Hilton and Levinson, 1998; Shafik, 1994). Others have proposed theoretical explanations for the relationship between pollution and economic growth (Selden and Song, 1995; Stokey, 1998; Jaeger, 1998; Jones and Manuelli, 1995; Andreoni and Levinson, 1998; Chaudhuri and Pfaff, 1997).[1] There are essentially two key questions being asked. The first is whether or not an inverted-U-shaped pollution-income path can be consistent with Pareto optimality. This is the subject of much of the theoretical literature. The second key question is whether there is sufficient empirical evidence to conclude that environmental quality does improve eventually with economic growth, for at least some subset of pollutants. This latter question is the focus of this paper. While the existing literature appears to demonstrate numerous circumstances in which pollution follows an inverse-U, eventually declining with income, we argue that the evidence is less robust than it appears.

Far from being an academic curiosity, this debate is of considerable importance to national and international environmental policy. Based on the existing research, some policy analysts have concluded that developing countries will *automatically* become cleaner as their economies grow (Beckerman, 1992; Bartlett, 1994). Others have argued that it is natural for the poorest countries to become more polluted as they develop. These types of conclusions depend on the apparently growing conventional wisdom that pollution follows a deterministic inverse-U-shaped environmental Kuznets curve.

In this paper we re-examine the empirical evidence documenting inverse-U-shaped pollution-income relationships using the air pollution data studied by the World Bank (1992) and by Grossman and Krueger (1995), with the benefits of a retrospective data cleaning and ten additional years of data. We analyze three common air pollutants: sulfur dioxide (SO_2), smoke, and total suspended particulates (TSP). These are the three pollutants for which the most complete data are available.[2] All three are widely considered to cause serious health and environmental problems. Two of the three, SO_2 and smoke, exhibit the most dramatic inverse-U-shaped patterns in the World Bank (1992) and in Grossman and Krueger (1995). We also test the sensitivity of the pollution-income relationship to the functional forms and econometric specifications used, to the inclusion of additional covariates besides income, and to the nations, cities, and years sampled. In addition, we construct 95-percent confidence bands around the estimated pollution-income relationships.

Our conclusion is that the evidence for an inverted-U is much less robust than previously thought. We find that the locations of the turning points, as well as their very existence, are sensitive to both slight variations in the data and to reasonable permutations of the econometric specification. Merely cleaning up the data, or including newly available observations, makes the inverse-U shape disappear. Furthermore, econometric specifications that extend the lag structure of GDP per capita as a

[1] In addition, recent special issues of two journals, Environment and Development Economics in November 1997 and Ecological Economics in May 1998 include papers on the environmental Kuznets curve.
[2] We also tested models on lead, NO_x, and other sizes of suspended particulate matter. Sample sizes were small, and the independent variables were generally insignificant.

dependent variable, include additional country-specific covariates, or include country-level fixed effects, generate predicted pollution-income relationships with very different shapes.

2. Data

The data on ambient pollution levels underlying this study are collected by the Global Environmental Monitoring System (GEMS), sponsored by the World Health Organization (WHO) and the United Nations.[3] The EPA maintains these data in its Aerometric Information Retrieval System (AIRS). For each pollution monitoring station, the data set we obtained contains the annual mean and maximum for each pollutant monitored, along with descriptive variables about the neighborhood and city in which the monitor is located.

Table 1 lists some descriptive statistics for both the original data used by Grossman and Krueger (1995), which they have graciously made available, and for the data available from AIRS as of December 1998. The new data contain substantially more usable observations than were originally available. For sulfur dioxide, the number of observations goes from 1352 to 2381, with 25 new cities, and three new countries. These data add 4 new years of observations, from 1989 to 1992, and 6 additional years of older observations, from 1971 to 1976. In addition, missing observations for existing cities have been filled in.

The new AIRS data also include revisions of some of the original observations. To determine the extent of these revisions, we matched the observations from the original data with those in the new data, and then compared the pollution concentration numbers. These matches were not always easy to make. We began by matching observations between the two data sets by pollutant, city, and year. In most cases there were several monitoring sites per city, so observations were then paired by comparing the number of measurements and mean values reported. For some cities the number of observations was consistently the same, for others it was consistently different, and for still others it was a mix.

Using our best efforts to match the old and the new observations, we found that observations that appeared to come from the same site and year often had very different reported pollution concentrations. We also found that 92 of 1021 observations in the original TSP data were obvious duplications, as were 76 of the 488 in the smoke data. These have been eliminated from the new data set. Table 2 gives summary statistics showing the extent of the revisions. For the 485 SO_2 observations that we are most certain that we have correctly matched to the original data set, the correlation between mean sulfur dioxide levels between the new and old data is only 0.75. For TSP and smoke this correlation is 1.0 and 0.77 respectively. The lower part of Table 2 shows summary statistics for the ratio of the new reported observation value to the value in the old data. If the data were identical, the mean of this ratio would be one, and the standard deviation would be zero. For SO_2 the mean of this ratio is 1.21, while the standard deviation is 1.73. In sum, since some of the early empirical work on this topic was completed, a large number of new observations have been added, and the existing data have been substantially revised. We should also note that the matching procedure we followed probably produces a downward biased picture of the extent of these revisions, because we are most likely to match the observations that have not changed.

In the analyses that follow, we examine the data on ambient concentrations of SO_2, TSP, and smoke together with a set of variables describing national income, political structure, investment, trade, and population density, as well as control variables that account for where the monitoring station was located. For national income we use real per capita gross domestic product, in 1985 dollars, from the Penn World Tables (PWT) as described in Summers and Heston (1991). This is the same income

[3] GEMS was initiated in the early 1970s to coordinate the worldwide collection of comparable measures of ambient air

measure used by most previous studies. Our measure of political structure is an index of the extent of democratic participation in government, from the Polity III data set described in Jaggers and Gurr (1995). This index, which ranges from 0 to 10 with 10 being most democratic, is available for every year and country in the AIRS data. We measure trade intensity using the ratio of imports plus exports to GDP, and we measure investment as a fraction of GDP, both from the PWT. We use population and country area data from a variety of sources to construct annual measures of national population density.[4]

3. The effects of changes in the data

To demonstrate the effects of the revisions to the existing data, we need to begin with a benchmark econometric specification. Because Grossman and Krueger's (1995) paper is in many ways the most carefully done and widely known work, we start with their specification. They estimate

$$Y_{it} = G_{it}\boldsymbol{b}_1 + G_{it}^2\boldsymbol{b}_2 + G_{it}^3\boldsymbol{b}_3 + L_{it}\boldsymbol{b}_4 + L_{it}^2\boldsymbol{b}_5 + L_{it}^3\boldsymbol{b}_6 + X_{it}^{'}\boldsymbol{b}_7 + m_i + \boldsymbol{n}_{it},$$

where G_{it} is per capita gross domestic product at time t for the country in which monitoring site i is located, L_{it} is a three-year average of lagged per capita GDP, and $\boldsymbol{X}_{it}$ are country and site-specific descriptors. This model was estimated using random effects, so m_i is assumed to be a site specific effect that is uncorrelated with the right-hand-side variables, and n_{it} is a normally distributed error term.

Table 3 estimates this equation for SO_2. Column 1 replicates the Grossman and Krueger results exactly, using their data. The dependent variable in column 1 is the median annual sulfur dioxide reading from each monitor. Because the version of the data we obtained from the EPA reports mean values

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and water quality. See Bennet et al. (1985) and UNEP and WHO (1983), (1984), (1992) and (1994) for reports on the history and results of the GEMS air monitoring project.

rather than medians, in column 2 we report results from an identical specification substituting means for medians, again using the original data. This difference in the dependent variable seems unimportant: the pattern of coefficient signs, sizes, and statistical significance remains largely unchanged.

Figure 1 plots the predicted pollution-income paths with all regressors other than income set at their means.[5] Line 1 in Figure 1 plots the results of column 1 of Table 1. Line 2 uses mean values from column 2, rather than the medians from column 1. The second line is virtually identical to the first, though it is somewhat higher due to the fact that the pollution data are skewed, with means higher than medians. Both plots peak at about $4000 per capita. Because the most recent public release of AIRS data contains only mean pollution readings, in the rest of the analysis we use means, relying on the comparison of columns 1 and 2 to show that the difference is insubstantial.

Column 3 of Table 3 uses the same sample of cities and years as columns 1 and 2, 1977 to 1988, but incorporates the corrections and additions in the latest release of the AIRS data. Since the earlier release contained missing descriptive statistics, the regressions in columns 1 and 2 contain an indicator variable for the cases when covariates were unavailable. The most recent data contain no such gaps, and so we drop the corresponding indicator variable. Similarly, we dropped a variable documenting the type of pollution monitor, available in the original data but not in the new version.[6] As can be seen from Table 3, even using the same observations and econometric specification, the changes in the data result in large changes in the regression results and the shape of the GDP/SO_2 relationship. Line 3 of Figure 1 depicts these differences. Rather than increasing and then peaking at $4,000, line 3 declines initially, then starts to increase at about $7,000, at nearly the same point where the second

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[4] For the fixed effect models reported below, this amounts to a measure of population, since area does not vary with time.

[5] In drawing this and subsequent figures, we have set lagged GDP equal to current GDP, as was done in Grossman and Krueger (1995), and for consistency we use the same method to calculate the peaks and troughs given in the tables.

[6] This variable was not significant in any of the original specifications.

regression line was actually decreasing at its highest rate. The line then starts to decrease again at about $14,000, about where the second regression line starts to increase.

Column 4 in Table 3 uses the most recent AIRS data, and all available observations from 1971 to 1992. The individual GDP coefficients are generally highly significantly different from zero, which is not true of all of the preceding regressions, perhaps due to the increase in sample size. Again, the estimated pollution-income equations change significantly from those fit using the original data, though the changes from column 3 are minor. Line 4 of Figure 1 plots the predicted values from column 4. The difference in the shape of the curve is insubstantial.

For the other air pollutants we studied, TSP and smoke, there were fewer changes to the data and therefore the regression results are less sensitive to those changes. (See Appendix Table 1.) In both the original and new data, TSP decreases monotonically with GDP, although the slopes at $10,000 and $12,000 are smaller in the new data. For smoke, in both the original and new data the pollution concentrations exhibit an inverted-U, with a peak at about $6,000.

Finally, the last line of Table 3 presents chi-squared statistics from a Hausman test of whether the random-effects error terms are uncorrelated across the monitoring stations. In three of the four samples, this hypothesis can be rejected, suggesting that fixed monitoring-station effects are more appropriate. Therefore, in the next section we use the most recent version of the AIRS data with a fixed effects model to explore the effects of changing the econometric specification of the pollution-income relationship.

4. The effects of changes in the specification

Because the reduced form relationships typically estimated in this literature are not driven by any particular economic model, there is little theoretical guidance for the correct specification. Consequently, we believe the best approach is to see if conclusions are robust across a variety of specifications. Table 4 summarizes the results of regressions for SO_2 using fixed monitoring-station effects with different covariates and functional forms. All these regressions use the most complete version of the data available to us, the same as that used in column 4 of Table 3. Column 1 of Table 4 is a fixed-effects version of the regression in column 4 of Table 3, excluding those regressors that do not vary over time.[7] The results are comparable, suggesting that although a Hausman test may reject the random-effects specification, in practice the predicted pollution income paths from the two models are comparable.

In column 2 we lengthen the lag structure of the income variable. Lagged values of GDP per capita, averaged over the previous three years, were included in the original specifications as a measure of permanent income. In other words, pollution is almost certainly positively correlated with temporary changes in GDP, as increases and decreases in economic activity generate more or less pollution. Of more interest are the effects of long-run secular changes in income, which may increase or decrease pollution levels, depending on the sources of economic growth and on the nature of any induced policy responses. If, for example, wealthier policymakers enact more stringent pollution regulations, then the effect of permanent income on GDP may be negative. To separate these two effects more distinctly, in column 2 we use a polynomial in the average GDP per capita for the past 10 years, rather than the 3-year lag in the original specification. These longer lags eliminate more of the temporary fluctuations from the measure of permanent income. They also provide more time for secular changes in GDP to become incorporated in social values, for those social values to be used to determine government policy, and then for those policy changes to be implemented. Comparing columns 1 and 2 of Table 4, these longer lags do not dramatically alter the regression results.

Column 3 of Table 4 adds a number of covariates to the specification. First, it adds the square of the time trend to measure nonlinearities in the time path of pollution. If environmental degradation or improvement has accelerated over time for reasons unrelated to GDP growth, and if the econometric models include only a linear time trend, the acceleration may be inaccurately attributed to GDP changes.

Column 3 also includes a measure of national trade intensity, an index of democratic government, relative GDP (national GDP divided by the average of all countries' GDPs), and the percentage of GDP going to investment. All are statistically significant, with the exception of relative GDP. Including all of these additional covariates alters the magnitude of the coefficients on the GDP polynomials, though not their general pattern.

In column 4 of Table 4, we include only trade intensity and the democracy index as additional covariates. In column 5 we substitute annual year indicators for the year quadratic, allowing even more flexibility in the aggregate time pattern of pollution. Neither change yields dramatic changes to the pattern of GDP coefficients nor to the predicted pollution-income path.

Finally, in columns 6 and 7 of Table 4, we estimate models in which the dependent variable is the log of the mean annual pollution reading at each monitoring station, rather than the level. Though the pattern of the GDP coefficients' signs are similar to those in levels regression, in columns 6 and 7 the measured effect of changes in income on pollution levels virtually disappears (even after re-scaling pollution from logs to levels).

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[7] Column 1 also replaces the time-invariant city-level measure of population density with an annual national-level measure.

Although there is no *a priori* reason to prefer any one of the specifications in Table 4 to the others, the specifications generally show a U-shaped, rather than inverted U-shaped relationship between income and sulfur dioxide pollution. This finding is troubling, for two reasons. First, if we assume that when GDP is zero pollution must also be zero, then we know that the true pollution-income relationship cannot be U-shaped. Second, even though the pattern of coefficients is similar across specifications in Table 4, the slopes at any particular income and the location of the turning points vary considerably. As a consequence, we feel that we can say very little about any underlying relationship between GDP and ambient levels of SO_2.

This conclusion, that we can conclude little about pollution-income patterns, holds even more strongly for smoke and TSP. For these pollutants, we ran various specifications with the new AIRS data, in a way similar to what we show in Tables 3 and 4 for SO_2. (See Appendix Table 2 for the results, and Appendix Figures 1 and 2 for the plots of those results.) For smoke and TSP the predicted pollution-income paths have inverted-U-shapes, though the location and magnitudes of the peaks depend on the specification.

Another means of demonstrating the uncertainty about the GDP-pollution relationship is to draw confidence bands around the entire predicted path, rather than around individual coefficients. Since the underlying variables, GDP, its polynomial, and lagged values, are correlated, the confidence bands will be wider than might be inferred from the coefficients' standard errors. One approach would be to use the joint confidence interval for *all* of the coefficients, not just the GDP coefficients. This approach might be appropriate if we were interested in possible pollution paths for a country for which we knew the values of the independent variables, but not the current pollution level. A second approach would be to draw confidence bands for the *future* path of pollution, starting at current GDP, and assuming that we know current pollution levels with certainty. This would result in a much narrower confidence band. We compromise between these two approaches and ignore the uncertainty in all of the coefficients aside from the GDP polynomials, including the intercept, and start at a GDP of zero.

Figure 2 depicts the confidence band for Grossman and Krueger's (1995) SO_2 specification, column 1 of Table 3. These bands are based on bootstrapped 95 percent joint confidence intervals for the GDP and lagged GDP polynomials. To interpret Figure 2, assume that the specification in column 1 of Table 3 is correct. In that case, we can say with 95 percent certainty that the "true" pollution-income cubic equation falls within the indicated region. These confidence bands are obviously wide enough to incorporate a variety of paths over the relevant range of GDP. We may have monotonically rising or falling pollution, U-shapes or inverted-U-shapes, or more complicated relationships. Of course, the confidence region shown assumes that the true relationship between GDP and pollution is the cubic functional form estimated. If this is not correct, the true confidence band could be even wider.

Figure 3 depicts the 95 percent confidence band for the fixed-effects regression from column 4 of Table 4, constructed in a similar manner. Uncertainty about the shape of the pollution-income path is equally apparent here. A variety of pollution-income paths may be described within the region depicted. For smoke and TSP, the GDP coefficients have higher standard errors and the confidence bands (not shown here) are wider than in the Figure 3 SO_2 regressions.

5. Conclusion

In sum, for three important air pollutants, SO_2, smoke, and TSP, we find that the estimated relationship between pollution and GDP is sensitive to both sample and empirical specification. We believe that, for these pollutants, there is little if any empirical support for the existence of an inverted-U-shaped "environmental Kuznets curve." However, we believe this statement deserves at least two qualifications.

First, there are theoretical arguments, such as those cited in our introduction, which suggest that an inverted-U-shaped relationship may not only be possible, but in fact may be quite plausible. It may well be the case that the existing data on a few pollutants, drawn from a few monitoring stations in a small non-representative sample of cities over a relatively short period of time, is simply insufficient to detect the true relationship between pollution and economic growth, should that be an inverted U. Alternatively, most of the world's nations may not yet have reached income levels sufficient to generate the turning points predicted by those theories.

The second point worth highlighting here is that while this paper shows that air quality does not necessarily *improve* with economic growth, we have found no evidence in these data that environmental quality necessarily *declines* with growth either. Our conclusion is simply that, for these pollutants, the available empirical evidence cannot be used to support either the proposition that economic growth helps the environment, or the proposition that it harms the environment.

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Table 1
Comparison of summary statistics

	Grossman and Krueger (1995)					AIRS				
SO_2	**Obs.**	**Mean**	**S.D.**	**Min.**	**Max.**	**Obs.**	**Mean**	**S.D.**	**Min.**	**Max.**
Median SO_2 Conc.	1352	33.2	33.3	0	291		Not available			
Mean SO_2 Conc.	1261	49.0	40.9	2.36	354	2401	49.4	50.9	0.782	1160
GDP per Capita	1352	7.51	4.83	0.619	17.3	2381	9.43	5.73	0.765	18.1
3-yr-avg. lag GDP	1352	7.18	4.62	0.626	16.2	2389	9.10	5.56	0.779	18.0
10-yr-avg. lag GDP						2389	8.48	5.25	0.753	16.8
Year	1352	1982	3.28	1977	1988	2401	1983	5.17	1971	1992
Population Density	1352	3.35	4.56	0.00210	24.7	2401	2.75	3.99	0.00210	24.7
Industrial	1352	0.291	0.455	0	1	2401	0.0875	0.283	0	1
Residential	1352	0.360	0.480	0	1	2401	0.820	0.384	0	1
Center City	1352	0.550	0.498	0	1	2401	0.862	0.345	0	1
Coastal	1352	0.555	0.497	0	1	2401	0.565	0.496	0	1
% GDP Invested						2381	23.1	5.49	4.20	41.5
Trade Intensity						2381	42.5	32.9	8.84	262
Democracy Index						2322	7.23	4.16	0	10
Relative GDP						2381	1.121	0.910	-0.85	2.10
# sites	239					285				
# cities	77					102				
# countries	42					45				
TSP	**Obs.**	**Mean**	**S.D.**	**Min.**	**Max.**	**Obs.**	**Mean**	**S.D.**	**Min.**	**Max.**
Median TSP Conc.	1021	147	127	0	715		Not available			
Mean TSP Conc.	1021	163	140	10.7	796	1092	177	146	9.80	796
GDP per Capita	1021	8.11	5.99	0.619	17.3	1085	6.95	5.65	0.765	17.5
3-yr-avg. lag GDP	1021	7.71	5.72	0.626	16.2	1092	6.65	5.39	0.779	17.3
10-yr-avg. lag GDP						1092	6.11	4.95	0.753	15.9
Year	1021	1982	3.29	1977	1988	1092	1984	4.88	1972	1992
Population Density	1021	3.07	4.16	0.00210	24.7	1092	3.84	4.59	0.00150	24.7
Industrial	1021	0.303	0.460	0	1	1092	0.0375	0.190	0	1
Residential	1021	0.347	0.476	0	1	1092	0.920	0.271	0	1
Center City	1021	0.467	0.499	0	1	1092	0.943	0.232	0	1
Coastal	1021	0.529	0.499	0	1	1092	0.509	0.500	0	1
Desert	1021	0.0411	0.199	0	1	1092	0.00916	0.0953	0	1
% GDP Invested						1085	22.9	6.15	3.70	39.3
Trade Intensity						1085	45.8	39.2	8.84	286
Democracy Index						1063	5.66	4.55	0	10
Relative GDP						1085	0.653	1.05	-1.08	2.03
# sites	161					149				
# cities	62					53				
# countries	29					30				
Smoke	**Obs.**	**Mean**	**S.D.**	**Min.**	**Max.**	**Obs.**	**Mean**	**S.D.**	**Min.**	**Max.**
Median Smoke Conc.	488	42.2	42.6	0	312		Not available			
Mean Smoke Conc.	487	53.4	48.6	1.30	325	710	56.7	50.7	1.300	307
GDP per Capita	488	6.81	3.00	1.34	12.2	687	6.78	3.22	1.293	13.5
3-yr-avg. lag GDP	488	6.61	2.88	1.25	11.4	687	6.60	3.05	1.187	12.4
10-yr-avg. lag GDP						687	6.22	2.84	1.117	11.6
Year	488	1982	3.33	1977	1988	710	1982	4.89	1972	1992
Population Density	488	3.64	5.30	0.00210	24.7	710	3.87	5.10	0.00210	24.7
Industrial	488	0.275	0.447	0	1	710	0	0	0	0
Residential	488	0.311	0.464	0	1	710	1	0	1	1
Center City	488	0.568	0.496	0	1	710	1	0	1	1
Coastal	488	0.607	0.489	0	1	710	0.513	0.500	0	1
Desert	488	0.107	0.309	0	1	710	0.0465	0.211	0	1
% GDP Invested						687	21.4	6.16	4.30	41.5
Trade Intensity						687	56.0	37.9	8.96	210
Democracy Index						646	6.13	4.36	0	10
Relative GDP						687	0.975	0.540	-0.350	1.75
# sites	87					96				
# cities	30					32				
# countries	19					21				

Note: Grossman and Krueger (1995) include dummy variables for the type of monitoring device and for missing land-use and location information. These are not available in the AIRS data.

Table 2

Comparison of mean pollutant levels from AIRS with Grossman and Krueger's (1995) data

	SO_2	TSP	Smoke
# of Paired City-Years	485	300	192
Correlation within Pairs	0.745	0.996	0.766
Mean of AIRS means	47.4	164	53.3
Mean of G&K means	47.2	164	56.2
Statistics for the ratio[1] of paired pollution levels			
Mean of the Ratio[2]	1.21	1.019	1.12
St. Dev. of the Ratio[3]	1.73	0.373	1.03
Min. Ratio	0.123	0.754	0.132
Max. Ratio	33.7	6.77	12.6

Notes:

[1] Ratio refers to the ratio of the mean pollutant concentration for a given city-year in the AIRS data set to the mean concentration in the Grossman and Krueger data.

[2] The expected mean of the ratio is 1 if the data has not been altered and if our pairing is correct.

[3] The expected standard deviation of the ratio is 0 if the data has not been altered and if our pairing is correct.

Table 3

Effects of changes in the data on sulfur dioxide regressions

Independent variables	1	2	3	4
GDP	-7.37	-5.72	-29.9**	-29.3**
	(9.15)	(9.71)	(10.2)	(7.41)
$(GDP)^2$	1.03	1.41	3.45**	4.06**
	(1.11)	(1.20)	(1.21)	(0.769)
$(GDP)^3$	-0.0337	-0.0543	-0.104*	-0.127**
	(0.0384)	(0.0415)	(0.0407)	(0.0232)
Lagged GDP	20.9*	14.7	10.6	14.1
	(9.75)	(10.5)	(11.0)	(7.32)
$(\text{Lagged GDP})^2$	-3.22*	-2.92*	-1.40	-2.85**
	(1.26)	(1.38)	(1.40)	(0.780)
$(\text{Lagged GDP})^3$	0.117*	0.109*	0.0382	0.0991**
	(0.0461)	(0.0507)	(0.0502)	(0.0239)**
Year	-1.40**	-1.50**	-0.475*	-1.51**
	(0.218)	(0.239)	(0.240)	(0.159)
Population Density	1.14	0.495	-0.647	-0.717
	(1.23)	(0.551)	(1.26)	(1.05)
Industrial	-0.485	-0.383	-34.6	-2.72
	(5.26)	(6.96)	(46.6)	(24.9)
Residential	-11.1*	-6.69	-30.2	-5.39
	(4.85)	(6.38)	(33.3)	(17.7)
Center City	3.06	11.4*	28.3	26.5
	(4.31)	(5.71)	(29.2)	(15.5)
Coastal	-12.7**	-15.6*	-22.8	-24.7*
	(3.78)	(5.12)	(11.8)	(8.94)
# obs.	1352	1261	1403	2381
# groups	239	233	227	282
R-squared				
within		0.0953	0.0316	0.0990
between		0.140	0.0183	0.0340
overall	0.273#	0.188	0.0425	0.0746
Turning Points				
Peak	$4,000	$3,718	$13,741	$20,081
	(355)	(649)	(1419)	(2592)
Trough	$13,534	$14,767	$7,145	$9,142
	(599)	(1297)	(915)	(877)
Slopes				
at $10,000	-5.30**	-4.90**	2.10	0.721
	(0.609)	(0.969)	(1.334)	(0.825)
at $12,000	-3.07**	-3.75**	1.66	1.92*
	(0.91)	(1.072)	(1.44)	(0.826)
Hausman Chi^2	81.7**	223**	11.7	21.5*

\# Indicates adjusted r-squared. These results are estimated using Grossman and Krueger's Stata program, which does not provide within and between r-squareds

* $p < 0.05$

** $p < 0.01$

Model	Dependent variable	Sample
(1)	median SO_2 concentration	Grossman and Krueger's (1995) data
(2)	mean SO_2 concentration	Grossman and Krueger's (1995) data
(3)	mean SO_2 concentration	New AIRS data: Only G&K's cities & years
(4)	mean SO_2 concentration	New AIRS data: All years & cities

Notes: Standard errors in parentheses. An overall constant term was included in all regressions. Grossman and Krueger (1995) also include dummy variables for monitor type and missing site information which were not significant.

Table 4

Effects of changes in the specification on sulfur dioxide regressions

Independent variables	1	2	3	4	5	6	7
GDP	-33.3**	-42.3**	-19.5	-34.7**	-39.2**	-0.410**	-0.302*
	(7.57	(6.50)	(10.3)	(6.79)	(7.18)	(0.139)	(0.129)
$(GDP)^2$	4.33**	4.67**	2.13*	3.78**	4.17**	0.0382*	0.0278*
	(0.781)	(0.698)	(0.848)	(0.717)	(0.781)	(0.0151)	(0.0136)
$(GDP)^3$	-0.133**	-0.133**	-0.0610**	-0.108**	-0.126**	-0.00110*	-0.000697
	(0.0235)	(0.0215)	(0.0238)	(0.0217)	(0.0242)	(0.000468)	(0.000411)
Lagged GDP	7.86	16.3*	13.8*	20.3**	27.8**	0.488**	0.399**
	(7.46)	(6.96)	(6.73)	(6.71)	(6.86)	(0.133)	(0.127)
$(\text{Lagged GDP})^2$	-2.35**	-2.86**	-1.55	-3.22**	-3.52**	-0.0523**	-0.0470**
	(0.787)	(0.778)	(0.797)	(0.761)	(0.822)	(0.0160)	(0.0144)
$(\text{Lagged GDP})^3$	0.0868**	0.0968**	0.0525	0.115**	0.129**	0.00177**	0.00150**
	(0.0241)	(0.026)	(0.0272)	(0.0255)	(0.0287)	(0.000556)	(0.000482)
Year	-1.49**	-1.20**	-568**	-2.28**			-0.0541**
	(0.174)	(0.215)	(106)	(0.266)			(0.00503)
$(\text{Year})^2$			0.143**				
			(0.0266)				
Population Density	14.2**	8.92	524**	520**	586**	9.80**	9.23**
	(4.68)	(4.80)	(46.2)	(46.1)	(45.7)	(0.887)	(0.872)
Trade Intensity			-0.582**	-0.600**	-0.450**	-0.00931**	-0.0110**
			(0.0868)	(0.0876)	(0.0915)	(0.00177)	(0.00166)
Democracy Index			-3.63**	-3.24**	-3.09**	-0.0400**	-0.0390**
			(0.509)	(0.499)	(0.494)	(0.00958)	(0.00945)
Relative GDP			-26.7				
			(20.2)				
Investment			0.661**				
			(0.21)				
# obs.	2381	2381	2314	2314	2314	2314	2314
# groups	282	282	267	267	267	267	267
R'(squared							
within	0.104	0.104	0.224	0.207	0.266	0.241	0.220
between	0.00220	0.00450	0.0196	0.0194	0.0178	0.122	0.121
overall	0.0195	0.0328	0.0866	0.0866	0.0756	0.143	0.150
Turning Points							
Peak	$18,800	$22,500	$39,700	-$64,700	-$151,000	$3,770	$3,120
	(1,460)	(4,970)	(49,300)	(152,000)	(764,000)	(3,860)	(2,388)
Trough	$9,790	$1,060	$5,650	$10,900	$8,300	$10,300	$12,800
	(798)	(835)	(5,070)	(683)	(845)	(1,654)	(948)
Slopes							
at $10,000	0.251*	-0.828	3.30	-1.33	2.47*	-0.00346	-0.0458*
	(0.987)	(1.08)	(2.69)	(1.06)	(1.12)	(0.0220)	(0.0200)
at $12,000	2.07*	1.59	4.49	1.78	5.47**	0.0285	0.0161
	(0.931)	(1.11)	(2.37)	(1.11)	(1.19)	(0.023)	(0.0210)
Hausman Chi^2	251**	22.7**	132**	155**	125**	635**	93.9**

* $p < 0.05$
** $p < 0.01$

Model	Dependent variable	Description
(1)	mean SO_2 concentration	Short set of explanatory variables, 3'(year lags
(2)	mean SO_2 concentration	Longer lag structure but no additional regressors
(3)	mean SO_2 concentration	All explanatory variables
(4)	mean SO_2 concentration	Base model explanatory variables
(5)	mean SO_2 concentration	Year dummies
(6)	ln(mean SO_2 concentration)	Log dependent, year dummies
(7)	ln(mean SO_2 concentration)	Log dependent

Note: Standard errors in parentheses. An overall constant term was also included in all regressions.

Figure 1: Plot of Table 3 regressions
Different data sets for sulfur dioxide

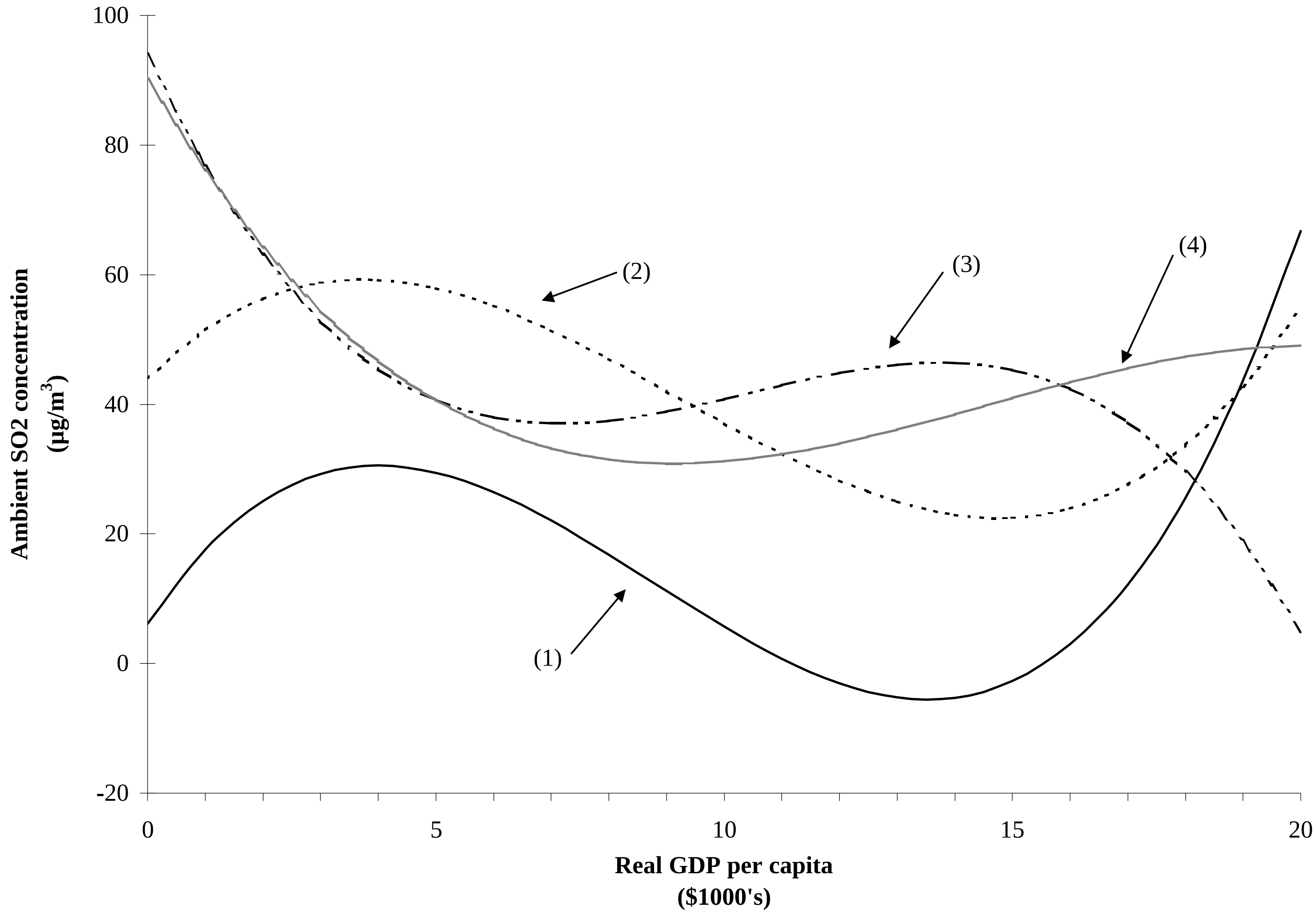


Figure 2: Regression estimate with 95% confidence bands

Random effects, from Table 3, regression 2

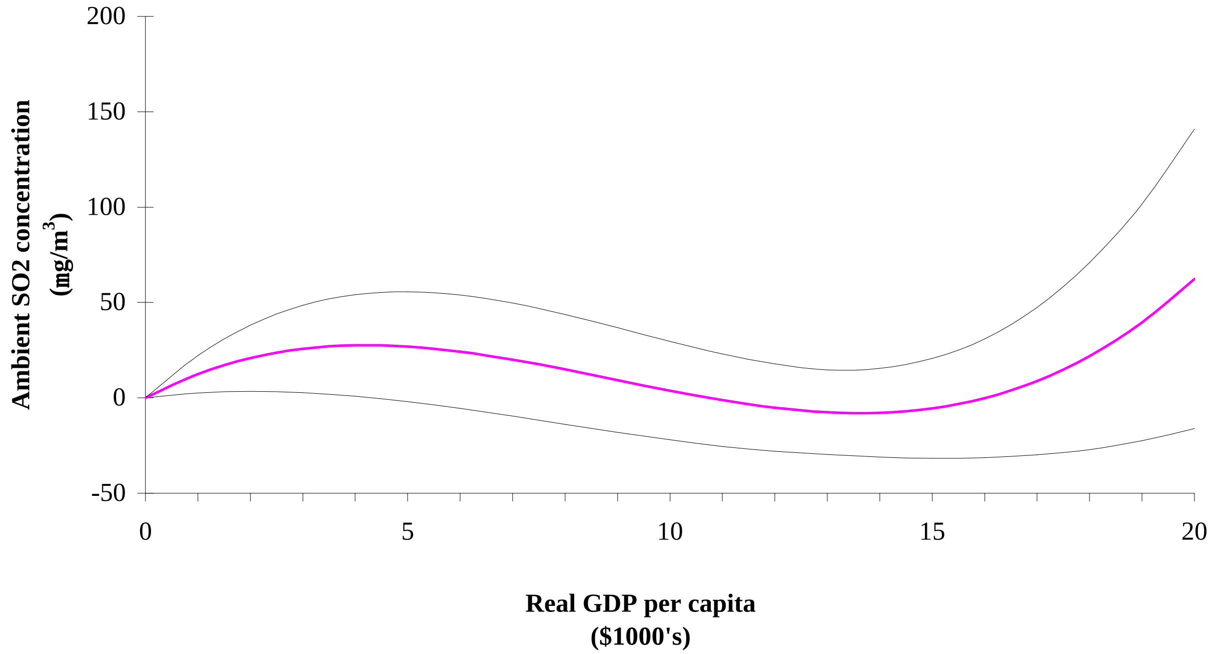
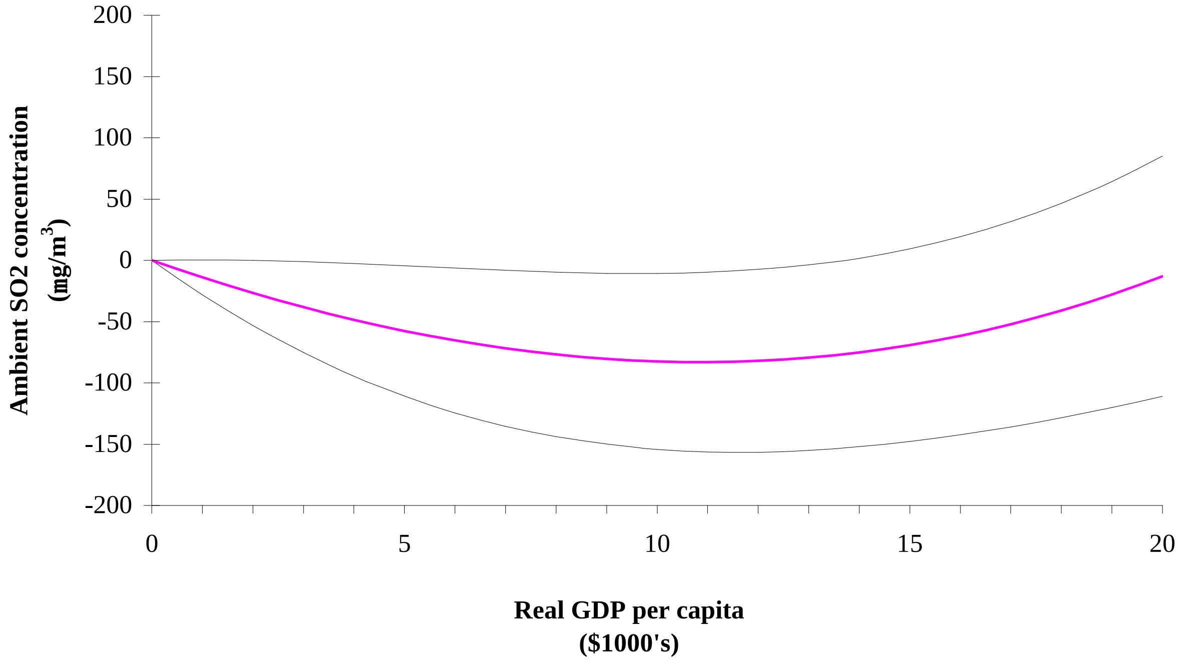


Figure 3: Regression estimate with 95% confidence bands

Fixed effects, from Table 4, regression 4



Appendix Table 1

Effects of changes in the data on TSP and smoke regressions

	TSP		Smoke	
Independent variables	1	2	3	4
GDP	17.4	22.3	24.5	18.4
	(21.5)	(21.1)	(20.9)	(21.1)
(GDP)^2	-0.922	-2.02	-7.64*	-2.22
	(2.65)	(2.34)	(3.58)	(3.17)
(GDP)^3	0.0136	0.0595	0.443**	0.102
	(0.0902)	(0.0737)	(0.171)	(0.139)
Lagged GDP	-60.7**	-43.6*	12.6	62.0**
	(23.3)	(20.9)	(22.0)	(23.2)
(Lagged GDP)^2	4.35	3.45	3.44	-9.07*
	(3.12)	(2.40)	(3.96)	(3.67)
(Lagged GDP)^3	-0.115	-0.0951	-0.313	0.373*
	(0.112)	(0.0783)	(0.199)	(0.170)
Year	0.744	-1.84**	-1.23**	-2.29**
	(0.631)	(0.462)	(0.358)	(0.254)
Population Density	-0.699	4.04*	2.39**	1.60
	(1.40)	(1.83)	(0.853	(0.952)
Industrial	23.8	-26.4	-11.6	(dropped)
	(17.4)	(61.1)	(10.7)	
Residential	7.35	-98.0*	-13.9	4450**
	(16.4)	(38.9)	(9.36)	(502)
Center City	26.2	-149**	4.05	(dropped)
	(14.5)	(42.2)	(8.86)	
Coastal	-21.1	-40.6*	-33.7**	-34.2**
	(12.1)	(17.2)	(8.35)	(9.16)
Desert	162**	252**	7.08	52.8*
	(26.1)	(58.1)	(11.2)	(25.2)
# obs.	1021	1085	488	687
# groups		148		92
R-squared				
within		0.0195		0.190
between		0.501		0.193
overall	0.485#	0.526	0.312#	0.270
Turning Points				
Peak	none	none	$6,194	$5,399
			$539	$237
Trough	none	none	$15,455	$10,447
			$6,598	$452
Slopes				
at $10,000	-5.16	-3.27	-8.05	-2.93
	(5.16)	(2.45)	(12.74)	(2.64)
at $12,000	-4.81*	-2.24	-7.78	14.6*
	(2.08)	(2.12)	(8.65)	(6.48)
Hausman Chi^2	122**	151**	4.81	24.6**

# Indicates adjusted r-squared. These results are estimated using Grossman and Krueger's Stata program, which does not provide within and between r-squareds.

***** $p < 0.05$
****** $p < 0.01$

Model	Dependent variable	Description
(1)	median TSP concentration	Grossman and Krueger's (1995) Results
(2)	mean TSP concentration	Their model using the new AIRS data
(3)	mean smoke concentration	Grossman and Krueger's (1995) Results
(4)	median smoke concentration	Their model using the new AIRS data

Notes: Standard errors in parentheses. An overall constant term was included in all regressions. Grossman and Krueger (1995) also include dummy variables for monitor type and missing site information, none of which were significant.

Appendix Table 2

Effects of changes in the specification on TSP and smoke regressions

Independent variables	TSP 1	TSP 2	TSP 3	TSP 4	Smoke 5	Smoke 6	Smoke 7	Smoke 8
GDP	60.6**	0.165	54.5**	0.161	55.6**	0.975**	68.2**	1.01**
	(20.1)	(0.103)	(20.7)	(0.107)	(19.8)	(0.327)	(21.8)	(0.353)
$(GDP)^2$	-3.58	-0.00402	-2.60	-0.00356	-7.13*	-0.149**	-9.24**	-0.157**
	(2.30)	(0.0118)	(2.39)	(0.0123)	(2.89)	(0.0479)	(3.18)	(0.0515)
$(GDP)^3$	0.0759	0.0000549	0.0347	-0.00000228	0.271*	0.00638**	0.363**	0.00677**
	(0.0730)	(0.000375)	(0.0762)	(0.000393)	(0.125)	(0.00207)	(0.137)	(0.00222)
Lagged GDP	-35.9	-0.157	-30.0	-0.164	-8.33	-0.846*	-47.8*	-1.47**
	(20.6)	(0.105)	(20.8)	(0.107)	(21.59)	(0.357)	(24.0)	(0.387)
$(Lagged\ GDP)^2$	2.62	0.00663	2.19	0.0124	0.959	0.138*	8.29*	0.251**
	(2.59)	(0.0133)	(2.71)	(0.0140)	(3.45)	(0.0573)	(3.93)	(0.0637)
$(Lagged\ GDP)^3$	-0.0750	-0.000357	-0.0553	-0.000571	-0.0593	-0.00709*	-0.396*	-0.0123**
	(0.0934)	(0.000479)	(0.0985)	(0.000508)	(0.170)	(0.00282)	(0.190)	(0.00308)
Year	-1.62	-0.00642			0.639	0.00442		
	(0.836)	(0.00429)			(0.742)	(0.0123)		
Population Density	-206	-0.153	-95.7	0.597	-1080**	-10.5	-526.2281	-0.034866
	(139)	(0.715)	(143)	(0.735)	(325)	(5.39)	(342)	(5.53)
Trade Intensity	0.478	0.00138	0.402	0.000944	0.0986	0.000886	0.288	0.00619*
	(0.267)	(0.00137)	(0.276)	(0.00142)	(0.146)	(0.00241)	(0.162)	(0.00262)
Democracy Index	-8.72**	-0.0394**	-9.70**	-0.0466**	-2.94**	-0.0337**	-2.39**	-0.0190
	(2.21)	(0.0113)	(2.23)	(0.0115)	(0.642)	(0.0106)	(0.684)	(0.0111)
# obs.	1056	1056	1056	1056	646	646	646	646
# groups	144	144	144	144	89	89	89	89
R-squared								
within	0.114	0.190	0.162	0.226	0.216	0.136	0.287	0.250
between	0.0981	0.178	0.143	0.0426	0.0414	0.0340	0.0337	0.0110
overall	0.156	0.247	0.240	0.0642	0.0761	0.0625	0.0686	0.0489
Turning Points								
Peak	$13,057	$7,013	$14,291	$10,082	$5,258	$4,227	$7,697	$7,591
	(2384)	(3147)	(2292)	(1370)	(586)	(1599)	(1342)	(1141)
Trough	$764,867	-$1,247	-$27,674	$179	$14,146	-$14,284	-$27,136	$3,705
	(53176425)	(12685)	(94255)	(4385)	(3543)	(64509)	(132202)	(1229)
Slopes								
at $10,000	5.71	-0.0304	10.0*	0.00139	-12.5*	-0.299**	-8.33	-0.251**
	(4.11)	(0.0211)	(4.54)	(0.0234)	(5.71)	(0.095)	(5.96)	(0.0970)
at $12,000	1.97	-0.0598**	5.63	-0.0390	-9.20	-0.435*	-16.4	-0.605**
	(3.99)	(0.0205)	(4.29)	(0.0221)	(10.9)	(0.181)	(11.1)	(0.180)
Hausman Chi^2	61.6*	35.4**	68.3**	79.2**	37.8**	32.7**	223**	19.9

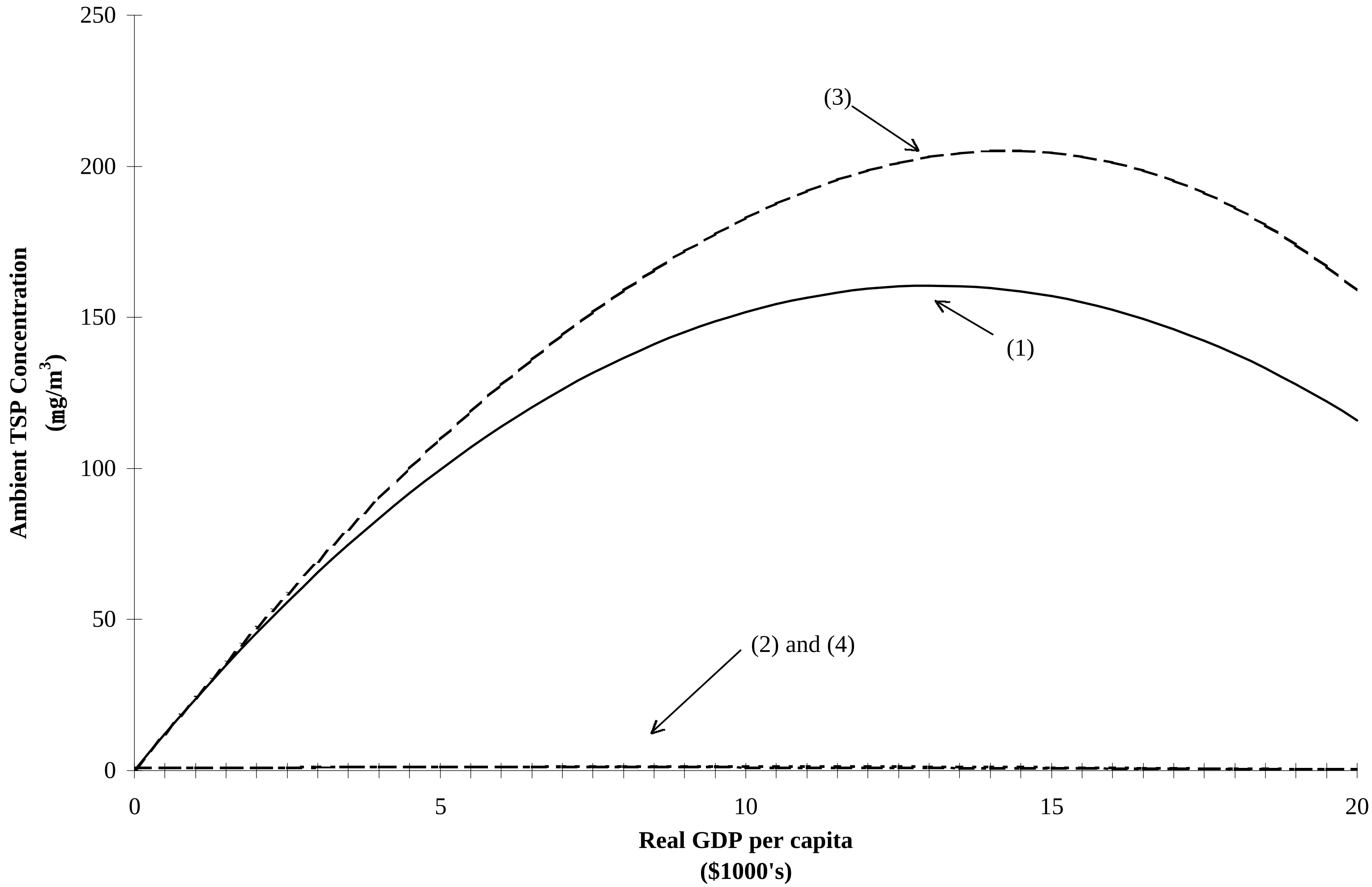
***** $p < 0.05$
****** $p < 0.01$

Model	Dependent variable	Model
1	mean TSP concentration	Base model explanatory variables
2	ln(mean TSP concentration)	Base model explanatory variables
3	mean TSP concentration	Year dummies
4	ln(mean TSP concentration)	Year dummies
5	mean smoke concentration	Base model explanatory variables
6	ln(mean smoke concentration)	Base model explanatory variables
7	mean smoke concentration	Year dummies
8	ln(mean smoke concentration)	Year dummies

Note:Standard errors in parentheses. An overall constant term was also included in each model.

Appendix Figure 1: Plot of Appendix Table 2 regressions

Different fixed effects specifications for TSP



Appendix Figure 2: Plot of Appendix Table 2 regressions

Different fixed effects specifications for smoke