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Environmental Quality and Development: Is There a Kuznets Curve for Air Pollution Emissions?[1]

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Several recent studies have identified inverted-U relationships between pollution and economic development. We investigate this question using a cross-national panel of data on emissions of four important air pollutants: suspended particulate matter, sulfur dioxide, oxides of nitrogen, and carbon monoxide. We find that per capita emissions of all four pollutants exhibit inverted-U relationships with per capita GDP. While this suggests that emissions will decrease in the very long run, we forecast continued rapid growth in global emissions over the next several decades. © 1994 Academic Press, Inc.

There is an emerging consensus that at least some forms of pollution exhibit inverted-U, or "Kuznets," relationships with economic development.[2] That is, while industrialization and agricultural modernization may initially lead to increased pollution, other factors may cause an eventual downturn, at least for some pollutants. Among these factors are: (i) positive income elasticities for environmental quality; (ii) changes in the composition of production and consumption; (iii) increasing levels of education and environmental awareness; and (iv) more open political systems. That is, the development trajectory for pollution is likely to reflect both market forces and changes in government regulation. As a result, it is reasonable to expect that economies would pass through "stages of development," in which at least some aspects of environmental quality first deteriorate and then improve.

In a recent paper Grossman and Krueger [11] use a cross-country panel of data on urban air pollution levels to estimate the point at which atmospheric concentrations of suspended particulate matter (SPM) and sulfur dioxide (SO_2) become decreasing functions of income. In particular, they estimate "turning points" for these pollutants that are under $5000 (in 1985 U.S. dollars) of per capita Gross Domestic Product (GDP) (see also Shafik and Bandyopadhyay [25]). Similar

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[2] The postulated relationship between pollution and development bears a striking resemblance to that between income inequality and development found by Kuznets [16, 17] (see also Ahluwalia [1] and Fields and Jakubson [9]).

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inverted-U results are also found for a broader measure of toxic emissions by Hettige *et al.* [13].[3]

This paper examines the same two air pollutants studied by Grossman and Krueger, along with oxides of nitrogen (NO_X) and carbon monoxide (CO). However, the aggregate emissions data used in this paper are qualitatively different from the urban air quality data they use. In particular, we hypothesize that *urban air quality will turn down at lower levels of per capita income than will aggregate emissions.* Reasons for this conjecture include: (i) urban air quality is of the most immediate importance from a public health perspective (justifiably increasing the attention it receives from policymakers), (ii) improvements in urban air quality can be achieved at relatively low cost compared to reductions in aggregate emissions (for instance, requiring taller smokestacks would reduce urban pollution at relatively low cost, but would not reduce aggregate emissions), (iii) rising land rents tend to cause industry to move out of urban areas as economies develop, and (iv) urban residents have incomes that are high relative to the national average (so that they may have disproportionate political clout).

Urban air quality data and aggregate emissions data yield different perspectives on the pollution–GDP process, and each measure has its own advantages. If one's objective is to understand the factors underlying the pollution faced by urban dwellers, then an analysis of urban air quality data is clearly the most appropriate. In contrast, if one seeks to understand environmental impact beyond urban areas, an analysis of aggregate emissions data may provide greater insight. More generally, we believe the most complete picture of the pollution–GDP process emerges from examining both types of data.

Using data on emissions across countries and across time from the Global Environment Monitoring System (GEMS), we present pooled cross-section, fixed-effects, and random-effects estimates of the relationship between emissions and GDP for each pollutant. The results generally confirm the inverted-U findings for urban air quality; however, we find substantially higher turning points, as hypothesized.

To assess the implications of any pollution–GDP relationship for the future path of global pollution, it is important to consider the interrelated impacts of three key factors: (i) the distribution of global income, (ii) the pattern of income growth rates among nations, and (iii) the pattern of population growth rates among nations. In this paper we explicitly examine the implications of our estimates by simulating or "forecasting" global emissions under a range of scenarios for income and population growth. Our projections suggest that while global emissions of these pollutants are likely to decline over the very long run, they are likely to increase for the next several decades.

I. THE EMISSIONS-GDP RELATIONSHIP

The focus of our analysis is on the relationship between per capita emissions, m, real per capita GDP, y, and population density, d,

$$m_{it} = \beta_0 + \beta_1 y_{it} + \beta_2 y_{it}^2 + \beta_d d_{it} + \varepsilon_{it}, \tag{1}$$

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[3] See also Lucas *et al.* [20] and Radetzki [24].

where i is a country index, t is a time index, and ε is a disturbance term with mean zero and finite variance.[4] Of particular importance are the signs and magnitudes of β_1 and β_2 in (1). Emissions can be said to exhibit a meaningful Kuznets relationship with per capita GDP if $\beta_1 > 0$ and $\beta_2 < 0$—and if the turning point, $-\beta_1/2\beta_2$, is a "reasonably" low number. Population density is expected to enter (1) with a negative sign, insofar as sparsely populated countries are likely to be less concerned about reducing per capita emissions, at every level of income, than more densely populated countries. Also, emissions associated with transportation may be lower when people live closer together.

A basic issue to address concerns the exclusion from Eq. (1) of explanatory variables other than per capita GDP and population density. It is important in this regard to distinguish between variables that are the endogenous consequences of growth and other, more exogenous factors. Potential examples of the former include the composition of output, the level of education, and the political structure. These factors *should* be omitted from this single-equation model, insofar as our objective is to assess both the direct and the indirect consequences of growth. In other words, to the extent one can speak of a "development path" that involves a systematic relationship among these variables and per capita GDP growth, one would want to exclude these variables from the analysis.

Of course, there are also likely to be exogenous factors that affect emissions. For instance, climate and geography vary widely among countries and may well be correlated with emissions.[5] Insofar as these factors cause the error terms in (1) to be correlated across all periods for a particular country (or among countries for a given period), pooled cross-section estimates that ignore this correlation will be inefficient. Moreover, if these omitted variables are correlated with per capita GDP, then both pooled cross-section and random-effects estimation of (1) can yield biased and inconsistent results (though the direction of bias in this case is not clear *a priori*) (Mundlak [23]; Hsiao [15, Chap. 3]).

To address these issues, we specify an error-components model in which

$$\varepsilon_{it} = c_i + v_t + u_{it}, \tag{2}$$

where c_i is a country effect, v_t is a year effect, and u_{it} is the remaining error term (it is potentially serially correlated). Dummy variables are included to capture the year effects. To control for the country effects, we estimate both fixed-effects and random-effects versions of the model.

II. THE DATA

The GDP measure for this study is the RGDPCH series on real per capita GDP (in 1985 U.S. dollars) drawn from the Penn Mark IV World Tables in Summers and Heston [26]. One advantage of these data is they use a common methodology, so that real comparisons can be made among countries and over time.

The GEMS aggregate emissions data used in this paper are obtained from the World Resources Institute (WRI [27]). In particular, the pollutants studied (SPM,

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[4] We test and reject a cubic polynomial specification (see below).

[5] Climate may affect heating and cooling needs, while endowments of fossil fuels and hydroelectric sites may affect relative energy prices.

TABLE I

Sample Characteristics

	Sample mean[a]	Standard deviation[a]	Number of observations
Sulfur dioxide (kg per capita)	61.81	55.12	67
Suspended particulates (kg per capita)	18.69	23.24	51
Oxides of nitrogen (kg per capita)	35.18	20.19	68
Carbon monoxide (kg per capita)	143.5	99.43	49
Per capita gross domestic product[b] (1985 U.S. dollars)	9341.05	3378.78	68

	Distribution of sample by income level		
	Low income	Middle income	High income
Number of countries in sample, by level of development[c]	2	6	22

[a] Calculated for the subsamples used in the pooled cross section and random-effects analyses.

[b] Mean and standard deviation are calculated for the subsample used to estimate the NO_X regressions. Means and standard deviations of per capita GDP are similar in the other regressions.

[c] Classification based on World Bank guidelines.

SO_2, NO_X, and CO) have been the focus of considerable public policy attention. SO_2 and NO_X both contribute to the acid rain problem. NO_X also contributes to the ground-level ozone problem. All of these pollutants can have important adverse health consequences.

The aggregate emissions data are constructed from estimates of fuel use, by type, combined with estimates of emissions per unit of fuel burned. An important issue in this regard is that the emissions coefficients used to construct the data are both country-specific and time-specific, so that an attempt has been made to capture contemporaneous abatement practices.[6] Nevertheless, it is likely that emissions are measured only imperfectly and that measurement errors for a given country persist across time. In particular, this latter point reinforces the importance of exploiting the panel nature of the data, thereby placing greater emphasis on time trends within each country.

The means and standard deviations for all the variables used in estimation are provided in Table I. This table also indicates the distribution of observations by

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[6] The data are published in Table 24.6 of WRI [27]. Information concerning the construction of the data was obtained through telephone contacts with analysts at WRI. The data are averages for the periods 1973–1975, 1979–1981, and 1982–1984, though many of the series are incomplete. Per capita measures are obtained by dividing emissions for each country by its population as reported in the Summers and Heston database. Because the emissions data are three-year averages, we use three-year averages for income, as well.

income level. Clearly, less-developed countries are under-represented in the sample.[7] Nevertheless, mean income in the sample is close to the turning points we estimate, and there is considerable variation within the sample, so that there are numerous countries on both the upward-sloping and downward-sloping portions of the curves we estimate.

III. ESTIMATION RESULTS

Tables II–V present our estimation results. A first issue concerns the homogeneity of the country effects. In all cases, the null hypothesis of homogeneity is rejected by a wide margin (the tables report F statistics for the null hypothesis that c_i is constant for all i). This suggests that pooled cross-sectional estimators are inefficient at best (and may yield biased coefficient estimates). This finding has important qualitative implications. In contrast to the panel estimates examined below, the pooled models all yield emissions–GDP relationships that are concave upward (i.e., they exhibit increasing marginal propensities to emit at higher levels of income).

In choosing between fixed-effects and random-effects estimation, an important issue is whether the country effects are correlated with the explanatory variables. In the absence of such correlation, random-effects estimation is consistent and efficient. In contrast, if such correlation exists, there may be omitted variable bias, necessitating fixed-effects estimation. The specification test we employ to help choose between these two approaches is due to Hausman [12] (see also Hsiao [15, p. 49]). In most cases, the test statistics reported in Tables II–V argue in favor of fixed-effects estimation.[8] However, one argument in favor of random-effects estimation is that it makes use of information from all countries in our sample, even those with only single observations (Biørn [5]; Hsiao [15, p. 193]). For this reason, we present both sets of estimates for all models.

Two final issues concern (i) the degree of the polynomial, and (ii) the presence of autocorrelation among the u_{it}. In all cases, cubic and higher-order terms were found not to be significantly different from zero even at the 10% level (t statistics are presented for the hypothesis that $\beta_3 = 0$). Also, neither the fixed-effects or random-effects models exhibit substantial first-order serial correlation among the u_{it}.[9]

Overall, the results are surprisingly strong given the small number of observations and the "noisy" nature of the emissions data. Indeed, the results appear to be quite stable across alternative formulations. Estimates of the main parameters of interest, β_1 and β_2, all have the expected signs and are typically different from

[7] While data availability causes the countries included in the samples for each pollutant to vary, the countries providing data for at least one pollutant are Austria, Belgium, Canada, China, Denmark, Finland, France, West Germany, Greece, Hungary, Iceland, India, Ireland, Israel, Italy, Japan, Kuwait, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Thailand, Turkey, United Kingdom, United States, and Yugoslavia.

[8] The SO_2 models are exceptions to this. Under the null hypothesis of zero correlation the test statistic has an asymptotic χ^2 distribution with the indicated degrees of freedom. Note that our Hausman test statistics are computed for the same samples used to compute the fixed-effects estimates (i.e., we exclude singleton observations in constructing this test).

[9] Durban–Watson statistics in all cases range between a low of 2.27 (for SO_2) and a high of 2.75 (for CO).

TABLE II

Estimation Results for SO_2 Emissions[a]

(Standard Errors in Parentheses)

	Without population density			With population density		
	Cross section	Fixed effects	Random effects	Cross section	Fixed effects	Random effects
Constant[b]	423.94*	−810.44	−148.41	480.76*	−188.56	0.539
	(310.0)		(335.9)	(303.8)		(348.6)
GDP per capita	−5.3092	385.78**	201.26***	32.771	415.02**	216.83***
	(70.43)	(181.6)	(73.85)	(71.25)	(182.6)	(74.29)
(GDP per capita)^2	3.9764	−21.633***	−9.4216**	1.4862	−23.826***	−10.534***
	(4.174)	(7.301)	(4.070)	(4.254)	(7.518)	(4.114)
Population density	—	—	—	−120.77**	−540.08	−155.53*
				(59.58)	(472.8)	(97.54)
Period effect (1979–1981 = 1)	−149.75	−11.022	−98.439*	−165.45	36.612	−83.651*
	(162.6)	(89.88)	(58.37)	(158.9)	(98.73)	(58.87)
Period effect (1982–1984 = 1)	−260.57*	−157.09*	−257.27***	−254.66*	−94.344	−236.31***
	(168.5)	(107.4)	(64.87)	(164.5)	(120.2)	(65.93)
R^2	0.166	0.954	—	0.219	0.955	—
Homogeneity test (DF)	—	27.762	—	—	25.146	—
		(22, 35)			(22, 34)	
Hausman's χ^2 (DF)	—	—	6.241	—	—	5.193
			(4)			(5)
t-statistic for cubic term	2.11	0.934	0.575	1.811	0.914	0.394
Turning point[c] (1985 U.S. Dollars)	(668)	8916	10,681	(−11,025)	8709	10,292
N	67	62	67	67	62	67

[a] Emissions are measured in kg × 10 per capita. Income is measured in thousands of 1985 U.S. Dollars. Density is measured as residents per hectare. One, two, or three asterisks indicate that a coefficient estimate is significantly different from zero at 10, 5, or 1% percent level, respectively.

[b] Constant terms for fixed-effect models include the mean of the estimated country effects.

[c] Turning points in parentheses indicate that curve is concave upward.

zero at high levels of significance. Thus, there appears to be ample evidence to reject the null hypothesis that emissions are monotonically increasing in per capita GDP for these pollutants (the exception being the CO models, which yield coefficient estimates with large standard errors). Moreover, population density typically enters with the predicted sign (though the coefficient estimates are not always significantly different from zero).[10]

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[10] The point estimates for the period effects are typically negative for SPM and SO_2 and positive for NO_X and CO. These results should be interpreted with caution. We do not feel that three periods are sufficient to separate secular trends from cyclical factors. Moreover, the estimates are typically not significantly different from zero in the preferred fixed-effects models.

TABLE III

Estimation Results for SPM Emissions[a]
(Standard Errors in Parentheses)

	Without population density			With population density		
	Cross section	Fixed effects	Random effects	Cross section	Fixed effects	Random effects
Constant[b]	382.50** (165.9)	−397.31	−191.19 (158.9)	345.71** (159.8)	−605.39	−124.27 (163.1)
GDP per capita	−66.841** (36.49)	141.87*** (41.72)	108.86*** (29.40)	−34.031 (37.87)	145.69*** (41.41)	114.34*** (29.27)
(GDP per capita)^2	4.6917** (2.090)	−7.2301*** (1.628)	−5.660*** (1.293)	2.8155* (2.168)	−7.0799*** (1.616)	−6.011*** (1.306)
Population density	—	—	—	−68.217** (30.24)	129.70 (104.6)	−68.130* (50.51)
Period effect (1979–1981 = 1)	−41.811 (80.55)	−16.727 (18.66)	−16.647 (14.97)	−27.493 (77.46)	−30.942* (21.74)	−11.228 (15.32)
Period effect (1982–1984 = 1)	−64.462 (82.08)	−30.138* (21.35)	−29.202** (16.69)	44.624 (79.15)	−48.328** (25.73)	−22.121 (17.29)
R^2	0.136	0.989	—	0.224	0.990	—
Homogeneity Test (DF)	—	120.85 (18, 26)	—	—	105.91 (18, 25)	—
Hausman's χ^2 (DF)	—	—	12.086 (4)	—	—	14.204 (5)
t statistic for cubic term	2.372	−0.995	−1.188	1.867	−0.899	−1.143
Turning point[c] (1985 U.S. dollars)	(7123)	9811	9617	(6044)	10,289	9511
N	51	49	51	51	49	51

[a] Emissions are measured in kg × 10 per capita. Income is measured in thousands of 1985 U.S. Dollars. Density is measured as residents per hectare. One, two, or three asterisks indicate that a coefficient estimate is significantly different from zero at 10, 5, or 1% level, respectively.

[b] Constant terms for fixed-effect models include the mean of the estimated country effects.

[c] Turning points in parentheses indicate that curve is concave upward.

Perhaps the most interesting findings concern the turning point estimates for per capita emissions (presented in the next to last row of each table). In contrast to Grossman and Krueger's finding that turning points for SPM and SO_2 are less than $5000 of per capita GDP (1985 U.S. dollars), our turning point estimates for these two pollutants uniformly exceed $8000. The turning point estimates do not appear sensitive to the inclusion of population density as a regressor, and both the random-effects and the fixed-effects models yield qualitatively similar results.

As alluded to in the opening of the paper, it is not at all surprising that urban air quality would improve prior to aggregate emissions. Urban pollution poses the greatest human health risks and can be shifted to nonurban areas at relatively low costs. There may also be market forces at work, insofar as increasing land rents in

TABLE IV

Estimation Results for NO_X Emissions[a]

(Standard Errors in Parentheses)

	Without population density			With population density		
	Cross section	Fixed effects	Random effects	Cross section	Fixed effects	Random effects
Constant[b]	96.663	−54.832	−92.883	82.574	126.69	−66.176
	(85.48)		(94.09)	(80.49)		(91.48)
GDP per capita	3.1509	73.524*	64.431***	21.441	83.677**	75.798***
	(18.81)	(44.46)	(20.07)	(18.67)	(44.25)	(20.05)
(GDP per capita)^2	2.6086***	−3.053**	−1.4796*	1.5186*	−3.730**	−2.124**
	(1.079)	(1.800)	(1.061)	(1.075)	(1.827)	(1.068)
Population density	—	—	—	−41.807***	−173.52*	−57.849***
				(13.71)	(115.2)	(22.28)
Period effect	−26.570	25.195	−1.194	−21.776	38.068**	3.6172
(1979–1981 = 1)	(38.58)	(20.05)	(13.38)	(36.30)	(21.49)	(13.26)
Period effect	−58.454*	9.438	−24.047*	−49.744*	26.760	−17.485
(1982–1984 = 1)	(39.36)	(24.14)	(14.90)	(37.11)	(26.38)	(14.84)
R^2	0.651	0.983	—	0.696	0.984	—
Homogeneity test	—	31.206	—	—	27.952	—
(DF)		(24, 38)			(24, 37)	
Hausman's χ^2	—	—	11.524	—	—	10.863
(DF)			(4)			(5)
t statistic for cubic term	1.084	−0.309	−0.090	0.667	−0.350)	−0.143
Turning point[c] (1985 U.S. dollars)	(−604)	12,041	21,773	(−7059)	11,217	17,843
N	68	67	68	68	67	68

[a] Emissions are measured in kg × 10 per capita. Income is measured in thousands of 1985 U.S. Dollars. Density is measured as residents per hectare. One, two, or three asterisks indicate that a coefficient estimate is significantly different from zero at 10, 5, or 1% level, respectively.

[b] Constant terms for fixed-effect models include the mean of the estimated country effects.

[c] Turning points in parentheses indicate that curve is concave upward.

urban areas create an incentive for manufacturing enterprises to move to less densely populated areas. Finally, insofar as urban residents have above average incomes, they may be able to secure government regulation of their air quality at a relatively early stage of overall development.

Turning to the NO_X and CO models, aggregate emissions of these pollutants also appear to peak at moderately high levels of income. However, the turning point estimates for these pollutants appear quite sensitive to the method of estimation, with the fixed-effects turning point estimates for CO being the lowest found for any of the four pollutants.

We emphasize that the pollutants studied in this paper should not be viewed as representative of all pollutants. In fact, it seems likely that the combination of

TABLE V

Estimation Results for CO Emissions[a]
(Standard Errors in Parentheses)

	Without population density			With population density		
	Cross section	Fixed effects	Random effects	Cross section	Fixed effects	Random effects
Constant[b]	1728.3** (791.8)	1034.9	72.194 (799.1)	1455.7** (744.5)	1562.8	183.36 (762.7)
GDP per capita	−226.63* (165.8)	274.86 (435.1)	242.97* (171.1)	−58.628 (166.0)	268.60 (444.4)	321.12** (172.0)
(GDP per capita)^2	22.033*** (8.823)	−22.022 (17.47)	−6.363 (8.997)	12.640* (8.896)	−22.522 (17.90)	−10.196 (9.149)
Population density	—	—	—	−284.13*** (102.7)	−315.95 (1055.)	−386.12** (162.1)
Period effect (1979–1981 = 1)	−491.38** (290.4)	31.835 (178.3)	−324.69*** (116.9)	−501.03** (270.7)	67.190 (216.9)	−307.81*** (118.3)
Period effect (1982–1984 = 1)	−596.70** (309.2)	68.016 (209.4)	−365.03*** (131.8)	−548.72** (288.7)	113.02 (261.2)	−333.73*** (134.0)
R^2	0.414	0.960	—	0.502	0.961	—
Homogeneity test (DF)	—	22.057 (16, 23)	—	—	17.578 (16, 22)	—
Hausman's χ^2 (DF)	—	—	16.274 (4)	—	—	12.264 (5)
t statistic for cubic term	1.685	−0.180	0.406	1.533	−0.212	0.472
Turning point[c] (1985 U.S. dollars)	(5143)	6241	19,092	(2319)	5963	15,747
N	49	44	49	49	44	49

[a] Emissions are measured in kg × 10 per capita. Income is measured in thousands of 1985 U.S. Dollars. Density is measured as residents per hectare. One, two, or three asterisks indicate that a coefficient estimate is significantly different from zero at 10, 5, or 1% level, respectively.

[b] Constant terms for fixed-effect models include the mean of the estimated country effects.

[c] Turning points in parentheses indicate that curve is concave upward.

important own-country pollution effects and relatively low abatement costs makes these pollutants among the most likely to exhibit inverted-U relationships with income (with turning points that are relatively low). Supporting this conjecture is the recent finding by Holtz-Eakin and Selden [14] that carbon dioxide emissions, which are costly to abate and have primarily global (as opposed to own-country) effects, appear to rise monotonically with income.[11] Clearly, any extrapolation from the results in this paper to other forms of pollution should be made with great care.

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[11] See also Diwan and Shafik [8].

IV. IMPLICATIONS FOR GLOBAL EMISSIONS

We now examine the implications of our estimates for the future path of global emissions. The main issue in this regard is the distribution of per capita GDP and population among the countries of the world. In the Summers and Heston data, average global per capita GDP in 1985 is only \$3766 (in 1985 U.S. dollars), and the global distribution of income is skewed toward zero. Thus, a majority of the world's population has yet to pass the turning points estimated above, making increased global emissions the likely outcome of income growth.

A second issue is that per capita GDP growth rates are likely to continue to vary among countries. The simple correlation in the Summers and Heston data between per capita GDP *levels* in 1975 and per capita GDP *growth* rates between 1975 and 1985 is -0.189. Moreover, there is substantial nonlinearity, with many of the poorest countries experiencing *negative* growth, and the richest nations tending to experience only moderate growth rates. Insofar as the fastest growing nations are on the upward-sloping portions of the emissions–GDP curves, increased global emissions can be expected.

A final issue is that population growth rates are likely to continue to vary among countries. In particular, the fastest population growth is likely to occur among countries on the upward-sloping portions of our emissions–GDP curves. This also tends to increase emissions.

Gathering arguments, future global emissions are likely to reflect the interaction of the following three relationships: emissions versus GDP, GDP growth versus GDP levels, and population growth versus GDP levels. To capture these issues, we use the models estimated in Section III in conjunction with country-by-country population and per capita GDP forecasts for 130 countries to obtain forecasts of global emissions.[12] For our population forecasts, we rely on the World Bank (Bos *et al.* [3]) population projections.[13] To forecast per capita GDP, we use the Summers and Heston RGDPCH series from 1952 to 1985 to estimate the following growth rate model:

$$\ln(y_{it}/y_{it-1}) = \gamma_{0t} + \gamma_1 \ln(y_{it-1}) + \gamma_2 \ln(y_{it-1})^2 + \theta_{it}. \tag{3}$$

The estimated model embodies a "convergence" relationship between income levels and growth rates, with low-income countries experiencing a "takeoff" to rapid growth, followed by decelerating growth at higher income levels.[14] While we

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[12] We use 1986 as our initial year. This is because 1986 is the most recent for which the Summers and Heston data include substantial representation by the poorer countries. Indeed, to obtain a total of 130 countries for our projections we had to extrapolate missing GDP numbers for several countries from their 1985 (or, for three countries, their 1984) levels.

[13] The "global" population growth rate for countries in the forecasting sample decelerates from 1.81% in 1986 to 1.58% in 2000, 0.74% in 2050, and 0.21% in 2100.

[14] The parameter estimates (with standard errors in parentheses) are $\gamma_1 = 0.00822(0.00186)$ and $\gamma_2 = -0.00212(0.00096)$ (the mean of the year effects is 0.00949). The coefficient estimates have quite narrow confidence intervals; however, the equation has little explanatory power ($R^2 = 0.06$), and the convergence hypothesis on which it is based is controversial. Baumol [4] and Mankiw *et al.* [22] find evidence in support of the hypothesis, whereas DeLong [7], Barro [2], Grossman and Helpman [10], and Levine and Renelt [18] do not find the evidence compelling. Indeed, the estimated model above would have substantially under-predicted per capita GDP growth between 1960 and 1985 for a number of the poorest countries. Nevertheless, the model seems adequate for our purpose, which is simply to explore

believe this model yields a plausible scenario for the evolution of per capita GDP, we also construct rapid-growth and slow-growth scenarios, in which per capita GDP growth rates are increased or decreased relative to this central case by 1 percentage point per year.[15]

One might simply use these income and population forecasts to project per capita emissions for each country using Eq. (1). However, simple extrapolations using these quadratic models can yield negative forecasts in the highest and lowest income countries. Thus, we transform our raw forecasts using a tobit functional form,

$$\tilde{m}_{it} = \Phi(\hat{m}_{it}/\hat{\sigma}) * \hat{m}_{it} + \hat{\sigma} * \phi(\hat{m}_{it}), \qquad (4)$$

where $\tilde{m}$ is the tobit forecast, $\hat{m}$ is the untransformed forecast, $\Phi(\ )$ is the standard normal cumulative distribution function, $\phi(\ )$ is the standard normal probability density function, and σ is the standard deviation of u_{it} in (2) (Maddala [21, p. 159]).[16] This results in a flattening of the predicted curve, with more gradual increases in emissions for lower income countries, a reduced peak, and an asymptotic tail at zero emissions. The primary advantage of this *ad hoc* transformation is that it possesses more reasonable asymptotic properties than the simple quadratic equations we estimate—without affecting the turning points implied by the underlying equations.[17]

Multiplying per capita emissions by population and summing over the countries in our forecasting sample yields our forecasts for global emissions presented in Figs. 1–4. In all cases, we forecast emissions to continue growing at rapid rates through the first half of the next century. This is true for both the fixed-effects and random-effects models, with and without population density. This is even true for the CO fixed-effects models, despite their low turning points. Also, the inclusion of population density as a regressor typically results in lower forecasts. Intuitively, while the direct effect of greater population is to increase pollution (holding emissions per capita constant), this may be at least partially offset if increased population density causes per capita emissions to decline.

In Table VI we summarize the results from our simulations of faster and slower economic growth. For each model, Table VI presents the year in which global emissions peak, along with the percentage increase from 1986 levels as of (i) the year 2000, (ii) the peak year, and (iii) the year 2100. In every case, accelerated

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the likely implications of our emissions–GDP estimates. (We have also experimented with forecasts based on historical 1-, 5- and 10-year growth rates. The resulting emissions forecasts are even greater than those presented in this paper.)

[15] The baseline growth rate forecasts peak at approximately $6900 (in 1985 U.S. dollars), at which point per capita GDP is forecast to grow at 1.76% per year. Beyond that point, growth rates diminish smoothly, so that at $30,000 of per capita GDP we forecast annual per capita income growth of only 1.30%. Taken together, the per capita GDP and population forecasts generate uniformly decelerating annual growth rates for global GDP (aggregated over the countries in our sample). Starting in 1986, global GDP growth slows from 2.78% per year to 2.62% in 2000, 1.89% in 2050, and 1.42% in 2100.

[16] Note in this regard that least-squares estimators from a noncensored sample coincide with tobit estimators.

[17] Alternatively, one might assign zero values to any negative forecasts; however, this would impart an upward bias to the forecasts. The tobit formulation lowers the positive forecasts at the same time as it raises the negative forecasts.

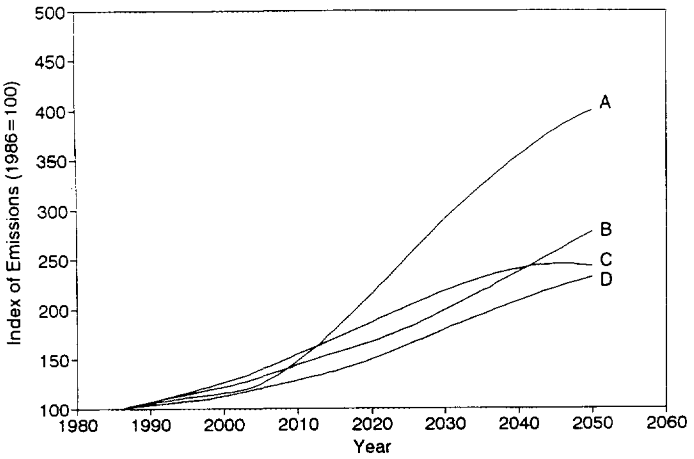

FIG. 1. Global emissions forecasts of SO_2. (A) Fixed-effects model without population density. (B) Random-effects model without population density. (C) Fixed-effects model with population density. (D) Random-effects model with population density

economic growth leads global emissions to decline in an earlier year than in the base line case, while slower economic growth has the opposite effect. In some cases, global turning points in the rapid growth case occur as early as the third decade of the next century. Very simply, more rapid growth causes the incomes of more countries to rise above the turning points for emissions in any given year. However, more rapid growth can also contribute to accelerated emissions growth over the near term (though not for all pollutants), and the global flows of all four emissions remain at or above their 1986 levels throughout the entire next century, even in the most optimistic scenarios.

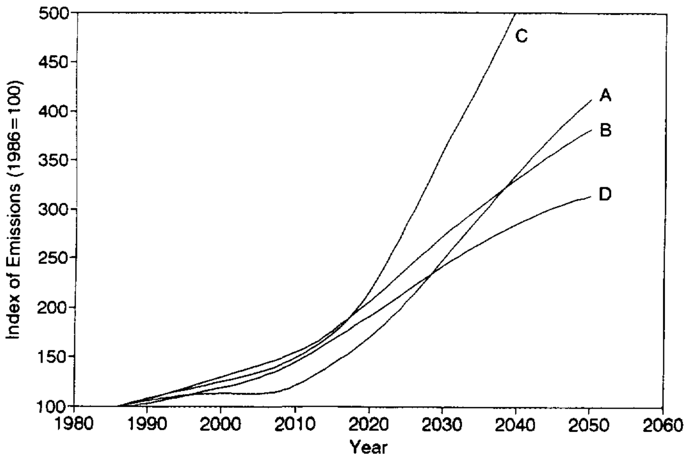

FIG. 2. Global emissions forecasts for SPM. (A) Fixed-effects model without population density. (B) Random-effects model without population density. (C) Fixed-effects model with population density. (D) Random-effects model with population density.

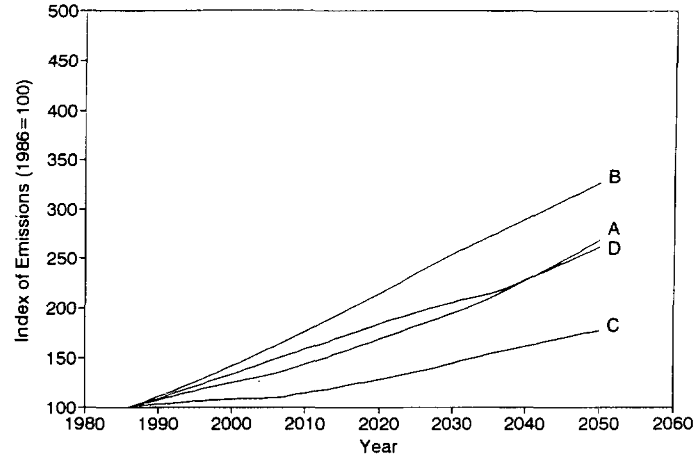

FIG. 3. Global emissions forecasts for NO_X. (A) Fixed-effects model without population density. (B) Random-effects model without population density. (C) Fixed-effects model with population density. (D) Random-effects model with population density.

These forecasts should be interpreted with caution for several reasons. First, no attempt is made to forecast changes in technology or their implications for emissions. Second, no attempt is made to incorporate either unilateral or multilateral responses to rising global emissions. Third, changes in global emissions should be viewed within the context of our discussion of the distinction between aggregate emissions data and urban air quality data. Thus, worldwide human exposure to air pollution may well decline prior to global emissions. Fourth, insofar as these forecasts reflect average historical trajectories, we cannot rule out the possibility that countries such as China, which is richly endowed with coal, may experience substantially higher emissions growth than we forecast (though the possibility also

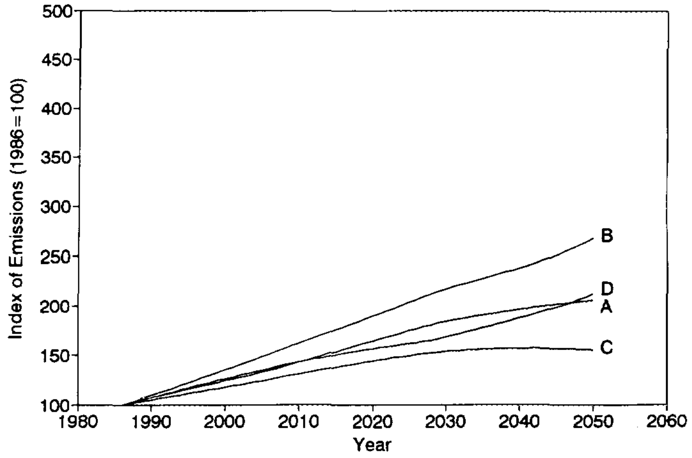

FIG. 4. Global emissions forecasts for CO. (A) Fixed-effects model without population density. (B) Random-effects model without population density. (C) Fixed-effects model with population density. (D) Random-effects model with population density.

TABLE VI
Sensitivity Analysis for Global Emissions Forecasts

Pollutant		Models without population density				Models with population density			
			Percentage increase above 1986 level as of:				Percentage increase above 1986 level as of:		
Model	GDP growth rate	Year of peak emissions	2000	Peak	2100	Year of peak emissions	2000	Peak	2100
			Sulfur dioxide (SO_2)						
Fixed-effects	Slow	2100[a]	17	247	247	2090	17	88	87
	Baseline	2085	16	354	287	2046	27	144	4
	Fast	2050	27	353	270	2026	44	144	−22
Random-effects	Slow	2100[a]	20	137	137	2100[a]	12	95	95
	Baseline	2100[a]	22	224	224	2061	13	140	107
	Fast	2061	30	231	156	2036	19	131	−1
			Suspended particulates (SPM)						
Fixed-effects	Slow	2100[a]	16	215	215	2100[a]	30	617	617
	Baseline	2089	13	421	372	2100[a]	25	1019	1019
	Fast	2050	3	397	368	2097	15	940	933
Random-effects	Slow	2100[a]	20	230	230	2100[a]	13	159	159
	Baseline	2093	30	325	315	2054	19	216	151
	Fast	2055	36	347	259	2048	31	209	5
			Oxides of nitrogen (NO_X)						
Fixed-effects	Slow	2100[a]	21	134	134	2100[a]	8	32	32
	Baseline	2079	26	226	223	2062	8	84	40
	Fast	2065	29	233	155	2035	9	86	−35
Random-effects	Slow	2100[a]	25	204	204	2100[a]	20	148	148
	Baseline	2100[a]	42	455	455	2099	36	308	308
	Fast	2088	60	497	440	2057	47	294	112
			Carbon monoxide (CO)						
Fixed-effects	Slow	2100[a]	26	136	136	2084	18	68	67
	Baseline	2050	24	106	78	2042	17	57	−3
	Fast	2030	24	75	−6	2024	18	44	−63
Random-effects	Slow	2100[a]	24	161	161	2100[a]	40	96	96
	Baseline	2100[a]	35	301	301	2087	26	184	173
	Fast	2082	45	294	213	2051	33	180	12

[a] Emissions continue to rise through the year 2100.

exists that other countries may systematically emit less pollution than the historical average). Finally, our forecasts do not reflect the fact that upper income countries may have been at least partially successful in shifting polluting activities to poorer countries (from which consumption goods are then imported). Insofar as this is true, income growth among the rich nations could even cause global emissions to rise (not fall) as their demand for imported goods increases.[18] For all of these

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[18] However, note that many important emissions sources, such as home heating, transportation, and the manufacture of nontraded goods, are largely unaffected by such trends. For additional analysis of the relationship between trade, development, and the environment see Birdsall and Wheeler [6], Low and Yeats [19], and Lucas *et al.* [20].

reasons, one should interpret our forecasts with caution. Nevertheless, we believe the forecasts provide a helpful method for using plausible scenarios for GDP and population growth to gain insights into the qualitative implications of our estimates.

V. CONCLUSION

This paper examines the hypothesis that while industrialization and agricultural modernization may reduce environmental quality in the early stages of development, this trend reverses as an economy continues to develop. Using emissions data for four air pollutants, we find substantial support for the inverted-U hypothesis, thereby providing independent confirmation of previous findings. However, we find substantially higher turning points than have previously been found for these pollutants—as seems reasonable given our use of aggregate emissions data as opposed to data on urban atmospheric concentrations.

Despite our finding that aggregate emissions of these pollutants eventually turn down, we forecast rising global emissions over the foreseeable future. Even in the most optimistic scenarios, we forecast that emissions will not return to current levels before the end of the next century unless concerted actions are taken that move us away from the historical emissions–GDP relationship. This is in large part because much of the world's population has yet to reach the turning points for emissions. Reinforcing this income distribution effect are the global patterns of population and GDP growth.

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