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Examining the Impact of Demographic Factors On Air Pollution

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This study adds to the emerging literature examining empirically the link between population size, other demographic factors and pollution. We contribute by using more robust estimation techniques and examine two air pollutants. By considering sulfur dioxide, we become the first study to explicitly examine the impact of demographic factors on a pollutant other than carbon dioxide at the cross-national level. We also take into account the urbanization rate and the average household size neglected by many prior cross-national econometric studies. For carbon dioxide emissions we find evidence that population increases are matched by proportional increases in emissions while a higher urbanization rate and lower average household size increase emissions. The results suggest particular concern for developing countries with their high population growth rates and a trend towards urbanization and smaller household sizes. We find a U-shaped relationship between population size and sulfur dioxide emissions. Beyond a threshold level at a small population size, the estimated elasticity increases with higher existing population levels. For sulfur dioxide, other demographic factors do not matter.

KEY WORDS: carbon dioxide; sulfur dioxide; demography and the environment; IPAT; Environmental Kuznets Curve.

"An endless stream of superficial arguments linking population with global environmental degradation constitutes yet a third cause of dissension. (...) Sorely lacking are empirical studies that carefully demonstrate relationships between the two variables." (Shaw, R.P. (1992). The Impact of Population Growth on Environment: The Debate Heats Up. *Environmental Impact Assessment Review* 12 (1-2), 11-36, p. 13).

INTRODUCTION

This article contributes to the general debate on the link between population growth and the environment by analyzing the impact of demographic factors on two air pollutants. At the same time, it also contributes to a much more focused debate on how population size and other demographic factors should be taken into account in future projections of air pollutant emissions. It is also relevant to the large and still growing body of literature on the so-called Environmental Kuznets Curve (EKC), which posits that environmental pollution is first increasing and then decreasing with rising per capita income levels (see for example Grossman and Krueger 1995, Cole et al. 1997).

Empirical studies which explicitly examine the link between population and pollution in a systematic quantitative manner are very few in number. Cramer (1998, 2001) and Cramer and Cheney (2000) examine the impact of population levels on air pollution in California and conclude that population is closely associated with some sources of emissions but not with others. Cramer's and Cramer and Cheney's focus on a single state in a developed country is interesting, but it also means that the global implications of their work are uncertain. Dietz and Rosa (1997) and York, Rosa and Dietz (2003) focus on carbon dioxide emissions and energy use and, in the context of the Impact-Population-Affluence-Technology (IPAT) model, examine the roles played by population, affluence and technology.[1] They find that the elasticity of CO_2 emissions and energy are close to unity (i.e. a 1 percent increase in population leads to an approximately 1 percent increase in CO_2 emissions). They do not estimate how these elasticities may vary with population levels. All of these results are based on cross-sectional data for one year only. Finally, Shi (2003), again in the context of the IPAT model, uses a panel of cross-sectional *and* time series data. Shi finds population elasticities for CO_2 of between 1.41 and 1.65, depending on the model used, but does not examine how these may vary with different population levels. Whilst a step in the right direction, Shi's study still estimates results for one pollutant only, CO_2, and also suffers from a potentially severe methodological problem: many of the variables used by Shi, particularly per capita income and CO_2 emissions, have a very strong upward trend over time. As such, they are not covariance stationary – a condition required for non-biased and consistent regression results – thereby raising question marks over the validity of the estimated coefficients and elasticities.

Some 'Environmental Kuznets Curve' (EKC) studies undertaken by economists have included population density as one of many determinants of pollution concentrations, but have tended to find mixed results (see for example, Grossman and Krueger, 1995; Panayotou, 1997; Hilton and Levinson, 1998). None of these studies have investigated the population-pollution relationship further, or examined the wider impact of population levels (as opposed to spatial density) or other demographic factors on pollution.

The aim of this paper is to provide a detailed analysis of the impact of total population size and other demographic factors on air pollution emissions and to correct the weaknesses outlined above. We build on the papers by Dietz and Rosa (1997), York et al. (2003) and Shi (2003) and improve on their studies in a number of ways. First, whereas these three studies examine only CO_2 and energy use, we extend the analysis to sulfur dioxide (SO_2) emissions, a pollutant with very different properties to CO_2 and hence potentially possessing a very different relationship with population. We also estimate results for CO_2 for means of comparison. Second, in contrast to Dietz and Rosa and York *et al*., we provide a cross-section *and* time-series panel data analysis. This allows us to capture changes over time and permits a more sophisticated research design controlling for latent country effects. Third, whilst Shi (2003) also uses a panel data approach we correct the methodological weakness with this study by ensuring that our variables are co-variance stationary by using a first-differenced estimator. Our estimated results are therefore consistent and free from bias. Fourth, we investigate the impact of a more comprehensive set of demographic factors on pollution including the age composition, the urbanization rate and the average household size. Many existing econometric studies neglect demographic factors other than total population size. Parikh and Shukla's (1995) analysis of the effect of the urbanization rate on energy use and greenhouse gas emissions in developing countries represents a notable exception in this regard.

METHODOLOGY

At the global level, equation (1) is not easy to test in a way that leads to reliable and non-spurious estimates. This is because of the lack of data on environmental degradation covering a sufficiently large number of countries over a sufficiently large period of time. It is for this reason that studies have tended to focus on CO_2 emissions and energy use, for which cross-country and time-series data are available. The time dimension is necessary in order to avoid the problem of one-period cross-sectional regressions, which are likely to lead to spurious results if population size or growth or any other explanatory variable is correlated with unobserved or latent country effects.

Like Dietz and Rosa (2002), Cramer (1998), Shi (2003) and York *et al*. (2003) we use a stochastic and non-tautological version of the famous IPAT model that originated from a dispute between Ehrlich and Holdren (1971) and Commoner et al. (1971):

$$I = f(P, A, T) \qquad (1)$$

where I is environmental impact, P is population, A is affluence and T is technology. The IPAT model is most famous in its tautological or definitional identity formulation, which follows from equation (2) if one defines A as consumption (C) per capita and T as pollution per unit of consumption:

$$I \equiv P \; x \; A \; x \; T, \;\; \text{if } A \equiv \frac{C}{P} \text{ and } T \equiv \frac{I}{C} \qquad (2)$$

In such a formulation the model or its linearized version might be useful for accounting or decomposition purposes as in, for example, Holdren (1991), Bongaarts (1992), Commoner (1991, 1993) and Preston (1996), even though there is some dispute as to how this should be done (O'Neill and Chen, 2002). It has also been used in sensitivity analysis for projecting future CO_2 emissions (for example, O'Neill, MacKellar and Lutz, 2001). However, it is not useful for an empirical estimation of the population elasticity. For such estimation, we need to define the variables in non-tautological terms.

Our starting point for empirical estimation is therefore equation (3), referred to as the stochastic IPAT model (STIRPAT) by Dietz and Rosa (1997);

$$I_i = aP_i^b A_i^c T_i^d e_i \qquad (3)$$

Where a is a constant, b, c and d are the exponents of P, A and T, respectively, that are to be estimated and e is the residual or error term. Subscript i denotes the cross-sectional units, namely countries in this paper.

If we now acknowledge the cross-sectional and time-series nature of our data, and express equation (3) in logarithms so that it becomes additive, we have;

$$lnI_{it} = a_i + k_t + b(lnP_{it}) + c(lnA_{it}) + d(lnT_{it}) + e_{it} \qquad (4)$$

Where subscript t denotes the time period. Note that, with panel data, our constant, a, becomes country specific and can therefore capture country specific (time invariant) determinants of I other than P, A and T. Important examples for such determinants are climatic differences and geographical factors (Neumayer, 2002, 2004). Note also that we now have a time specific constant for each year, k, which captures effects which are common to all countries but which change over time, other than P, A and T.

Equation (4) provides our basic estimating equation, allowing a number of modifications and extensions to examine different aspects of the population-pollution relationship. Our estimation framework can be thought of as a modified version of the traditional Environmental Kuznets Curve (EKC) framework familiar to economists. The modifications are twofold. First, we do not use emissions per capita as our dependent variable, but use total emissions and include population size as a further explanatory variable. The traditional EKC framework implicitly assumes a population elasticity of one, which is of course only one possibility and may conflict with reality. Instead, our aim is to estimate this elasticity. Equation (4) therefore represents the more general estimation framework compared to the traditional EKC methodology. Second, contrary to some EKC studies we do not estimate a reduced-form equation in which income is the only explanatory variable, but distinguish between various effects that are reminiscent of the distinction between scale, composition and technique in some EKC studies (e.g., Selden, Forest and Lockhart, 1999).

Note that the linear relationship between (logged) emissions and (logged) population implies that we estimate the direct effect of population on emissions only, but not the indirect effects that might work via the impact of population on either *A* or *T*. This has been critically noted by a number of participants in the ongoing discussion about the usefulness of IPAT (e.g., MacKellar et al., 1995). Such complex interaction effects are beyond what can be achieved in this paper and are left for future research.

Cramer (2001) is concerned about potential feedbacks of pollution on population. Of course, the direct effect is likely to be small as mortality from pollution is very small (and zero at the moment with respect to CO_2 emissions). At the local level, there might be reason to be concerned about simultaneity bias as pollution might have an effect on net migration (Cramer, 2001, p. 23). However, at the cross-national level we see no reason to be concerned about this question.

When estimating equation (4) our measures of *I* are carbon dioxide and sulfur dioxide emissions. In keeping with the previous IPAT literature, *A* is measured as per capita GDP. Technology, *T*, is a broad term which is intended to reflect technological, cultural, and institutional determinants of *I* i.e. anything that could affect I/C (emissions per unit of consumption or production). In our standard model we use two measures of *T*, a country's energy intensity (total energy use per unit of GDP) and the share of manufacturing output in GDP. Energy intensity provides a measure of 'energy productivity' and as such should be directly related to the level and types of technology currently in place within a country. Similarly, manufacturing share provides a measure of the industrial structure of an economy, an obvious determinant of impact per unit of production. Energy intensity is partly determined by the sectoral structure of the economy, but we hope to cover the impact of technology *T* more comprehensively by including both variables in our estimations. Other aspects of 'technology' not captured by energy intensity and the manufacturing share will be picked up by the error term, *e*.

As concerns *P*, the most common approach is to simply use total population levels. However, as MacKellar et al. (1995) and others have pointed out, it is not a priori clear that only the individual, rather than, say, households or communities, is the relevant demographic unit. To this one can add that a whole range of other demographic factors beyond simple population levels might also impact on emissions. For example, the impact on emissions could differ across age groups, likely reflecting a number of issues, including consumption habits and patterns, work and leisure activities and attitudes to environmental issues (Tonn, Waidley and Petrich, 2001). One would expect that the economically active part of the population between the ages 14 and 64 has a higher impact on emissions than the retired above the age of 64 or the age group encompassing children and adolescents below the age of 14. A higher urbanization rate can also be expected to have a positive impact on emissions due to the typically more pollution intensive behavioral patterns of those in urban areas. For instance, in developing countries in particular, we would expect those in urban areas to utilize cars, motor cycles and buses to a greater extent than those in rural areas. Similarly, agricultural products are transported to the cities, often from places far away – see Parikh and Shukla (1995) who provide an early analysis of the effect of urbanization on energy use and greenhouse gas emissions in developing countries. We agree with O'Neill and Chen (2002, p. 60) who suggest that the effect of urbanization on emissions represents a promising but underdeveloped avenue of research. Lastly, household size can be expected to have an impact on emissions as households with greater size are likely to benefit from economies of scale in using space, energy use and transportation. Cramer (1998) analyses such an effect on local air pollution in California, but it is to be seen whether it holds in a cross-national setting as well.[2] For this reason, we include variables relating to the age structure of population, relating to the urban versus rural settlement pattern and relating to the average household size in our estimations.

The great advantage of using panel data over a simple cross-sectional sample is that one can control for the country-specific fixed effects a_i. Failure to do so leads to biased estimates if these fixed or latent effects are correlated with the explanatory variables, as is likely to be the case. However, unfortunately the use of panel data also leads to more complications if some or all of the variables in the estimating equation follow a trend over time. Such trending typically implies what econometricians call non-stationarity. One implication of non-stationarity is that the estimated coefficients and their standard errors cannot be trusted. In formal terms, a variable is defined as stationary if its variance and its expected value do not depend on time and the covariance between the value of the variable at time t and at time t + s does not depend on time. Only statistical inference with stationary variables provides valid results. In simple words, this is because if variables are non-stationary then any correlation between the explanatory and the dependent variable could be due to the trending in both variables that is caused by a third variable not included in the model. We tested for the non-stationarity of the variables in our model formally with the help of Levin et al.'s (2002) unit root test for panel data. For the dependent variables and several of the explanatory variables we could not reject the hypothesis of non-stationarity. Fortunately, it is often the case that if a variable X_t is non-stationary it is still what is called difference-stationary. This means that a transformation of the original variable called first differencing leads to a transformed variable $Y_t = (X_t - X_{t-1})$ that is stationary. A non-stationary variable that is difference-stationary is also said to be integrated of order one, or I(1), whereas the first differenced transformation is integrated of order zero, or I(0). We therefore took first differences of all the variables included in our regressions. We also tested the first-differenced variables and rejected the hypothesis of non-stationarity for all variables. First differencing also eliminates the country specific effects since $a_i - a_i = 0$.

Our CO_2 sample covers 86 countries and 24 years (1975-98), providing 2064 observations in total. For SO_2 our data cover 54 countries and 20 years (1971-90), providing 1080 observations in total. However, because of the first differencing transformation of the variables we lose the first year of the data such that the sample comprises 1978 and 1026 observations, respectively. The number of observations was constrained by the availability of sulfur dioxide emissions, manufacturing share and energy intensity data. Appendix 1 provides a list of countries included in the samples. They make up approximately 82 per cent of world population in the case of CO_2 emissions and approximately 72 per cent of world population in the case of SO_2 emissions. Appendix 2 provides more information on variable definitions and the sources of all data. We computed variance inflation factors, which suggested no reason to be concerned about potential collinearity problems.

ECONOMETRIC ANALYSIS AND RESULTS

Estimation results for CO_2 emissions are provided in Table 1. Column I reports results for the basic model, in which total population size is the only demographic aspect looked at. The results are generally in line with expectations.[3] Since all variables are expressed in logarithms, the estimated coefficients can be interpreted as elasticities. Affluence has the expected positive impact on emissions and its elasticity is just below one. The manufacturing share is insignificant, but a higher energy intensity is associated with higher emissions. The estimated population elasticity, for example, is close to unitary, suggesting that a one per cent increase in total population size raises CO_2 emissions by about an equal proportion. This confirms the results reported by Dietz and Rosa (1997) and York et al. (2003).

< Insert Table 1 about here >

As a next step, we investigate whether the emission elasticity of the population variable changes with population size. Our second model, for which results are reported in column II, therefore allows for a non-linear relationship between population and pollution emissions by including population squared (POP^2). The linear term becomes statistically insignificant, which suggests that the relationship is not quadratic.[4] We therefore only include the linear population term in the estimations that follow. Similarly, we have tested for non-linear relationships of the other explanatory variables, but have not found relevant evidence.[5]

In column III we additionally look at the age composition of population. We add two variables, namely the percentage of population that is below 14 and the percentage of population that is between 14 and 64 years old. Note that the share of elderly people above 64 years cannot be simultaneously added as the three shares add up to one and are therefore collinear. Adding the age composition hardly affects the population elasticity, which remains close to unitary. Neither the affluence nor the technology variables are much affected in either this or consecutive estimations and are therefore not further discussed. A higher percentage of the age group between 14 and 64 years old has a positive impact on emissions that is only marginally significant, however. As expected, a higher share of very young people has no statistically significant impact on emissions.

In column IV we take the urban versus rural settlement pattern into account in adding the share of urbanized population. The population elasticity is now slightly below one at 0.92. A higher rate of urbanization has the expected positive impact on emissions. The share of population in the economically active age groups now becomes marginally insignificant. The reason for this could be the high correlation between the two variables (partial correlation coefficient of 0.65).

Lastly, in column V we add the average household size to our model. Note that this variable is available for all countries in the sample, but not over the entire estimation period. Hence the number of observations is smaller in column V than in the other regressions. The population elasticity is again very close to unitary. The urbanization rate maintains its positive and statistically significant impact on emissions. A higher average household size is associated with lower emissions, as expected. Note that the population share of the economically active age groups now becomes more clearly insignificant. This suggests that its initial statistical significance might be entirely due to its correlation with the urbanization rate as pointed out above and its correlation with the average household size (partial correlation coefficient of -0.58). In other words, it would appear that the urbanization rate and average household size are the demographic factors that really matter. Interestingly, the coefficient size of the energy intensity variable rises once average household size is controlled for.

< Insert Table 2 about here >

Table 2 reports results for a similar set of estimations, but with SO_2 emissions as the dependent variable. In column I it can be seen that affluence and energy intensity have the expected positive effects on SO_2 emissions, with the income elasticity being again close to unity. The simple linear population term is insignificant, however. In column II we investigate whether this is due to a non-linear effect of population size. The results suggest that this is indeed the case as both the linear and the squared population terms are statistically significant. This indicates that emissions experience a U-shaped relationship with population. Differentiating our estimated equation with respect to population and setting this equal to zero allows us to identify the turning point level of population: The estimated turning point is at around 5.4 million people. Thus, whilst we do find a U-shaped relationship between emissions and population, population generates an increase in emissions for all populations over 5.4 million (around 23 percent of countries in our sample have a population below this threshold). The inclusion of a quadratic term in model (2) means we cannot interpret the estimated coefficients on POP and POP^2 as elasticities, as actual elasticities will in fact depend on the level of population. Elasticities can be calculated by partially differentiating our estimated equation with respect to population. If our equation to be estimated is as follows;

$$lnI_{it} = a_i + k_t + b(lnP_{it}) + c(lnP_{it})^2 + d(lnA_{it}) + f(lnT_{it}) + e_{it} \quad (5)$$

then the elasticity of I with respect to P, which we may call E_p, can be calculated as;

$$E_p = b + 2c(lnP_{it}) \quad (6)$$

Equation (6) therefore allows us to calculate elasticities for varying levels of population. The elasticity is –0.86 for countries with a population of one million, approximately the current population size of Swaziland. It is 0.31 at a population of 10 million (approximately the population of Portugal), 1.13 at a population of 50 million (approximately the population of Myanmar) and reaches 2.66 at a population of one billion (approximately India's current population size). Setting equation (6) equal to zero and solving for P also provides the level of population at the turning point as referred to above. Our results therefore clearly suggest that the marginal impact of population on sulfur dioxide emissions is an increasing function of the level of population i.e. the greater the level of population, the greater the environmental impact of each additional unit of population.

As a next step, column III reports results from the model that examines the role played by the age structure of the population. Because we found total population size to have a non-linear effect on emissions, we retain the squared term in all estimations. It can be seen that the age structure of population has no statistically significant impact on emissions. Interestingly, the same is true for the urbanization rate added to the model in column IV and the average household size added in column V. We address this striking difference to our results for CO_2 emissions in the following section where we discuss the implications of our findings.

DISCUSSION

The results reported above demonstrate that the link between population size and emissions of environmental pollutants is a complex one. There are clear differences between SO_2 and CO_2 emissions. For CO_2 emissions, the situation in developing countries gives particular reason for concern. They are the countries which will experience substantial economic and population growth in coming decades, in addition to which they are also the countries where urbanization rates are likely to rise and average household size is likely to decline. In our sample, the mean urbanization rate for developing countries is around 56 per cent, whereas it is 78 per cent in developed countries (see table 3).[6] The average household size in developing countries is 4.9, but only 2.6 in developed countries. Importantly, however, the trend is clearly pointing towards higher urbanization and lower household sizes in the future developing world, which will amplify the emission increases due to overall population growth. Young people in developing countries will move away earlier from their family home, will marry at a later age and their parents will increasingly live in separate homes. O'Neill, MacKellar and Lutz (2001, p. 72) report projections that see the average household size in developing countries decreasing to between 2.4 and 3 over this century. With respect to the age structure of population, we find only weak evidence in one estimation that a higher share of the economically active age group between 14 and 64 years old has a positive impact on emissions. If such a link were to exist, then it would again paint a bleak picture for developing countries. This is because their current average share of young people below 14 is almost 36 per cent, double the value in developed countries. These youngsters in developing countries will soon enter the economically active age group.

< Insert Table 3 about here >

Our results therefore suggest that future demographic change will have the strongest effect on CO_2 emissions in the developing world. In contrast, in developed countries demographic factors will not change much in the future. Not only do they have low and sometimes zero (or even negative) current and projected population growth rates, but their urbanization rate will not increase as dramatically as in developing countries, their average household size is already very low and they do not have a huge cohort of youngsters entering the economically active age group.

For SO_2 emissions, the implications of demographic change are entirely different. Increases in total population size can also be expected to increase emissions, but only for population sizes above 5.4 million people. The population elasticity is not constant, but increases with population size. This is again bad news for developing countries as on average they have bigger populations. In our sample their mean population size is around 65.3 million people with a median at around 15.2 million, whereas the mean is around 33 million and the median at around 9.7 million in developed countries. Apart from increases in total population size, none of the other demographic factors like urbanization rate, age group composition or average household size matter. What explains this stark contrast in results? The most likely explanation is that SO_2 and CO_2 emissions differ in their sources. CO_2 emissions are generated by a great variety of economic and consumption activities that are influenced by demographic factors. SO_2 emissions on the other hand mainly derive from stationary sources and from the production of electricity in particular. On the whole, more SO_2 emissions will be generated for more people, but other demographic factors will not impact on emissions.

CONCLUSIONS

This study used large panels of cross-section and time-series data and improved on the methodology employed by previous studies. For CO_2 emissions, the estimated pollution elasticity of population is very close to one in all estimations. We thus confirm the results of Dietz and Rosa (1997) and York et al. (2003) who found a similar elasticity in their one-period cross-sectional sample and provide evidence against Shi's (2003) much higher estimate of between 1.41 and 1.65. One possible explanation is that the fixed effects bias in the simple cross-sectional sample is less severe than the bias due to the non-stationarity of the variables in Shi's (2003) analysis. Our research design deals effectively with both fixed effects and non-stationarity problems and therefore leads to more valid and reliable results.

In addition, we have looked at a comprehensive set of demographic factors. Our results have particular significance for developing countries. Such countries typically have higher population growth, a trend towards urbanization and smaller average households sizes and a large proportion of youths entering the economically active age group. Whilst CO_2 emissions are often still lower in developing countries than in developed countries (on average 2.5 times lower), our results show that population increases, changes in the demographic structure and the rise in affluence can be expected to close this gap.

Furthermore this paper has been the first to estimate population elasticities for a pollutant such as sulfur dioxide (SO_2). For SO_2 emissions population increases also have a positive impact on emissions for all but small population sizes and the population elasticity rises with higher population levels. Again, this affects developing countries more as they have on average both higher population growth rates and higher existing population levels. Demographic factors other than total population size have not been found to have any impact on emissions. We explained this striking difference in results with the fact that SO_2 emissions are mainly generated by fixed sources, particularly in the electricity sector, and are therefore less sensitive to changes in consumption patterns and habits following changes in these demographic factors.

Our results are also relevant to the large body of literature on the Environmental Kuznets Curve (EKC). First, we find that the population elasticity is close to one for CO_2 emissions suggesting that the EKC approach of taking per capita emissions as the dependent variable, thus implicitly assuming a population elasticity of one, will not lead to biased results. Our findings for SO_2 emissions are different. Here, the EKC approach is likely to lead to biased results as it fails to take into account the fact that the population elasticity is non-linear in population size. Second, we find that other demographic factors such as the urbanization rate and average household size are significant determinants of CO_2 emissions, but not of SO_2 emissions. This suggests that EKC studies, at least those addressing CO_2 emissions, will lead to inaccurate results since they typically fail to take such demographic factors into account. Thus, non-economic factors such as population structure and other demographic aspects are potentially important determinants of pollution emissions, yet are often neglected in economic analyses of pollution.

In terms of future research, more detailed analysis is needed to understand why the pollution elasticity of population is increasing in population size for SO_2 emissions. Why does population growth in countries with already high population levels lead to higher emission increases than growth in countries with lower levels of population? Holdren (1991) speculates that settlement patterns might change with higher population levels and that economies might have to resort to lower quality energy resources. He also suggests that ‘where rates of population growth (…) are high, the attendant pressures can swamp the capacities of societies to plan and adapt in ways that could abate or reduce the environmental impacts of energy supply' (p. 249). Furthermore, our explanation for the differences in results for CO_2 emissions and SO_2 emissions is rather tentative and somewhat speculative at this stage and needs further exploration. More detailed attention is also needed to account for the indirect effects that population growth and other demographic changes can have on the environment. In non-reported analysis we tested for interaction effects of the various demographic variables with our variables of affluence and technology. These interaction effects generally failed to assume statistical significance. This does not imply that interaction and feedback effects are not important. Rather, they might be more difficult to take into account adequately and their modeling and estimation represents a challenging task. Clearly, these questions deserve more systematic attention and the present authors would like to tackle these and related questions in future research.

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ENDNOTES

[1] Like the current paper, existing studies mainly look at air pollution for reasons of data availability. Taking a broader focus, York, Rosa and Dietz (2003b) examine the impact of demographic factors on so-called ecological footprints. Ecological footprints supposedly measure the total land area hypothetically required to provide all the resources to and absorb all the pollution generated by a country's economy. We do not follow this path. For one reason, this can only be done in a cross-sectional analysis, in which one cannot control for many sources of estimation bias. More importantly, one of us has argued that the concept of ecological footprints does not represent a valid, reliable or methodologically sound indicator (see Neumayer 2003, pp. 172-177, for details).

[2] Liu, Daily, Ehrlich and Luck (2003) show that the growing number of households puts pressure on endangered species in so-called biodiversity hotspots.

[3] Note that the R^2 values are quite small. This is no reason for concern as R^2 is typically very small for models estimated in first differenced variables.

[4] If the squared term is included in the estimations of columns III to V, then both the linear and the squared term are statistically insignificant, buttressing the conclusion that the relationship between population size and CO_2 emissions is linear rather than quadratic.

[5] This result might be surprising with respect to the average income level since some EKC studies have found a non-linear relationship of per capita income and CO_2 emissions. Note, however, that the non-linear effect is likely to work through *T* and that these studies use reduced-form estimations in which emissions are regressed on income without controlling for *T*.

[6] The term developed countries refers to the United States, Canada, Western Europe, Japan, Australia and New Zealand.

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TABLE 1

Estimation Results for CO2 emissions

	I	II	III	IV	V
GDPpc	0.877	0.876	0.867	0.863	0.892
	(5.90)***	(5.91)***	(5.79)***	(5.77)***	(5.29)***
MANFsh	0.020	0.013	0.019	0.013	-0.023
	(0.18)	(0.12)	(0.18)	(0.12)	(-0.14)
ENERGYint	0.346	0.351	0.342	0.346	0.543
	(3.58)***	(3.65)***	(3.56)***	(3.61)***	(4.02)***
POP	1.034	-3.054	1.078	0.922	0.980
	(3.27)***	(-1.42)	(3.51)***	(2.79)***	(3.87)***
$(POP)^2$		0.136			
		(2.06)**			
% POP < 14			0.172	0.065	0.010
			(0.53)	(0.21)	(0.03)
% POP 15-64			0.995	0.871	0.425
			(1.72)*	(1.49)	(0.86)
% URBAN				0.663	0.700
				(1.90)*	(2.00)**
HOUSEHOLDSIZE					-0.499
					(-2.67)***
R^2	0.06	0.06	0.06	0.06	0.07
Observations	1978	1978	1978	1978	1707
No. of countries	86	86	86	86	86

All variables are held in logged form and estimated in first differences with ordinary least squares (OLS) and panel-corrected standard errors. Coefficients of year-specific time dummies and constant not reported. t-values in brackets.

* significant at .1 level ** at .05 level *** at .01 level

TABLE 2

Estimation Results for SO2 emissions

	I	II	III	IV	V
GDPpc	1.038	1.012	1.031	1.034	1.162
	(4.91)***	(4.72)***	(5.27)***	(5.20)***	(10.42)***
MANFsh	0.043	0.031	0.030	0.031	-0.015
	(0.47)	(0.35)	(0.34)	(0.34)	(0.16)
ENERGYint	0.845	0.851	0.856	0.856	0.925
	(5.30)***	(5.34)***	(5.50)***	(5.50)***	(9.69)***
POP	0.501	-7.908	-8.495	-8.653	-6.114
	(0.72)	(-1.77)*	(-1.82)*	(-2.05)**	(-1.89)*
$(POP)^2$		0.255	0.274	0.280	0.225
		(1.99)**	(2.12)**	(2.51)**	(2.44)**
% POP < 14			-0.351	-0.344	-0.329
			(-0.21)	(-0.21)	(-0.81)
% POP 15-64			-1.232	-1.198	-1.441
			(-0.42)	(-0.40)	(-1.60)
% URBAN				-0.137	-0.441
				(-0.18)	(-1.02)
HOUSEHOLDSIZE					-0.257
					(-0.88)
R^2	0.09	0.10	0.10	0.10	0.10
Observations	1026	1026	1026	1026	880
No. of countries	54	54	54	54	54

All variables are held in logged form and estimated in first differences with ordinary least squares (OLS) and panel-corrected standard errors. Coefficients of year-specific time dummies and constant not reported. t-values in brackets.

* significant at .1 level ** at .05 level *** at .01 level

TABLE 3

Descriptive information on demographic factors of countries in sample (1998 unless specified otherwise)

	Countries	Mean	Median
Population (million)	All	56.7	13.2
	Developed	33	9.7
	Developing	65.3	15.2
Population growth in 1990s (%)	All	1.77	1.78
	Developed	0.63	0.53
	Developing	2.19	2.24
Share of under 14 year olds (%)	All	31.1	32.5
	Developed	18.7	18.5
	Developing	35.6	35.6
Share of 15 to 64 year olds (%)	All	61.3	61.8
	Developed	66.7	67.9
	Developing	59.3	60.2
Urbanization rate (%)	All	61.7	62.3
	Developed	77.9	77.1
	Developing	55.9	55.1
Average household size	All	4.3	4.3
	Developed	2.6	2.6
	Developing	4.9	4.8

APPENDIX 1

Countries included in the CO_2 estimation results:

Algeria, Argentina, Australia, Austria, Bangladesh, Belgium, Benin, Bolivia, Brazil, Brunei, Cameroon, Canada, Chile, China, Colombia, Congo (Dem. Rep.), Congo (Rep.), Costa Rica, Côte d'Ivoire, Cyprus, Denmark, Dominican Republic, Ecuador, Egypt, El Salvador, Finland, France, Gabon, Ghana, Greece, Guatemala, Haiti, Honduras, Hong Kong, Hungary, Iceland, India, Indonesia, Iran, Ireland, Israel, Italy, Jamaica, Japan, Jordan, Kenya, Luxembourg, Malaysia, Malta, Mexico, Morocco, Nepal, Netherlands, New Zealand, Nicaragua, Nigeria, Norway, Pakistan, Paraguay, Peru, Philippines, Portugal, Romania, Saudi Arabia, Senegal, Singapore, South Africa, South Korea, Spain, Sri Lanka, Sudan, Sweden, Switzerland, Syria, Thailand, Togo, Trinidad and Tobago, Tunisia, Turkey, United Arab Emirates, United Kingdom, United States, Uruguay, Venezuela, Zambia, Zimbabwe.

Countries included in the SO_2 estimation results:

Algeria, Argentina, Australia, Austria, Belgium, Bolivia, Brazil, Chile, China, Colombia, Denmark, Ecuador, Egypt, Finland, France, Ghana, Greece, Guatemala, Honduras, Hong Kong, Hungary, India, Indonesia, Ireland, Israel, Italy, Japan, Kenya, Luxembourg, Malaysia, Mexico, Morocco, Netherlands, New Zealand, Nicaragua, Nigeria, Norway, Peru, Philippines, Portugal, Saudi Arabia, South Korea, Spain, Sri Lanka, Sudan, Sweden, Switzerland, Syria, Thailand, Trinidad and Tobago, United Kingdom, United States, Uruguay, Venezuela.

APPENDIX 2

Variable:	Source:
Sulfur dioxide emissions	ASL and Associates http://www.asl-associates.com/sulfur1.htmT
Carbon dioxide emissions Population Age structure of population Urbanization rate GDP per capita Energy intensity Manufacturing share of GDP	All from: World Bank (2002)
Average household size	ITU (2002) and World Bank (2002)