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ECONOMIC GROWTH AND THE ENVIRONMENT

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ABSTRACT

Using data assembled by the Global Environmental Monitoring System we examine the reduced-form relationship between various environmental indicators and the level of a country's per capita income. Our study covers four types of indicators: concentrations of urban air pollution; measures of the state of the oxygen regime in river basins; concentrations of fecal contaminants in river basins; and concentrations of heavy metals in river basins. We find no evidence that environmental quality deteriorates steadily with economic growth. Rather, for most indicators, economic growth brings an initial phase of deterioration followed by a subsequent phase of improvement. The turning points for the different pollutants vary, but in most cases they come before a country reaches a per capita income of $8,000.

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1. Introduction

Will continued economic growth throughout the world bring ever greater harm to the earth's environment? Or do increases in income and wealth sew the seeds for the amelioration of ecological problems? The answers to these questions are critical for the design of appropriate development strategies for lesser developed countries.

Exhaustible and renewable natural resources serve as inputs into the production of many goods and services. If the composition of output and the methods of production were immutable, then damage to the environment would be linked unavoidably to the scale of global economic activity. But substantial evidence suggests that development gives rise to a structural transformation in what an economy produces (see Syrquin, 1989). And societies have shown remarkable ingenuity in harnessing new technologies to conserve scarce resources. In principle, the forces leading to change in the composition and techniques of production may be sufficiently strong so as to more than offset the adverse effects of increased economic activity on the environment. In this paper we address this empirical issue using panel data on ambient pollution levels in many countries.

Examination of the empirical relationship between national income and measures of environmental quality began with our paper on the likely environmental impacts of a North American Free Trade Agreement (Grossman and Krueger, 1993). There we estimated reduced-form regression models relating three indicators of urban air pollution to characteristics of the site and city where pollution was being monitored and to the national income of the country in which the city was located. Selten and Song (1992) and Holtz-Eakin and Selten (1992) have used similar methods to relate estimated rates of emission of several air pollutants to the national income level of the emitting country. The World Bank Development Report (1992) also reports evidence on the relationship between some measures of environmental quality and levels of national GDP. These studies tend to find that environmental degradation and income have an inverted U-shaped relationship, with pollution increasing with income at low levels of income and decreasing with income at high levels of income.

The main contribution of the present paper is that it employs a common methodology to investigate the relationship between the scale of economic activity and environmental quality for a broad set of environmental indicators. We attempt to include in our study all of the dimensions of environmental quality for which actual measurements have been taken by comparable methods in a variety of countries. To this end, we use all of the available panel data in the Global Environmental Monitoring System's (GEMS) tracking of urban air quality in different cities in the developed and developing world. And we use much of the panel data from the GEMS monitoring of water quality in river basins around the globe. Although these measures are far from a comprehensive list of all relevant variables describing the state of the ecosystem, the variety in the types of pollutants included in our investigation may allow generalization (with caveats) to some other types of environmental problems, and it is more comprehensive than that used in previous studies.

In the next section we describe the environmental indicators used in this study and the sources of our data. We discuss briefly the anthropogenic sources of the various pollutants and the health hazards they pose, and note the forms of environmental degradation that are absent from our data. Section 3 details the common methodology that we employ in analyzing the cross-national and time-series pollution data. The results of our analysis are presented and discussed in Section 4. The final section comments on the lessons to be drawn from our study.

2. The Environmental Indicators

Environmental quality has many dimensions. Our lives are affected by the air we breathe, the water we drink, the beauty we observe in nature, and the diversity of species with which we come into contact. The productivity of our resources in producing goods and services is influenced by climate, rainfall, and the nutrients in the soil. We experience discomfort from excessive noise and crowding, and from the risk of nuclear catastrophe. Each of these dimensions of environmental quality (and others) may respond to economic growth in a different way. Therefore, a study of environment and growth should aim to be as comprehensive as possible.

Unfortunately, a paucity of data limits the scope of any such study. Only in recent years have the various aspects of environmental quality been carefully assessed and only a small number of indicators have been comparably measured in a variety of countries at different stages of development. Comparability and reliability are the central aims of the effort spearheaded by the Global Environmental Monitoring System (GEMS), a joint project of the World Health Organization and the United Nations Environmental Programme. For almost two decades the GEMS has monitored air and water quality in a cross-section of countries. These panel data provide the basis for our research.

The GEMS/Air project monitors air pollution in selected urban areas. Concentrations of sulphur dioxide (SO_2) and suspended particulate matter are measured on a daily (or sometimes less frequent) basis and the raw data are used to calculate the median, 80th percentile, 95th percentile and 98th percentile observation in a given year.[1] GEMS also reports information about the monitoring stations, including the nature of the land use nearby and the type of the monitoring instrument used. As some of the methods used to measure suspended particulates reflect primarily concentrations of coarser, heavier particles while others capture quantities of finer, lighter particles, and as the different types of particles pose different health risks, we have chosen to divide the sample for suspended particles into two subsamples, one for "heavy particles" and the other for "smoke".

Participation in the GEMS/Air project has varied over time. For SO_2, the sample contained 47 cities in 28 countries in 1977, 52 cities in 32 countries in 1982, and 27 cities in 14 countries in 1988. A total of 42 countries are represented in the sample. Heavy particles were monitored in 21 cities in 11 countries in 1977, 36 cities in 17 countries in 1982, and 26 cities in 13 countries in 1988, with 29 countries represented in all. The sample for smoke included 18 cities in 13 countries in 1977, 13 cities in nine countries in 1982, and seven cities in four countries in 1988, with a total of 19 countries in all. In all cases, monitoring sites were chosen to be fairly representative of the geographic and economic conditions that exist in different regions of the world (Bennett et al., 1985).

The air quality variables in our study are among the most commonly-used indicators of air pollution in cities and other densely populated areas. Sulphur dioxide and suspended particles are found in great quantities in many cities and their severe effects on human health and the natural environment have long been recognized. Important forms of urban air pollution absent from our sample include nitrogen oxides, carbon monoxide, and lead. Perhaps more important

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[1] The GEMS data for 1977-1984 are published by the World Health Organization in the series Air Quality in Selected Urban Areas. We obtained unpublished data for 1985-1988 from the U.S. Environmental Protection Agency.

is the omission of the air pollutants that affect the global atmosphere, and specifically those that contribute to ozone depletion and to the greenhouse effect. These would include chlorofluorocarbons (CFC's), carbon dioxide, methane, nitrous oxide, and tropospheric ozone.

Both sulphur dioxide and suspended particulate matter (especially, the finer particles) have been linked to lung damage and other respiratory disease.[2] Sulphur dioxide is emitted naturally by volcanoes, decaying organic matter, and sea spray. The major anthropogenic sources include the burning of fossil fuels in electricity generation and home heating, and the smelting of non-ferrous ores (World Resources Institute, 1988). Automobile exhaust and certain chemical manufacturers are also sources of SO_2 in some countries (Kormondy, 1989). Particulates are generated naturally by dust, sea spray, forest fires, and volcanoes. Economic activities responsible for pollution of this sort include certain industrial processes and domestic fuel combustion.

The GEMS/Water project monitors various dimensions of water quality in river basins, lakes, and groundwater aquifers. The number of observations from lake and groundwater stations is, however, too small for any meaningful statistical analysis. Therefore, we focus our attention on the data that describe the state of river basins. In choosing where to locate its monitoring stations, GEMS/Water has given priority to rivers that are major sources of water supply for municipalities, irrigation, livestock and selected industries. A number of stations were included to monitor international rivers and rivers discharging into oceans and seas. Again, the project aimed for representative global coverage. The available water data cover the period from 1979 to 1990. By January 1990, the project had the active participation of 287 river stations in

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[2] For example, Lave and Seskin (1970) find that variation in SO_2 and population density together explain two-thirds of the variation in death from bronchitis in a sample of U.S. cities. See also Dockery, et al. (1993) and U.S. EPA (1982).

58 different countries. Each such station reports 13 basic chemical, physical, and microbiological variables, several globally significant pollutants including various heavy metals and pesticides, and a number of site-specific, optional variables. Information also is provided about the measurement method and frequency of observation, as well as the exact location of the monitoring station.[3] Our study makes use of all variables that can be considered indicators of water quality, provided that they have anthropogenic constituents and that at least ten countries are represented in the sample.

We focus on three categories of indicators relating to water quality. First, we examine the state of the oxygen regime. Aquatic life requires dissolved oxygen to metabolize organic carbon. Contamination of river water by human sewage or industrial discharges (by, for example, pulp and paper mills) increases the concentration of organic carbon in forms usable by bacteria. The more numerous are the bacteria, the greater is the demand for dissolved oxygen, leaving less oxygen for fish and other higher forms of aquatic life. At high levels of contamination the fish population begins to die off. A similar problem can arise when river water is over-enriched by nutrients such as are contained in runoff from agricultural areas where fertilizers are used intensively. Excess nitrogen and phosphorus promote algal growth. Then the decay of dying algae consumes oxygen that is lost to the fish population.

Some GEMS/Water stations directly monitor the level of dissolved oxygen in a river as an indication of the state of the oxygen regime. Other stations measure instead the contamination by organic compounds as an indication of the competing demands for oxygen. One measure of

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[3] Summary data are published triennially by the Global Environmental Monitoring System in the series GEMS/Water Data Summary. We obtained raw data from Robert Bisson of the Canada Centre for Inland Waters, which is the WHO Collaborating Centre for Surface and Groundwater Quality.

this, called biological oxygen demand (BOD), is the amount of natural oxidation that occurs in a sample of water in a given period of time; another measure, called chemical oxygen demand (COD) is the amount of oxygen consumed when a chemical oxidant is added to a sample of water. Whereas dissolved oxygen is a direct measure of water quality, BOD and COD are inverse measures, indicating the presence of contaminants that will eventually cause oxygen loss. Some stations measure all three water quality indicators. We investigate the relationship between levels of income and all three of these indicators of the state of the oxygen regime, as well as the concentration of nitrates in the river water.

Pathogenic contamination is our second indicator of water quality. Pathogens in sewage cause a variety of debilitating and sometimes fatal diseases such as gastroenteritis, typhoid, dysentery, cholera, hepatitis, schistosomiasis, and giardiasis. The presence of pathogens is not a consequence of economic activity per se, but rather contamination occurs when raw sewage is discharged without adequate treatment. The GEMS/Water project monitors fecal coliform -- which are harmless bacteria found in great numbers in human and animal feces -- as an indicator of the presence of the harmful pathogens. The data set includes concentrations of fecal coliform in rivers in 42 different countries. In some cases, GEMS has monitored total coliform instead of (or in addition to) fecal coliform. Total coliform are a broader class of bacteria which, unlike fecal coliform, include some organisms that are found naturally in the environment. For this reason, the concentration of total coliform is considered to be an inferior indicator of fecal contamination. Nonetheless, we estimate the relationship between levels of national income and concentrations of total coliform found in rivers located in 22 countries.

Heavy metals comprise our third category of water pollution. Metals discharged by industry, mining, and agriculture accumulate into bottom sediment, which then is released slowly over time. The metals show up in drinking water and bioaccumulate in fish and shellfish that are later ingested by humans. The GEMS/Water project monitors a number of heavy metals (as well as some other toxics), but the sample sizes for some are too small to allow statistical analysis. We examine concentrations of lead, cadmium, arsenic, mercury and nickel, all of which have reasonable numbers of observations from rivers located in at least ten countries. The health risks associated with these particular metals are many: lead causes convulsions, anemia, kidney damage, brain damage, cancer, and birth defects; cadmium is associated with tumors, renal dysfunction, hypertension, and arteriosclerosis; arsenic induces vomiting, poisoning, liver damage, and kidney damage; mercury contributes to irritability, depression, kidney and liver damage, and birth defects; and nickel causes gastrointestinal and central nervous system damage and cancer.

As we have noted, the GEMS data do not cover all dimensions of environmental quality. Besides the air pollutants that affect global atmospheric conditions, important omissions include industrial waste, soil degradation, deforestation, and loss of biodiversity. While we view our inability to examine the effects of growth on these forms of environmental damage as unfortunate, we believe that there is much to be learned from studying how the many indicators of air and water quality respond to changes in output levels.

3. Methodological Issues

To study the relationship between pollution and growth we estimate several reduced-form equations that relate the level of pollution in a location (air or water) to a flexible function of the current and lagged income per capita in the country and to other covariates. An alternative to our reduced-form approach would be to model the structural equations relating environmental regulations, technology, and industrial composition to GDP, and then to link the level of pollution to the regulations, technology and industrial composition. We think there are two main advantages to a reduced-form approach. First, the reduced-form estimates give us the net effect of a nation's income on pollution. If the structural equations were estimated, one would need to solve back to find the net effect of income changes on pollution, and confidence in the implied estimates would depend upon the precision and potential biases of the estimates at every stage. Second, the reduced-form approach spares us from having to collect data on pollution regulations and the state of technology, data which are not readily available and are of questionable validity. A limitation of the reduced-form approach, however, is that it is unclear why the estimated relationship between pollution and income exists. Nevertheless, we think that documenting the reduced-form relationship between pollution and income is an important first step.

Specifically, we estimate:

$$(1) \qquad Y_{it} = G_{it}\beta_1 + G_{it}^2\beta_2 + G_{it}^3\beta_3 + \bar{G}_{it-}\beta_4 + \bar{G}_{it-}^2\beta_5 + \bar{G}_{it-}^3\beta_6 + X_{it}^{\prime}\beta_7 + \epsilon_{it}$$

where Y_{it} is a measure of water or air pollution in station i in year t, G_{it} is GDP per capita in year t in the country in which station i is located, $\bar{G}_{it-}$ is the average GDP per capita over the prior three years, X_{it} is a vector of other covariates, and ϵ_{it} is an error term. The β's are parameters to be estimated.

For the air pollutants, the dependent variable is defined as the median daily concentration of the pollutant at each site over the course of the year. The mean values of the air pollutants were not reported. Other percentiles of air pollutants were reported, and our analysis of the 95th percentile concentrations indicated qualitatively similar results. For the water pollutants, we used the mean value of the pollutant over the course of the year as our dependent variable, because median values were omitted whenever there were fewer than four observations above the minimum detectable level of the measuring device.

Except for two pollutants, we measure the dependent variables as a concentration level (e.g., μg per cubic meter). The exceptions are total coliform and fecal coliform, which we measure as $\log(1+Y)$, where Y is the concentration level. The reasons for this transformation are: (i) the coliform grow exponentially; (ii) the distribution of the coliform is (highly) positively skewed; and (iii) we cannot take the log of Y in some cases because the level of coliform is reported as zero whenever the reading falls below the minimum detectable level of the measuring device.

The key GDP variable is taken from Summers and Heston (1991), and in principle measures output per capita in relation to a common set of international prices.[4] Although our measures of pollution pertain to specific cities or sites on rivers, GDP is measured at the country level. Since environmental standards are often set at a national level, using country-level GDP per capita (as opposed to local income) is arguably appropriate. Moreover, data on city or river level GDP per capita are not readily available, and are not as comparable across countries as is the Summers and Heston data. We have included a cubic of the average GDP per capita in the preceding three years to proxy the effect of "permanent income" and because past income is likely to be a relevant determinant of current environmental standards. As a practical matter, however, lagged and current GDP per capita are highly correlated, so including just current (or

[4] The Summers and Heston data are only available through 1988, whereas the water pollution data are available through 1990. World Bank GDP estimates, however, are available through 1990. To increase the sample we used the ratio of the Summers and Heston GDP data to World Bank GDP data in 1988 to index-link the World Bank data in 1989 and 1990.

just lagged) GDP per capita does not qualitatively change the results. Experimentation with unrestricted dummies indicating ranges of GDP suggested that the cubic specification is flexible enough to describe the varied relationships between pollution and GDP.

The other variables that we include as covariates were selected on the basis of scientific and economic considerations. In the models for air pollutants we include dummy variables indicating the location within the city (central city or suburban) and the land use near the monitoring station (industrial, commercial, residential, or unknown). We also included the population density of the city, a dummy indicating whether the city is located along a coast line (reflecting the disbursement properties of the local atmosphere), and -- for the two types of suspended particles -- a dummy indicating whether the city is located within 100 miles of a desert. For pollutants that were measured with different measuring devices at different stations, we also included dummies indicating the type of measuring device, to account for the fact that some monitoring devices are more sensitive than others.[5] In all of our estimates we include a linear time trend. When we experimented by including unrestricted year dummies, the coefficients were approximately linear, and the other coefficients were not meaningfully different.

A different set of covariates are appropriate for the water pollutants. In addition to the GDP per capita terms and the time trend, in these models we include the mean annual water temperature in the river in which the monitoring station is located.[6] This is a pertinent

[5] All of these variables except population density, location on a coast, and location near a desert, are available in the GEMS data. We derived the other variables by inspecting maps or country almanacs.

[6] For about one-third of the observations, we lacked information on the mean annual water temperature. In these cases we imputed temperature values by first running a regression of the mean water temperature on the latitude of the river for the subsample containing mean temperature, and then constructing fitted values using the estimated regression coefficient and the latitude of the river with missing temperature data. In practice we suspect this procedure works

explanatory variable because, for many pollutants, the rate of dissolution depends on the temperature of the water. Finally, where appropriate we included dummies indicating the type of measuring device used to monitor the pollutant.

A final methodological issue concerns the appropriate estimator of equation (1). If there are any characteristics of the monitoring sites that influence pollution but are not included in our list of independent variables, these will induce a temporal correlation in the error term, ϵ_{it}. To account for this, we estimate equation (1) by Generalize Least Squares (GLS). More specifically, we assume the error term is the sum of two components:

$$\epsilon_{it} = \alpha_i + \epsilon'_{it}$$

where α_i is a site-specific random component and ϵ'_{it} is an idiosyncratic error component. We assume $cov(\alpha_i,\alpha_j)=0$ and $cov(\epsilon'_{it},\epsilon'_{jt})=0$ for $i \neq j$ and $t \neq s$. We employ a random- effects estimator that takes into account the unbalanced nature of our panel.

4. Results

We have estimated equation (1) for each of the pollutants described in Section 2. The GLS estimates are reported in Appendix Tables A1-A4. The tables also show the p-values for the three current income variables, the three lagged income variables, and the six income variables taken together. In view of the strong multicolinearity between current and lagged GDP, as well as among powers of GDP, it is difficult to infer much about the individual coefficients. However, in most cases the collection of current and lagged GDP terms are highly

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well because latitude accounts for over 70 percent of the variation in mean water temperature.

significant. It appears therefore that national income is an important determinant of local air and water pollution.

Figures 1-4 present graphs that summarize the shape of the estimated reduced-form relationship between per capita GDP and each of the pollutants. Each figure relates to one class of environmental quality indicators: urban air quality, oxygen regime in rivers, fecal contamination of rivers, and heavy metal pollution in rivers. The graphs were constructed by multiplying GDP, GDP-squared and GDP-cubed by the sum of the estimated coefficients for current and lagged GDP. We normalized by adding to this the mean value of the other variables multiplied by their corresponding coefficients. Formally, we plot $\hat{Y}_{it}$, where

$$(2) \qquad \hat{Y}_{it} = G_{it}(\hat{\beta}_1 + \hat{\beta}_4) + G_{it}^2(\hat{\beta}_2 + \hat{\beta}_5) + G_{it}^3(\hat{\beta}_3 + \hat{\beta}_6) + \overline{X}_{it}'\hat{\beta}_7$$

and all variables are defined as before. Each graph shows the predicted level of pollution at a hypothetical site in a country with the indicated per capita GDP (and the same level of GDP in each of the prior three years) and with mean values for the other site-specific variables. On the left-hand side of each graph we present a scale showing the original units of measurements. On the right-hand side we show an alternative scale obtained by dividing pollution levels by the standard deviation for that pollutant across all monitoring stations in our sample. This scale provides a common metric with which the different pollutants can be compared. We have set the vertical range of all of the graphs equal to four standard deviations of the dependent variable. The relative slopes of the curves therefore reveal the relative sensitivity of the different pollutants to changes in income.

In addition to the estimated (cubic) relationship between pollution and GDP, the graphs display the mean residual from the fitted equation for each \$2,000 income interval. The sizes of these points have been scaled to be proportional to the number of observations in each cell. The mean residuals suggest that, in most cases, the assumed cubic functional form does not do injustice to the shape of the observed relationship between pollution and GDP. We also see from the graphs that there are relatively few observations for most pollutants at the upper extremes of income. As a consequence, the shape of the estimated relationship may be imprecisely estimated at these extreme points.

We discuss first the indicators of urban air quality. Sulphur dioxide and smoke display an inverted U-shaped relationship with GDP; pollution appears to rise with GDP at low levels of income, but eventually to reach a peak, and then to fall with GDP at higher levels of income. In the case of sulphur dioxide, the estimated relationship turns up again at very high levels of income, but the relatively small number of observations for sites with incomes above $16,000 means that we cannot have much confidence in the shape of the curve in this range. We find a monotonically decreasing relationship between heavy particles and per capita GDP at all levels of income in the sample range. In all three of these cases, the income variables are jointly significant at the one percent level. Although the income variables are highly correlated, the lagged GDP terms tend to have the lower p-values, perhaps indicating that past income has been a major determinant of current pollution standards.

In Table 1 we examine more closely a question of major importance: Are increases in per capita GDP eventually associated with an improvement in environmental quality? The table shows the income level at which each environmental problem appears to reach its worst proportions (if such an income level can be identified). We report also the standard errors for these estimated "peaks".[7] Concentrations of sulphur dioxide and smoke are found to peak at a relatively early stage in national development (that is, at a level of income roughly equal to that of Mexico or Malaysia today). The table also reports the estimated slope of the relationship between pollution and per capita GDP at $10,000 and $12,000, and the associated standard errors. These estimates allow us to assess how confident we can be that pollution problems actually will be abating once a country reaches a middle-income level. For all three urban air pollutants, we find that increases in income are associated with lower concentrations at both $10,000 and $12,000, and we can reject the hypothesis that the relationship is actually flat or upward sloping for five of the six estimates.

Next we turn to the oxygen regime in rivers. The income terms are jointly significant at less than the one percent level in two cases (dissolved oxygen and nitrates), at less than the ten percent level in one case (BOD), and at only the 22% level in the remaining case (COD). Again the lagged income terms tend to be more significant than the current income terms. And again we find an inverted U-shaped relationships between income and the three measures of environmental damage, and a U-shaped relationship between income and the one direct measure of environmental quality (i.e., dissolved oxygen).

In Table 1 we see that the turning points for these water quality indicators come somewhat later than those for urban air quality. The estimated turning points are at least $7,500 for three of the measures, and in the case of the fourth (dissolved oxygen) the confidence interval includes a wide range of incomes. As for our tests of the association between environmental quality and per capita GDP in the middle-income range, we find a statistically significant beneficial

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[7] The peaks are a non-linear function of the estimated coefficient. Standard errors were calculated by the Delta method.

relationship only for dissolved oxygen (at both $10,000 and $12,000) and for nitrates (at $12,000). However, inasmuch as BOD, COD, and dissolved oxygen all are indicator variables for essentially the same phenomenon, the consistency of the estimates across these different samples gives us some added confidence in each one.

Our third group of environmental indicators relates to fecal contamination of rivers. The findings for fecal coliform are quite similar to those we have seen before. The income terms are jointly significant at less than the one percent level, and the lagged income terms are themselves significant whereas the current income terms are not. This latter result is quite plausible, because fecal contamination does not stem from economic activity per se. Since contamination can be controlled by the treatment of raw sewage, our result could be explained by a lagged response of treatment plant construction to per capita income growth.

Figure 3 indicates that increases in per capita GDP are associated with roughly constant levels of fecal coliform until a country reaches a real income level of about $8,000. Thereafter, fecal contamination falls sharply with income. The estimated slope of the relationship is significantly negative at both the $10,000 and $12,000 levels of per capita GDP.

The results relating to total coliform are rather baffling. Concentrations of total coliforms are found to rise with income at first, then fall, then rise again sharply. By $10,000, the relationship is upward sloping, and statistically significant. Moreover, current income is more significantly associated with this indicator than past income. We have no explanation for these findings. Perhaps they reflect a spurious relationship inasmuch as the presence of some types of coliform does not necessarily indicate fecal contamination, and these bacteria have many non-anthropogenic sources.

Finally, we turn to the heavy metals. A statistically significant relationship exists between concentrations of pollution and current and lagged GDP only for lead, cadmium and arsenic.[8] For lead, the relationship is mostly downward sloping; for cadmium it is flat, with perhaps a slight downturn at high levels of income; for arsenic it resembles an inverted U. The peak concentration of arsenic is estimated to occur at a per capita GDP of $4900, with a standard error of $250. The estimated slope of the curve is negative for lead and arsenic at both $10,000 and $12,000, and is statistically significant in each case.

To summarize, we find little evidence that environmental quality deteriorates steadily with economic growth. Rather, we find for most indicators that economic growth brings an initial phase of deterioration followed by a subsequent phase of improvement. We suspect that the eventual improvement reflects, in part, an increased demand for (and supply of) environmental protection at higher levels of national income. The turning points for the different pollutants vary, but in most cases they occur before a country reaches a per capita income of $8,000. For seven of the fourteen indicators we find a statistically significant positive relationship between environmental quality and income for a middle-income country with a per capita GDP of $10,000. Only in one case (total coliform) do we find a significant adverse relationship at this income level.

Let us comment briefly on some of the other covariates included in our models. For the most part these variables have plausible effects. For example, dissolved oxygen is negatively associated with mean water temperature, whereas BOD, COD, and the coliforms are all positively associated with temperature, as the physical properties of water would lead one to expect. Air pollution is less severe in coastal cities (all else being equal), perhaps reflecting the

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[8] Note that the numbers of observations in our samples for the heavy metals is much smaller than for most of the other pollutants.

disbursement caused by offshore winds or a smaller average inflow of pollution from neighboring cities. On the other hand, heavy particles are found in higher concentrations in cities located near to a dessert, while smoke is especially prevalent in densely populated areas.

Of particular interest are the estimated coefficients on the time variable. These coefficients indicate the extent to which environmental problems have been worsening or abating with time, apart from the effects of an expanding world economy. The state of the environment may deteriorate with time if concentrations of pollutants accumulate or if consumer tastes shift toward pollution-intensive goods. The opposite may occur if technological innovation makes abatement less costly or if increasing awareness causes an autonomous shift in public demands for environmental safeguards. We find that, at least as regards sulphur dioxide and smoke, urban air quality has tended to improve over time, once the effects of income have been controlled for. However, the opposite is true for most measures of river contamination.

5. Conclusions

We have examined the reduced-form relationship between national GDP and various indicators of local environmental conditions using panel data from the Global Environmental Monitoring System. Our indicator variables relate to urban air pollution and contamination in river basins. While admittedly these measures cover relatively few dimensions of environmental quality, our study is the most comprehensive possible given the limited availability of comparable data from different countries.

Contrary to the alarmist cries of some environmental groups, we find no evidence that economic growth does unavoidable harm to the natural habitat. Instead we find that while increases in GDP may be associated with worsening environmental conditions in very poor countries, air and water quality appears to benefit from economic growth once some critical level of income has been reached. The turning points in these inverted U-shaped relationships vary for the different pollutants, but in almost every case they occur at an income of less than $8,000 (1985 dollars). For a country with an income of $10,000, the hypothesis that further growth will be associated with deterioration of environmental conditions can be rejected at the 5 percent level of significance for many of our pollution measures.

Several points need to be emphasized concerning the interpretation of our findings. First, even for those dimensions of environmental quality where growth seems to have been associated with improving conditions, there is no reason to believe that the process has been an automatic one. In principle, environmental quality might improve automatically when countries develop if they substitute cleaner technologies for dirtier ones, or if there is a very pronounced effect on pollution of the typical patterns of structural transformation. Our methodology does not allow us to reject these hypotheses, or even to investigate the means by which income changes influence environmental outcomes. However, a review of the available evidence on instances of pollution abatement (see, e.g., OECD, 1991) suggests that the strongest link between income and pollution in fact is via an induced *policy response*; as nations or regions experience greater prosperity, their citizens demand that more attention be paid to the non-economic aspects of their living conditions. The richer countries, which tend to have relatively cleaner urban air and relatively cleaner river basins also have relatively more stringent environmental standards and stricter enforcement of their environmental laws than the middle income and poorer countries, many of which still have pressing environmental problems to address.

Second, it is possible that downward sloping and inverted U-shaped patterns might arise because, as countries develop, they cease to produce certain pollution-intensive goods, and begin instead to import these products from other countries with less restrictive environmental protection laws. If this is the main explanation for the (eventual) inverse relationship between a country's income and pollution, then future development patterns could not mimic those of the past; developing countries will not always be able to find still poorer countries to serve as havens for the production of pollution-intensive goods. However, the available evidence does not support the hypothesis that cross-country differences in environmental standards are an important determinant of the global pattern of international trade (see, e.g., Tobey, 1990, and Grossman and Krueger, 1993). While some "environmental dumping" undoubtedly takes place, the volume of such trade is almost surely too small to account for the reduced pollution that has been observed to accompany episodes of economic growth.

Finally, it should be stressed that there is nothing at all inevitable about the relationships that have been observed in the past. These patterns reflected the technological, political, and economic conditions that existed at the time. The low-income countries of today have a unique opportunity to learn from this history and thereby avoid some of the mistakes of earlier growth experiences. With the increased awareness of environmental hazards and the development in recent years of new technologies that are cleaner than ever before, we might hope to see the low-income countries turn their attention to preservation of the environment at earlier stages of development than has previously been the case.

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Table 1

Estimated GDP Per Capita at Peak Pollution Level,
and Derivatives of Pollution with respect to GDP at $10,000 and $12,000

(Standard Errors in Parentheses)

Pollutant	Peak GDP	Derivative at $10,000	Derivative at $12,000
Sulphur Dioxide	$4,053 (355)	-5.295 (.780)	-3.065 (.910)
Smoke	6,151 (539)	-8.053 (3.570)	-7.780 (8.651)
Heavy Particles	NA	-5.161 (2.271)	-4.811 (2.080)
Dissolved Oxygen	2,703[a] (5,328)	.202 (.070)	.277 (.080)
BOD	7,623 (3,307)	-.358 (.503)	-.612 (.777)
COD	7,853 (2,235)	-3.494 (3.470)	-7.106 (5.445)
Nitrates	10,524 (500)	.110 (.118)	-.384 (.132)
Fecal Coliform	7,955 (1,296)	-.164 (.075)	-.391 (.085)
Total Coliform	3,043 (309)	1.083 (.323)	2.950 (.895)
Lead	1,887 (2,838)	-.007 (.002)	-.005 (.002)
Cadmium	11,632 (1,096)	.005 (.006)	-.002 (.004)
Arsenic	4,900 (250)	-.0014 (.0003)	-.0011 (.0002)
Mercury	5,047 (1,315)	-.057 (.039)	-.013 (.037)
Nickel	4,113 (3,825)	-.001 (.001)	-.0009 (.0006)

a. We report the trough rather than the peak for dissolved oxygen, because higher levels are desirable in this case.

NA Not applicable (because relationship is monotonically decreasing).

Figure 1: The Relationship Between Per Capita GDP and Urban Air Pollution

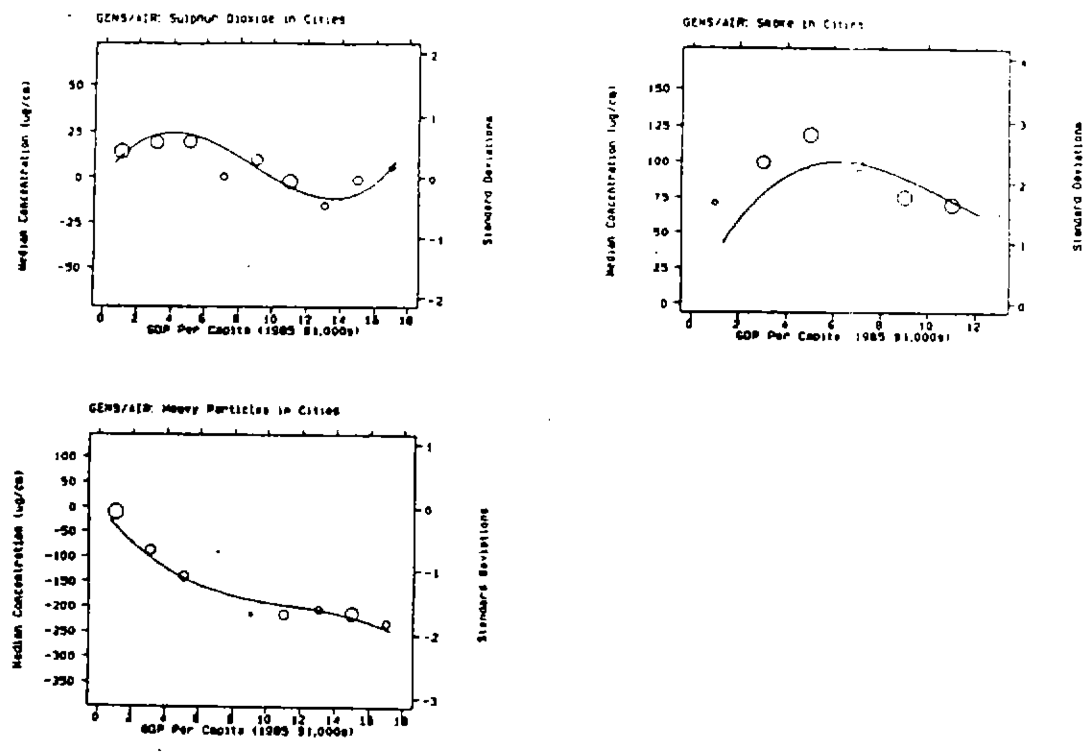

Figure 2: The Relationship Between Per Capita GDP and the Oxygen Regime in Rivers

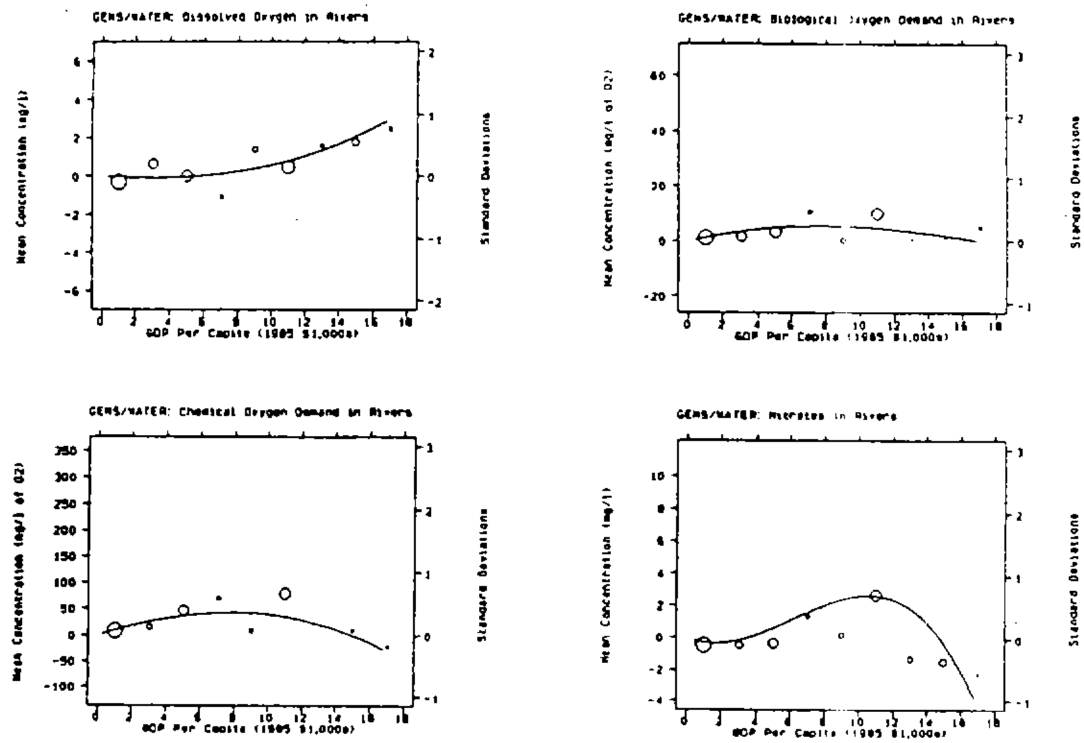

Figure 3: The Relationship Between Per Capita GDP
and Fecal Contamination of Rivers

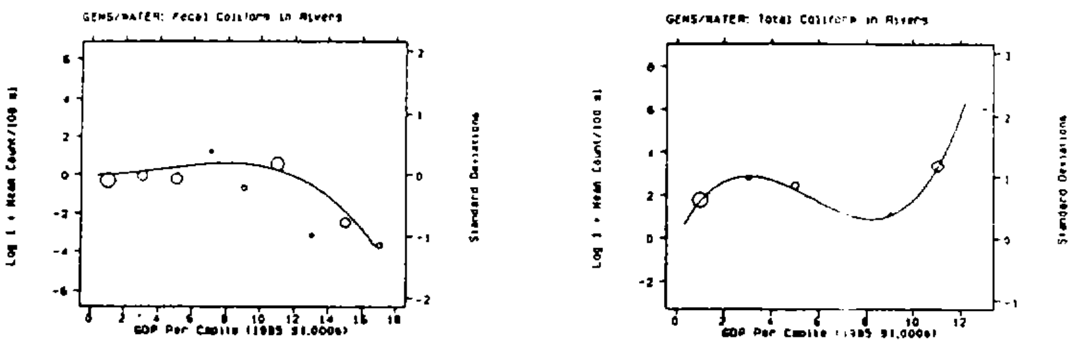

Figure 4: The Relationship Between Per Capita GDP and Heavy Metal Contamination of Rivers

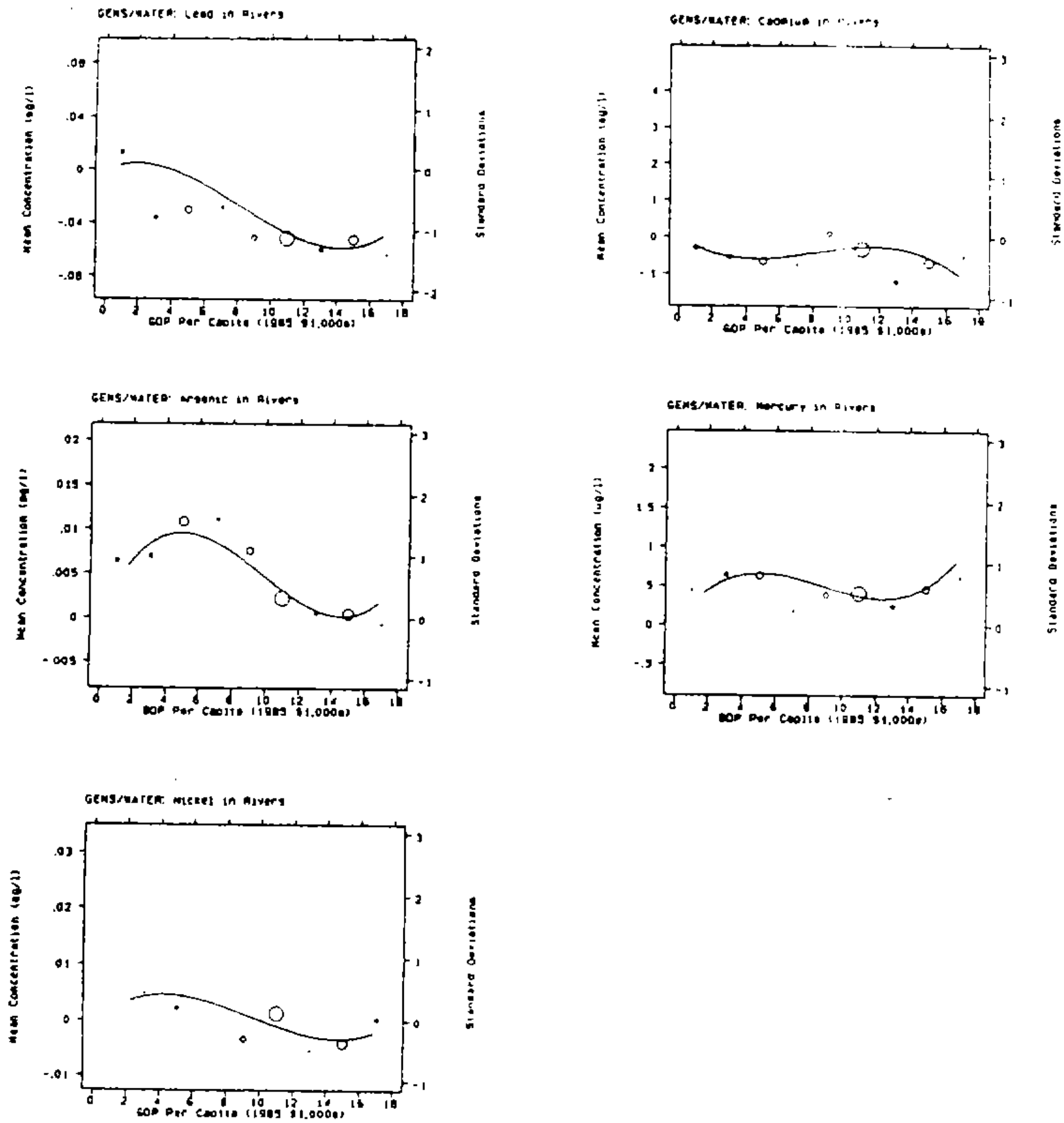

TABLE A1

The Determinants of Urban Air Pollution
Random Effects Estimation
Dependent Variable is Annual Median Concentration in $\mu g/m^3$

(Standard Errors in Parentheses)

Variable	Sulphur Dioxide	Smoke	Heavy Particles
Income (thousands)	- 7.37 (9.16)	24.54 (20.87)	17.36 (21.54)
Income squared	1.03 (1.11)	- 7.64 (3.59)	- 0.922 (2.685)
Income cubed	- 0.0337 (0.0384)	0.443 (0.171)	0.0136 (0.0903)
Lagged income	20.89 (9.76)	12.59 (22.00)	-60.69 (23.33)
Lagged income squared	- 3.22 (1.26)	3.44 (3.97)	4.35 (3.12)
Lagged income cubed	0.117 (0.0461)	- 0.313 (0.199)	- 0.115 (0.112)
Coast	-12.72 (3.79)	-33.68 (8.35)	-21.11 (12.12)
Desert	—	7.08 (11.19)	161.6 (26.1)
Central City	3.06 (4.31)	4.05 (8.87)	26.24 (14.45)
Industrial	0.485 (5.26)	-11.56 (10.75)	23.80 (17.37)
Residential	-11.11 (4.85)	-13.92 (9.37)	7.35 (16.35)
Population Density (pop/sq mile)	1.14 (1.23)	2.39 (0.853)	- 0.699 (1.404)
Year	- 1.40 (0.218)	- 1.23 (0.359)	0.744 (0.631)

TABLE A1 - continued

Variable	Sulphur Dioxide	Smoke	Heavy Particles
P-value (income and lagged income combined)	< .0001	< .0001	< .0001
P-value (income only)	.852	< .0001	.556
P-value (lagged income only)	.096	< .0001	.0003
Mean of Dependent Variable	33.24	42.21	146.62
σ^2_α	856	1677	5774
σ^2_ϵ	396	340	1752
σ^2_y	1109	1818	16078
Sample size	1352	488	1021

Notes: Equations also include an intercept, a dummy to indicate that the type of area is unknown, and a dummy to indicate that the measurement device is a gas bubbler. σ^2_α is the estimated variance of the common-to-site component of the residuals and σ^2_ϵ is the estimated variance of the idiosyncratic component. σ^2_y is the sample variance of the dependent variable (median concentration measured in $\mu g/m^3$).

TABLE A2

The Oxygen Regime in Rivers
Random Effects Estimation
Dependent Variable is Annual Mean Concentration in mg/l

(Standard Errors in Parentheses)

Variable	Dissolved Oxygen	BOD	COD	Nitrates
Income (thousands)	1.33 (0.70)	1.41 (4.54)	-19.66 (21.54)	- 1.16 (1.34)
Income squared	- 0.127 (0.081)	0.335 (0.614)	0.498 (4.664)	0.188 (0.171)
Income cubed	0.004 (0.003)	- 0.022 (0.024)	0.015 (0.182)	- 0.007 (0.006)
Lagged income	- 1.38 (0.73)	0.151 (4.766)	29.90 (39.01)	0.726 (1.401)
Lagged income squared	0.134 (0.091)	- 0.458 (0.687)	- 1.02 (5.36)	- 0.036 (0.190)
Lagged income cubed	- 0.003 (0.003)	0.024 (0.029)	- 0.026 (0.221)	- 0.002 (0.007)
Mean Temperature	- 0.098 (0.022)	0.246 (0.131)	1.22 (0.81)	0.023 (0.034)
Year	- 0.061 (0.019)	0.031 (0.108)	0.786 (0.671)	- 0.077 (0.036)
P-value (income and lagged income combined)	.0004	.069	.224	.0003
P-value (income only)	.209	.039	.352	.663
P-value (lagged income only)	.113	.105	.154	.084
Mean of Dependent Variable	8.12	6.65	48.44	1.53
σ^2_α	5.14	243	5301	12.28
σ^2_ϵ	3.95	101	2557	6.30
σ^2_y	10.58	513	14304	15.02
Sample size	1599	1284	850	1017

Notes to Table A2: Equations also include an intercept. Where mean temperature is missing in the data, an estimate based on site lattitude is used. σ^2_α is the estimated variance of the common-to-site component of the residuals and σ^2_ϵ is the estimated variance of the idiosyncratic component. σ^2_y is the sample variance of the dependent variable (mean concentration measured in mg/l).

TABLE A3

Fecal Contamination of Rivers
Random Effects Estimation
Dependent Variable is 1 + Log Annual Mean Concentration in count/100 ml

(Standard Errors in Parentheses)

Variable	Fecal Coliforms	Total Coliforms
Income (thousands)	− 0.846 (0.624)	− 3.71 (2.17)
Income squared	0.110 (0.072)	0.473 (0.332)
Income cubed	− 0.0038 (0.0024)	− 0.016 (0.014)
Lagged income	0.825 (0.657)	5.88 (2.32)
Lagged income squared	− 0.076 (0.081)	− 0.962 (0.383)
Lagged income cubed	0.001 (0.003)	− 0.045 (0.018)
Mean Temperature	0.063 (0.021)	0.095 (0.037)
Year	0.113 (0.018)	0.192 (0.038)
P-value (income and lagged income combined)	< .0001	.0013
P-value (income only)	.479	.003
P-value (lagged income only)	.005	.040
Mean of Dependent Variable	6.83	8.32
σ^2_α	5.61	4.80
σ^2_ϵ	2.64	2.40
σ^2_y	10.11	8.18
Sample size	1261	494

Notes to Table A3: Equations also include an intercept and a dummy to indicate sampling method. Where mean temperature is missing in the data, an estimate based on site lattitude is used. σ^2_a is the estimated variance of the common-to-site component of the residuals and σ^2_ϵ is the estimated variance of the idiosyncratic component. σ^2_y is the sample variance of the dependent variable (1 + log mean concentration measured in count/100 ml).

TABLE A4

Heavy Metal Contamination of Rivers
Random Effects Estimation
Dependent Variable is Annual Mean Concentration

(Standard Errors in Parentheses)

Variable	Lead	Cadmium	Arsenic	Mercury	Nickel
Income (thousands)	- 0.020 (0.032)	- 0.033 (0.114)	0.0034 (0.0031)	0.246 (0.514)	- 0.019 (0.020)
Income squared	0.0005 (0.0029)	0.011 (0.010)	- 0.0003 (0.0003)	- 0.039 (0.047)	0.0017 (0.0016)
Income cubed	0.00002 (0.00009)	- 0.0005 (0.0003)	0.00001 (0.00001)	0.0015 (0.0015)	- 0.00005 (0.00004)
Lagged income	0.025 (0.034)	0.0024 (0.1256)	0.0010 (0.0031)	0.055 (0.533)	0.022 (0.021)
Lagged income squared	- 0.002 (0.003)	- 0.0067 (0.0119)	- 0.0003 (0.0003)	- 0.003 (0.052)	- 0.0021 (0.0019)
Lagged income cubed	0.0003 (0.00010)	0.0004 (0.029)	0.00001 (0.00001)	0.00007 (0.00166)	0.00006 (0.00005)
Mean Temperature	0.0009 (0.0007)	- 0.0038 (0.0018)	- 0.0004 (0.0001)	- 0.010 (0.011)	0.000002 (0.00019)
Year	0.0006 (0.0006)	0.0041 (0.0020)	0.0003 (0.0001)	- 0.018 (0.010)	- 0.00048 (0.00017)
P-value (income and lagged income combined)	.003	.016	< .0001	.670	.289
P-value (income only)	.370	.022	.696	.565	.629
P-value (lagged inc only)	.580	.040	.128	.995	.657
Mean of Dependent Variable	.019	.044	.0056	.286	.009
σ^2_α	.0024	.0046	.000027	.631	.000029
σ^2_ϵ	.0015	.0162	.000009	.322	.000060
σ^2_y	.0021	.028	.000048	.619	.000123
Sample Size	610	649	368	637	350

Notes to Table A4: Equations also include an intercept and a dummy indicating sampling method. Where mean temperature is missing in the data, an estimate based on site lattitude is used. σ^2_α is the estimated variance of the common-to-site component of the residuals and σ^2_ϵ is the estimated variance of the idiosyncratic component. σ^2_y is the sample variance of the dependent variable (median concentration measured in μg/l for mercury, mg/l for all others).