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Choking on Modernity: A Human Ecology of Air Pollution

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Ground-level air pollution has serious effects on the natural environment and human health, but it has not received the same attention in the sociological literature as the greenhouse gases polluting the upper atmosphere. To address questions about the effects of social structural forces on environmental impacts, we analyze cross-national time-series data (1990–2000) to assess influences on the emission of ground-level air pollutants: sulfur dioxide, nitrogen oxides, carbon monoxide, and non-methane volatile organic compounds. Drawing on human ecological theory, we move beyond previous analyses by assessing demographic effects on pollution emissions in a nuanced way by dividing population into the number of households and average household size. We found that the number of households has a greater effect on SO₂ emissions than average household size. This suggests that the effect of population on the environment is not simply due to its size and growth, but also to its distribution across households. The difference we found has important implications, since the global growth rate in the number of households is greater than the growth rate in population. Furthermore, while the population growth rate in less developed nations is over four times that in developed nations, the household growth rate is only double. This finding suggests that developed nations will contribute more to air pollution in the coming years than would be assumed based on population growth alone. Keywords: air pollution; structural human ecology; households; environmental demography; STIRPAT.

The environmental crises that have emerged during the modern era are some of the greatest challenges facing societies around the world. Global climate change, biodiversity loss, nuclear waste, and chemical toxins, among other problems, represent severe threats to societal well-being, due to their global scale and ubiquity. Understanding the social structural forces that contribute to these problems is an important part of developing effective means of avoiding worsening crises over the course of the twenty-first century. Recently, sociology has turned its attention to analyzing the factors that influence these environmental problems, producing an extensive body of research (see Rudel, Roberts, and Carmin 2011 for review).

This body of research has sought to develop an understanding of the relationship between social structural factors and environmental impacts, asking which aspects of modern and modernizing societies exacerbate or ameliorate threats to ecological sustainability. Here we adopt a structural human ecology perspective to deepen this line of research substantively and empirically. We provide rigorous tests to assess threats to the quality of an essential resource for human life everywhere: the terrestrial, oxygenated air that engulfs the planet. Greenhouse gases are measures of stresses to large-scale earth systems (like the climate system). But, unlike greenhouse gases that impact the upper atmosphere, ground-level air pollutants have immediate effects on life chances and on what most people value, including aesthetics and, especially, human health. Our empirical task of examining time-based connections between structural factors and impacts is made possible by the recent availability of longitudinal data on air pollutants for the vast majority of the world's nations.

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Compared to analyses of greenhouse gases, quantitative empirical analyses of ground-level air pollution have been remarkably sparse in sociology (for exceptions, see Bollen 1982; Cole and Neumeyer 2004; Cramer 1998; Jorgenson, Dick, and Mahutga 2007). This inattention is ironic since public opinion polls over the past decade show air pollution among the highest (Gallup 2008) or *the* highest public environmental concern (CBS and *The New York Times* 2007), and the topic has been recognized for some time by scholars as one of pressing political importance (Gonzalez 2006). The presumed causal sequence behind air pollutants is from anthropogenic (human generated) structural drivers to ecological alterations that, in turn, produce proximate effects, such as impacts on health and longevity, and long-term threats to sustainability. How ground-level air pollutants shape the life chances (Weber [1924] 1948) of people in all social classes as well as their quality of life (Campbell, Converse, and Rodgers 1976) is of pivotal sociological importance. The study of air pollution opens an opportunistic window for testing whether structural forces affect air pollution emissions differently than greenhouse gas emissions and other global impacts.

Drawing on theory in structural human ecology, our focus is on a novel assessment of demographic effects on environmental impact, where we separate the effects of population into those stemming from changes in number of households and those stemming from changes in the average number of people per household. In this analysis, we include a wider range of air pollutants than typically has been examined in other studies: sulfur dioxide (SO₂), nitrogen oxides (NO_x), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs). We also examine a larger sample of nations than most previous analyses, which may, by improving the precision of parameter estimates of structural factors, help to reach more robust conclusions. Furthermore, we use panel data that permits us to control for temporally invariant unobserved heterogeneity, i.e., unidentified and omitted independent variables that vary by nation cross-sectionally but are effectively constant over time within nations, such as a nation's topography, soil type, and whether or not it is landlocked. Therefore, the modeling strategy focuses on the effects of *change* in factors within nations, rather than differences across nations.

The Sociological Importance of Air Pollution: Life Chances, Human Health, and Other Consequences

A nation's commitment to curtailing ground-level air pollution represents one best-case scenario for addressing not only pollution but environmental problems in general because ground-level air pollution (1) can be curtailed or mitigated with available technologies; (2) is initially concentrated near the sites of the emissions and within the jurisdictions of relevant political entities; (3) clearly affects human health, longevity, and quality of life; and (4) has measurable economic effects. In contrast, diffuse air pollutants, like greenhouse gases, while representing a very serious threat to the global commons, due to their contribution to global climate change, are neither concentrated nor immediate in their effects. The most serious impacts of climate change may not occur for decades, will not necessarily be greatest in the nations responsible for the highest greenhouse gas emissions, and are more difficult to remedy than ground-level air pollutants.

Ground-level air pollution directly affects the life chances of people around the world, an issue of core sociological interest. Life chances for Max Weber ([1924] 1948), the originator of this idea, were determined by one's position in the class structure and the access it provided to societal resources. Hence, Weber's specification emphasized the parameters of one's chances in a lifetime, but not one's immediate life. In contrast, concerns with health, including morbidity (disease rates) and mortality (death rates), directly shape the chances one will live a full and healthy life. There is mounting evidence that air pollution is responsible for heart disease and heart attacks (Peters et al. 2004), strokes (Wellenius, Schwartz, and Mittleman 2005), learning disabilities and damage to child development, the epidemic rise in asthma rates among children and a variety of other respiratory illnesses (Working Group on Public Health and Fossil Fuel Combustion 1997), and genetic

mutations in laboratory animals (Somers et al. 2002). It would be challenging to counter argue effectively that air pollutants are immaterial to social life, to life chances, and to quality of life, all foundational sociological concerns.

But a concern with health effects does not end the sociological significance of air pollutants. All of the pollutants we examine are “precursor” gases that interact with other gases in the atmosphere to create greenhouse gases that contribute to global climate change (IPCC 2006:4). Additionally, SO₂ and NO_x lead to acid rain, which damages plants and a variety of ecosystems, contributing to forest loss, acidification of lakes, and agricultural damage among other effects (Akimoto 2003; EPA 2010). In short, the air pollutants we examine damage ecosystems, harm human health, and generate a variety of economic costs.

Structural Human Ecology: A Framework for Analyzing Coupled Human and Natural Systems

Although our analysis can speak to a variety of theoretical debates, our focus is on the demographic and technological factors emphasized by the structural human ecology tradition. We recognize other theoretical issues in the course of our analyses, but maintain a focus on demography and technology. Structural human ecology emphasizes that basic features of all ecosystems, such as demographic and resource factors, and the material conditions of human ecosystems, such as the mode and scale of production and consumption, are key drivers of anthropogenic environmental change (Catton 1980; Dietz and Rosa 1994). An early example of structural human ecology is the work of William Catton and Riley Dunlap (Catton 1980; Dunlap and Catton 1979) and a more recent, sustained effort was launched by Thomas Dietz and Eugene Rosa (1994, 1997) who reformulated (statistically and sociologically) concepts from the ecological sciences and from sociology to connect demographics, technology, and economic processes to environment impacts. The robustness of that reconceptualization has been subjected to a variety of empirical tests (Cole and Neumayer 2004; Dietz, Rosa, and York 2007, 2009; Rosa, York, and Dietz 2004; Shi 2003; York 2007a, 2007b, 2008; York, Rosa, and Dietz 2003a, 2003b, 2003c).

Population size and growth rates of all species are fundamental features structuring their interaction with ecosystems and the demands they place on them. In the case of humans, ecologists have underscored this nexus between population and environment by arguing for a direct relationship between the size of human populations and the impacts imposed on the environment (Ehrlich and Holdren 1971). In our analyses we assess the influence of demographic factors on emissions of air pollution, taking economic, social, and political context and other factors into account with appropriate statistical controls. Hence, the STIRPAT (*ST*ochastic *I*mpacts by *R*egression on *P*opulation, *A*ffluence, and *T*echnology) model (Dietz and Rosa 1994), the statistical formulation that organizes our analysis, incorporates the complex nature of the connection between population and other factors influencing air pollution.

Making use of data that to our knowledge has not been utilized in any environmental analyses in the sociological literature, we nuance the population effects by dividing population into number of households and average household size. Population growth rates are declining around the world, accompanied by a rapid decline in the average household size (i.e., fewer people per household), leading to rapid growth in the number of households (Kellman 2003; UN Population Division 2002, 2009). While population has been a core factor in the human ecology tradition (e.g., Perz, Walker, and Caldas 2006), the importance of a relationship between households and resource use is attracting a growing number of scholars, because the household is the locus of many consumption choices. J. Liu and colleagues (2003), consistent with growing theoretical opinion among ecologists, present evidence showing number of households stresses the environment more than population growth per se. There are good reasons for this view. The household is both the locus of and the physical structure where the majority of decisions about environmentally significant

consumption are made: about housing type, size, and location, patterns of energy use, types of transportation, levels of energy efficiency in behavior or infrastructure, and aspects of lifestyles, such as dietary decisions (Cramer 1998; O'Neill and Chen 2002). For example, the consumption of energy for indoor temperature control is only modestly affected by the number of people per household (Lutzenhiser and Hackett 1993; O'Neill and Chen 2002). Therefore, the number of households likely has a more substantial influence on national energy consumption than average household size. Transportation, too, is likely more sensitive to the number of households since their growth is primarily in the urban periphery where low-density, suburban landscapes prevail. This results in more passenger vehicles and more commuting adding to gasoline consumption and pollution (UNEP forthcoming).

Population distribution across households (e.g., more households versus greater number of people per household) will likely affect air pollution, because of its effects on transportation and household energy use (Lutzenhiser and Hackett 1993), the generation of which at energy plants is a major source of many air pollutants (EPA 2010). Furthermore, fuelwood for heating and cooking, which contributes to CO emissions, is typically tied to households rather than individuals (Knight and Rosa forthcoming). Still further, the use of chemicals, such as paints and cleaners responsible for NMVOCs, is likely tied more closely to the number of households than the number of people per se, since the growth in new homes and the size of a home more likely determine the amount of painting and cleaning that is required, rather than the number of people in the home, and the square footage of houses does not rise proportionately with the number of residents (Lutzenhiser and Hackett 1993). Likewise, fertilizer use for landscape aesthetics (e.g., lawns), a source of NO_x emissions, is probably more directly tied to the number of households, since, assuming lot size, like house size, does not increase proportionately with the number of people in a household, the area needing landscaping should track the number of houses more closely than the number of people per house.

By separating population into number of households and average household size (i.e., population divided by the number of households), we explicitly assess the effects on pollution emissions from the distribution of population across households. For example, we can assess whether, with the same population size, having many households with few people in each has a different effect on pollution emissions than having few households with many in each. Other demographic factors, in particular the age structure (e.g., the dependency ratio, which is the ratio of old and young people to working aged people) and urbanization, measured as the percentage of the population living in urban areas, have been shown to affect impacts (York 2007a, 2007b; York et al. 2003a). In our data set the dependency ratio is correlated with household size ($r = .68$) and with urbanization ($r = -.44$), both significant at the .001 level. This suggests that the number of households may be partially responsible for these previous findings. If number of households has a greater effect on pollution than average household size, this has substantial implications for future rates of emissions, since the number of households around the world is growing much faster than population (UN Centre for Human Settlements 2001).

Other Theoretical Considerations

The political economy tradition in environmental sociology has identified modernization and economic globalization as key forces leading to environmental degradation, since the massive scale of production and consumption that has come to characterize the modern world is dependent on high levels of resource extraction and energy use and, therefore, pollution emissions (Jorgenson and Clark 2009; Schnaiberg 1980). Countering this view, ecological modernization theory has suggested that the forces of modernization, after initial degradation, may lead to environmental improvements, since they lead to more awareness of environmental problems and efforts to incorporate environmental concerns into the institutions of modernity (Mol 1995; Mol and Sonnenfeld 2000; York and Rosa 2003). The empirical assessment of this debate has focused on how economic development and urbanization affect the environment. Its research questions

center on whether growth in GDP per capita consistently leads to increases in environmental impacts or whether, once nations become “modernized” and affluent, they become better at addressing ecological deterioration (Rudel et al. 2011).

Neoclassical economists have reconceptualized the idea developed by economist Simon Kuznets that the distribution of income in any particular society is a nonlinear function of national affluence. Kuznets (1955) argued that the relationship between national income and its distribution follows an inverted-U where income becomes more concentrated during the early phases of economic growth but only up to a point, after which further increases in average national income result in a more equitable distribution. Applied to the environment, the Kuznets argument parallels ecological modernization with its prediction that environmental impacts increase in the early stages of development, reach a turning point, and then decline as economies mature (Grossman and Krueger 1995). The theoretical justification for this reconceptualization is the assumption that environmental quality is a luxury good, only affordable to wealthy nations, which have the resources to invest in environmentally benign technologies and production processes. Hence, from this perspective, in the early stages of economic development environmental degradation is expected to increase because developing societies cannot afford to mitigate the environmental costs of development, but after a turning point is reached investment in environmental protection escalates and an improvement in environmental quality ensues. Likewise, some scholars have argued that urban development may accompany the emergence of ecologically rational institutions that facilitate the development of environmentally benign production processes, and, therefore, pollution may follow an environmental Kuznets curve relative to urbanization, rather than GDP per capita (Ehrhardt-Martinez, Crenshaw, and Jenkins 2002). To address these predictions, we test for a nonlinear relationship of the type proposed by ecological modernization theory and the environmental Kuznets curve between GDP per capita and pollution and urbanization and pollution.

A related, but distinct debate comes from the world-systems perspective, which seeks to assess the effects on the environment of the structural position of nations in the global economy, including trade relationships, foreign investment, and militarization (Jorgenson and Clark 2009; Roberts, Grimes, and Manale 2003). We control for key factors highlighted by modernization and world-system analysts. Additionally, we control for factors derived from the world polity literature (Frank, Hironaka, and Schofer 2000; Shandra et al. 2009), which suggests that democracy may help curb environment problems by leading to better environmental policy.

Methods and Data

The structural human ecology framework disciplining our analysis (Dietz and Rosa 1994) operationalizes the coupling of human ecosystems with social systems. The ecosystem part of the framework is summarized by the $I = PAT$ function in the field of ecology that emphasizes the multiplicative relationship among population (P), affluence or consumption (A), and technology (T) in creating impacts (I) to the environment. Dietz and Rosa (1994) reformulated the equation in stochastic terms to permit hypothesis testing and the inclusion of social structural factors, opening the way for a wide variety of systematic analyses. The STIRPAT formulation is:

$$I = aP^b A^c T^d e \quad (1)$$

where “ a ” is a scaling parameter, b , c , and d are parameters to be estimated, and e is the error term. Population (P) and affluence (A) are typically operationalized as total population size and GDP per capita. There is no widely accepted operationalized measure of technology (T), so in this formulation it is typically analyzed as part of the estimated residuals. We address this limitation here by including several variables that are indicators of technological infrastructure. Versions of this basic

framework have been used to assess a wide variety of environmental impacts (Cole and Neumayer 2004; Cramer 1998; Knight and Rosa forthcoming; Rosa et al., 2004; Shandra et al. 2004; Shi 2003; York 2007a, 2007b, 2008; York et al. 2003a, 2003b, 2003c). The parameters of the model are estimated using additive regression procedures once all continuous variables have been converted to logarithmic form. Logging such variables has the added advantage of making STIRPAT an ecological elasticity model where interpretation of the parameters is easy: each coefficient indicates the percentage change in the dependent variable (environmental impact) from a 1 percent change in the relevant independent variable, controlling for other contextual and structural variables in the model. A polynomial specification, typically a quadratic (i.e., X_i^2), is used to test for nonlinear relationships in logarithmic form between GDP per capita and emissions, and urbanization and emissions, since there is a considerable literature suggesting such relationships exist (Cavlovic et al. 2000; Ehrhardt-Martinez et al. 2002; Stern 2004).

To examine ground-level air pollutants stemming from social forces, we use data for three time periods (1990, 1995, and 2000) for all 126 nations for which data are available, including for our independent variables (see Table 1). Hence, our data permits the application of longitudinal models and more sophisticated analyses than can be done with a single cross-section analysis. We estimate a fixed-effects version of STIRPAT. To accomplish this, we convert all variables into natural logarithms and estimate the equation:

$$\ln(y_{it}) = B_1 \ln(x_{it1}) + B_2 \ln(x_{it2}) + \dots + B_k \ln(x_{itk}) + u_i + w_t + e_{it} \quad (2)$$

Here the subscript i represents each unit of analysis (nation) and the subscript t the time period, y_{it} is the dependent variable in original units for each nation at each point in time, x_{itk} represent the independent variables in original units for each nation at each point in time, B_k represents the elasticity coefficient for each independent variable, u_i is a nation-specific disturbance term that is constant over time (i.e., the nation specific y -intercept), w_t is a period specific disturbance term constant across nations, and e_{it} is the stochastic disturbance term specific to each nation at each point in time.

Hausman tests indicate that the random-effects versions of our models are misspecified, hence our preference for fixed-effects models. Nonetheless, below we compare the fixed-effects results with random-effects models and cross-sectional models. We also include period dummy variables to control for factors that are constant across nations but vary over time (w_t), like the international price of commodities such as oil. Thus, the fixed-effects model including period dummies is robust even when potentially there are omitted control variables. It, thereby, more closely approximates experimental conditions than most other statistical models.

Description of the Dependent Variables

Summary statistics for all variables in the models are presented in Table 2. The data on the four types of air pollutants, explained below, that we analyze are from the Emission Database for Global Atmospheric Research (EDGAR 2008). The Emission Database for Global Atmospheric Research is an information system under the joint project of the Mission of the Netherlands Environmental Assessment Agency, the Netherlands Organization for Applied Scientific Research, the European Joint Research Center-Institute for Environmental Sustainability, and the Max Planck Institute for Chemistry-Atmospheric Chemistry. EDGAR gathers and stores global emission inventories of direct and indirect greenhouse gases from anthropogenic sources including halocarbons and aerosols. The Emission Database for Global Atmospheric Research system provides global, regional, and national emissions data. The Emission Database for Global Atmospheric Research database comprises: fossil-fuel related sources; biofuel combustion; industrial production and consumption processes (including solvent use); agriculture and land use-related sources, including waste treatment; and

Table 1 • Percentage Change in Population and Number of Households between 1990 and 2000 for Nations in Analysis

<i>Nation</i>	<i>Change in Number of Households (%)</i>	<i>Change in Population (%)</i>
Albania	+10.37	-6.92
Algeria	+36.55	+20.45
Argentina	+21.84	+13.24
Armenia	+5.52	-13.05
Australia	+24.11	+12.23
Austria	+10.42	+3.90
Azerbaijan	+11.10	+12.43
Bahrain	+26.61	+36.32
Bangladesh	+30.27	+23.94
Belarus	+7.80	-1.81
Bolivia	+24.70	+24.71
Botswana	+38.58	+22.79
Bulgaria	+4.05	-7.55
Burkina Faso	+18.26	+32.34
Burundi	+32.86	+14.39
Cambodia	+33.97	+30.87
Cameroon	+47.34	+27.51
Canada	+24.51	+10.72
Central African Republic	+31.73	+25.93
Chad	+18.42	+35.69
Chile	+31.02	+16.94
China	+31.27	+11.28
Colombia	+35.82	+20.45
Congo, Democratic Republic	+45.83	+32.54
Cote d'Ivoire	+41.77	+32.22
Croatia	+6.11	-5.81
Czech Republic	+6.63	-0.87
Denmark	+7.96	+3.84
Djibouti	+58.39	+28.06
Dominican Republic	+35.05	+16.57
Ecuador	+42.44	+19.80
Egypt	+30.10	+20.86
El Salvador	+34.58	+22.90
Eritrea	+34.40	+17.07
Estonia	+11.45	-12.71
Ethiopia	+36.46	+25.63
Fiji	+18.46	+12.05
Finland	+10.66	+3.81
France	+11.52	+3.81
Gambia	+51.24	+40.64
Georgia	+0.82	-13.55
Germany	+6.85	+3.50
Ghana	+43.95	+28.35
Greece	+15.65	+7.45
Guatemala	+26.27	+25.56
Guinea	+33.04	+35.65
Guinea-Bissau	+21.70	+34.48
Guyana	+9.95	+2.01
Haiti	+26.09	+15.60
Honduras	+43.71	+32.01
Hungary	+2.71	-1.57
India	+25.68	+19.60

Table 1 • Percentage Change in Population and Number of Households between 1990 and 2000 for Nations in Analysis (Continued)

<i>Nation</i>	<i>Change in Number of Households (%)</i>	<i>Change in Population (%)</i>
Indonesia	+28.71	+15.77
Iran	+43.40	+17.03
Ireland	+18.68	+8.55
Italy	+10.29	+4.40
Jamaica	+7.72	+8.34
Japan	+16.87	+2.75
Jordan	+53.95	+53.22
Kenya	+53.98	+30.98
Korea, Republic	+26.79	+9.66
Kuwait	+16.39	+3.06
Kyrgyz Republic	+8.65	+11.13
Latvia	+4.77	-11.18
Lesotho	+28.50	+12.24
Lithuania	+14.09	-5.37
Macedonia	+12.95	+5.25
Madagascar	+31.57	+34.46
Malawi	-3.20	+21.70
Malaysia	+34.64	+28.87
Mali	+28.63	+30.96
Mauritania	+23.21	+30.25
Mauritius	+16.19	+12.29
Mexico	+34.50	+17.71
Moldova	+7.79	-2.05
Mongolia	+29.31	+13.87
Morocco	+28.13	+16.40
Mozambique	+8.45	+33.37
Namibia	+28.03	+35.54
Nepal	+32.04	+27.81
New Zealand	+20.81	+11.89
Nicaragua	+41.77	+24.26
Niger	+23.19	+39.07
Nigeria	+68.67	+29.86
Norway	+13.00	+5.88
Oman	+37.40	+32.50
Pakistan	+21.88	+27.87
Panama	+34.26	+22.36
Paraguay	+44.47	+26.73
Peru	+29.55	+19.30
Philippines	+35.34	+23.99
Poland	+8.26	+8.88
Portugal	+11.63	+3.33
Romania	+8.84	-3.29
Rwanda	+30.60	+13.08
Saudi Arabia	+42.81	+26.14
Senegal	+33.36	+29.65
Slovak Republic	+11.01	+2.00
Slovenia	+11.60	-4.46
South Africa	+16.19	+25.00
Spain	+11.40	+3.67
Sri Lanka	+18.25	+13.76

(continued)

Table 1 • Percentage Change in Population and Number of Households between 1990 and 2000 for Nations in Analysis (Continued)

<i>Nation</i>	<i>Change in Number of Households (%)</i>	<i>Change in Population (%)</i>
Sudan	+4.71	+26.23
Swaziland	+109.69	+35.71
Sweden	+10.60	+3.62
Switzerland	+16.14	+7.04
Syria	+38.71	+30.91
Tajikistan	+19.12	+16.13
Tanzania	+27.05	+32.52
Thailand	+29.51	+12.44
Togo	+38.79	+35.40
Trinidad and Tobago	+11.98	+5.72
Tunisia	+30.96	+17.28
Turkey	+38.60	+20.06
Uganda	+20.03	+36.89
Ukraine	+8.90	-5.23
United Arab Emirates	+41.89	+83.14
United Kingdom	+11.16	+3.79
United States	+15.55	+13.06
Uruguay	+12.10	+7.60
Uzbekistan	+19.86	+20.19
Venezuela	+36.50	+23.09
Vietnam	+32.09	+18.61
Yemen	+75.58	+48.41
Zambia	+23.02	+27.76
Zimbabwe	+43.22	+19.22
World	+24.97	+14.71

Table 2 • Summary Statistics for All Variables in Models

<i>Variable</i>	<i>Mean</i>	<i>Std. Dev.</i>	<i>Min.</i>	<i>Max.</i>
SO ₂	4.999	2.022	.531	10.445
NO _x	5.269	1.626	1.281	9.875
CO	7.529	1.598	3.640	11.456
NMVOG	5.844	1.603	1.792	9.885
Number of households	14.771	1.564	11.277	19.704
Average household size	1.504	.370	.727	2.439
Dependency ratio	-.379	.284	-1.063	.150
Urban population (%)	3.786	.588	1.686	4.587
GDP per capita	8.310	1.142	6.178	10.451
Agriculture (% GDP)	2.489	1.033	-1.035	4.054
Manufacturing (% GDP)	2.676	.523	.948	3.596
HH consumption exp. (% GDP)	4.194	.227	3.201	4.933
Gov. consumption exp. (% GDP)	2.642	.421	1.143	4.155
FDI stock (% GDP)	2.382	1.176	-4.643	4.880
Exports (% GDP)	3.387	.588	1.639	4.824
Imports (% GDP)	3.558	.512	1.533	4.807
Military personnel per capita	-5.400	.948	-7.985	-2.878
Expenditure per soldier	8.799	1.608	.006	12.282
Democracy	2.247	6.808	-10	+10

Notes: The summary statistics are for the pooled data representing 301 observations across 126 nations. All variables except democracy are in natural logarithmic form.

selected natural sources, including forest fires. Most data are from international statistical data sources and most emission factors are from international publications to ensure a consistent approach across countries. The Emission Database for Global Atmospheric Research, the flagship European environmental data center, provides the most comprehensive data available on these pollutants. These data are generally accepted as the most reliable available and are widely used by scientists (cf. Emmons et al. 2010; Park 2010). To date, the Emission Database for Global Atmospheric Research has compiled and released data for the years 1990, 1995, and 2000 for most nations of the world and these periods are the focus of our analyses. Each dependent variable is measured in thousands of metric tons of emissions per calendar year.

Sulfur dioxide (SO_2) is formed when fuel containing sulfur, such as coal and oil, is burned or when crude oil is converted into gasoline, or in the extraction of metals from ore. Most SO_2 emissions are due to fuel (particularly coal) combustion to generate electricity.

Nitrogen oxides (NO_x) is the generic term for NO and NO_2 that are emitted from a wide range of combustion sources. Typically, NO is the dominant gas emitted at the exhaust point, but NO cycles to NO_2 rapidly in the atmosphere due to the influence of photochemistry. NO_x is generated by fertilizer use and by the combustion of fuels at high temperatures as in motor vehicles, electrical utilities, and other industrial and commercial activities that burn fuels.

Carbon monoxide (CO), a toxic gas, is formed when fuel containing carbon is not burned completely. Its primary sources in the United States and many other nations are motor vehicle exhausts (~ 60 percent) and industrial processes, but it also stems from the combustion of biomass, such as in residential wood burning and forest fires (EPA 2010:6).

Volatile organic compounds (VOCs) are organic chemicals that vaporize at room temperature because of their vapor pressures. Methane (CH_4), a VOC and important greenhouse gas, is relatively inert in the atmosphere and plays a minor role in ground-level ozone formation. The term non-methane VOCs (NMVOCs) is sometimes used to differentiate other VOCs from methane, since they have different sources and different effects. Common sources of NMVOCs include motor vehicles, industrial processes, building and finishing materials (e.g., solvents, paints, and glues), and housekeeping and maintenance products.

Description of the Independent Variables

Data for all independent variables are from the World Bank (2007) except foreign direct investment, which comes from the United Nations (UN) Conference on Trade and Development (2011), and number of households, which comes from the UN Centre for Human Settlements (2001). The key demographic factors include number of households and average household size, which together decompose population and allow for a more subtle assessment of how population influences environmental impacts than has been done in previous studies. The UN Centre for Human Settlements (2001) provides the only reliable estimates of which we are aware for the number of households for most nations in the world. We had to interpolate the number of households for 1990 and 1995, since this source only reports the values for 1985 and 2000. We assumed that the number of households grew at the same rate from 1990 to 1995 as it did on average for the whole period of 1985 to 2000. Since the source also provides an estimate of the expected growth rate from 2000 to 2005, we averaged this rate with the assumed growth rate from 1990 to 1995 to get an estimate for the growth rate from 1995 to 2000. We then estimated the growth rate from 1985 to 1990 by setting it to counterbalance the estimated growth rate from 1995 to 2000, so that the three growth rates together (1985–1990, 1990–1995, and 1995–2000) are consistent with the measured average growth rate from 1985 to 2000. This approach, by allowing for changes in the growth rate (based on information for the projected growth rate from 2000–2005), gives slightly more refined estimates for the number of households at the three time periods included in our models than would be obtained by simply assuming that the growth rate from 1985–2000 was constant. Average household size was calculated by dividing total population (World Bank 2007) by the number of households.

We include urbanization (percentage of population living in urban areas) and the dependency ratio (ratio of people under 15 and over 64 years of age to those aged 15 through 64, the most economically productive sector of the population). Both variables have been included in other published analyses (e.g., York 2007a; York et al. 2003a). Since the effects found for them may be connected to household composition, our analyses allow an assessment of whether these factors have an effect independent of household size and number. We also include the quadratic of urbanization (i.e., urbanization squared) to test for a nonlinear relationship between urbanization and air pollution emissions (Ehrhardt-Martinez et al. 2002). To estimate the effects of economic development on air pollution, we include GDP per capita measured in purchasing power parity (in constant 2000 US\$) and its quadratic (i.e., GDP per capita squared) to test for a nonlinear (in log form) relationship between GDP per capita and air pollution emissions (Stern 2004).¹

To fine-tune the assessment of economic factors and to take into account predominant production technologies, we include a variety of other economic indicators. We use the percentage of GDP from the manufacturing sector to assess the effects of structural changes in the economy, such as the shift away from heavy industry toward services in more affluent nations. In the models for NO_x and CO, we also included the percentage of GDP from the agricultural sector, since agricultural chemicals contribute considerably to NO_x emissions while burning and deforestation contribute substantially to CO emissions. We include household consumption expenditures (percent GDP) and government consumption expenditures (percent GDP) to assess whether the type of spending in an economy affects pollution emissions. To control for connections to the global economy and the penetration of foreign capital (factors deemed important by world-system theorists), we include exports (percent GDP) and imports (percent GDP) as well as foreign direct investment (FDI) stocks (percent GDP). For the FDI analysis, we also include an interaction effect between FDI and GDP per capita, since world-systems analysts suggest that FDI affects nations in the Global South differently from those in the North. We use the World Bank's categorization of nations to construct the interaction term, where "high income" nations are coded 0, and all other nations 1. Thus we have two variables, "FDI stock (percent GDP)" and "FDI stock (percent GDP) for lower income," which is the multiplicative product of FDI stock and the binary variable. We also include two variables to assess the effects of militarization on the environment: military personnel per capita and government expenditures per soldier (see Jorgenson and Clark 2009).

Our final independent variable, democracy, is taken from a collection of measures developed by the Polity IV Project (2009), which has been prominently used by other sociologists (e.g., Kurzman and Leahey 2004). Specifically, we used the "POLITY2" measure of political regime that ranges from -10 to +10, created by subtracting an 11-point (0 through 10) autocracy scale from an 11-point democracy scale.² Since the potential effects of political regime on emissions likely take some time to unfold, we use a five-year average of the democracy measure—i.e., the value for 1990 is the average score from 1986 through 1990, for 1995 it is the average from 1991 through 1995, and for 2000 it is the average from 1996 through 2000. We name this indicator "democracy."

Results

The fixed-effects models presented below control for omitted factors that vary cross-nationally but are temporally invariant, such as geographic, climatic, and geological factors, as well as the effects of the historical legacy preceding the periods examined here (e.g., the era during which a nation began to industrialize). The models, therefore, control for characteristics unique to each

1. We centered the log of GDP per capita, by subtracting the sample mean (8.407), before squaring it to reduce collinearity between the log-linear term and the quadratic. Likewise, we centered the log of urbanization by subtracting its mean (3.835) before squaring.

2. With the POLITY2 measure, cases where the government is in transition are prorated across the span of the transition. In cases where there is anarchy, a value of 0 is used.

nation, factoring out, for example, temporally invariant effects of being a post-Soviet state. Likewise, the models control (via the period dummies) for cross-sectionally invariant factors that vary over time such as international commodity prices. Thus, these models focus on *change* over time within nations, not on cross-sectional differences or on general average global trends.

All models that include percent urban population and GDP per capita are first estimated including a quadratic form to test for a nonlinear relationship. If a quadratic term was not significant, we reestimated models excluding that quadratic to make the interpretation easier. We present the “within R^2 ” indicating the proportion of variance within nations over time that is explained.

We first present a basic STIRPAT model that includes the household variables and GDP per capita (see Table 3). In addition to noting two-tailed significance tests, we also note one-tailed tests, since the hypotheses clearly predict the direction for our key variables, the expectation being that the household variables will have positive effects on pollution emissions. The results show that number of households has a positive and significant effect on all pollutants, although for CO the effect is only significant with a one-tailed test. The coefficient for average household size is positive for all pollutants, but significant only for SO_2 , NO_x , and NMVOCs. In all models, the number of households has a larger coefficient than average household size, a point developed below. For SO_2 , NO_x , and NMVOCs the quadratic for GDP per capita was not significant, so we present the model with only the log-linear term. For SO_2 , NO_x , and NMVOCs, GDP per capita has a positive and significant coefficient, although for the latter the coefficient is only significant with a one-tailed test. For CO the quadratic term for GDP per capita was significant, so we present the model with both GDP per capita terms. The log-linear GDP per capita coefficient is positive, whereas the quadratic is negative, which generates an environmental Kuznets curve with a turning point at approximately \$6,300 per capita.

Table 4 presents the saturated models, which include all variables in the previous models but add the age dependency ratio, urbanization, the percentage of GDP from the manufacturing sector, which is the most pollution intensive sector of the economy, household consumption expenditures (percent GDP), government consumption expenditures (percent GDP), foreign direct investment stocks (percent GDP) and the FDI interaction term for lower income nations,³ exports (percent GDP), imports (percent GDP), military personnel per capita, expenditures per soldier, and the democracy variable. Since agricultural chemicals are a major source of NO_x and land burning and other practices associated with farming are a substantial source of CO, we also include the percentage of GDP in the agricultural sector in the models for these two pollutants. In the SO_2 model the coefficients for number of households and average household size are significant, but none of the other factors are. In the NO_x model the coefficients for number of households and average

Table 3 • Basic Fixed-Effects Models for the Emissions of Each of Four Pollutants: SO_2 , NO_x , CO, and NMVOC

	SO_2 Coef. (SE)	NO_x Coef. (SE)	CO Coef. (SE)	NMVOC Coef. (SE)
Number of households	3.356 (.470)***	1.667 (.450)***	1.027 (.575)†	1.000 (.385)**
Average household size	2.197 (.488)***	1.450 (.467)**	.575 (.613)	.915 (.400)*
GDP per capita	.425 (.208)*	.594 (.199)**	.149 (.241)	.303 (.170)†
GDP per capita ²			-.216 (.109)*	
Within R^2	.362	.381	.115	.236
N (nations)	301 (126)	301 (126)	301 (126)	301 (126)

Notes: All variables except democracy are in natural logarithmic form. All models were first estimated with a quadratic for GDP per capita. If the quadratic coefficient was not significant, we report the results from the model reestimated excluding the quadratic term.

* $p < .05$ ** $p < .01$ *** $p < .001$ (two-tailed tests)

† $p < .05$ (one-tailed test)

3. The lower income dummy variable is not in the model, since it is perfectly collinear with the nation specific intercepts from the fixed-effects model.

Table 4 • Saturated Fixed-Effects Models for the Emissions of Each of Four Pollutants: SO₂, NO_x, CO, and NMVOC

	SO ₂ Coef. (SE)	NO _x Coef. (SE)	CO Coef. (SE)	NMVOC Coef. (SE)
Number of households	2.906 (.589)***	.921 (.554)†	.969 (.667)	.701 (.475)
Average household size	1.992 (.569)***	.958 (.537)†	.575 (.656)	.395 (.459)
Dependency ratio	.016 (.472)	-.591 (.445)	.196 (.536)	.528 (.381)
Urban population (%)	-.106 (.358)	-.070 (.336)	.177 (.404)	.205 (.289)
GDP per capita	.320 (.249)	.550 (.248)*	.441 (.299)	.258 (.200)
Agriculture (% GDP)		.311 (.135)*	.118 (.163)	
Manufacturing (% GDP)	.140 (.118)	.241 (.111)*	.143 (.133)	.233 (.095)*
HH consumption expenditures (% GDP)	-.141 (.381)	-.061 (.357)	.368 (.430)	.083 (.307)
Gov. consumption expenditure (% GDP)	.154 (.130)	.259 (.122)*	.190 (.147)	.136 (.105)
FDI stock (% GDP)	-.108 (.094)	-.039 (.088)	-.160 (.106)	-.075 (.076)
FDI stock (% GDP) for lower income	.077 (.090)	.031 (.085)	.176 (.103)†	.088 (.072)
Exports (% GDP)	.071 (.184)	-.035 (.173)	.101 (.208)	-.088 (.149)
Imports (% GDP)	-.025 (.192)	-.043 (.180)	-.308 (.217)	-.091 (.155)
Military personnel per capita	.036 (.075)	.024 (.070)	.003 (.084)	-.019 (.060)
Expenditure per soldier	-.030 (.031)	.020 (.029)	.016 (.034)	.019 (.025)
Democracy	.011 (.009)	.011 (.008)	.013 (.010)	.013 (.007)†
Within R ²	.407	.452	.153	.311
N (nations)	301 (126)	301 (126)	301 (126)	301 (126)

Notes: All variables except democracy are in natural logarithmic form. All models were first estimated with quadratics for urban population (percent) and GDP per capita. If either or both of the quadratic coefficients were not significant, we report the results from the model reestimated excluding the quadratic term or terms.

* $p < .05$ ** $p < .01$ *** $p < .001$ (two-tailed tests)

† $p < .05$ (one-tailed test)

household size are positive and significant using one-tailed tests. GDP per capita has a positive and significant effect, as do manufacturing, agriculture, and government consumption. For CO, none of the factors have a significant effect, except FDI stock for lower income nations. In the NMVOC model, only manufacturing and democracy have significant effects, although the latter only with a one-tailed test.

There are some limitations to the saturated models (Table 4). The large number of variables, including some moderately correlated with one another, lead to potential multicollinearity problems. The standard test for multicollinearity, the variance inflation factor,⁴ shows that in the saturated models the highest average variance inflation factor for any model is 4.25, while the highest variance inflation factor for a single factor is 13.99. While William Greene (2000) suggests that values under 20 are not necessarily problematic and Robert O'Brien (2007) shows that even VIF values considerably higher than 20 may not be especially problematic, particularly with a reasonably large sample, it is generally considered desirable to have VIF values below 10. While multicollinearity does not bias coefficient estimates or significance tests, it increases the standard error, making it harder to reject the null hypothesis. This means that some factors having an effect on the dependent variable may not register as statistically significant (a type II error). Thus, although problems with multicollinearity in our models appear to be fairly modest, they are not trivial. This degree of multicollinearity likely explains why some of the factors that are significant

4. Since variance is parsed in a complex fashion in fixed-effects models, making a single simple variance inflation factor measure unfeasible, we ran the same models presented here in a simple ordinary least squares regression model with all the data pooled to assess the variance inflation factor.

in the basic models (Table 3) are not significant in the saturated models (Table 4). The basic models have the virtue of parsimony and very low multicollinearity, with a highest variance inflation factor of 1.92, while the saturated models have the virtue of reducing potential bias due to omitted control variables. We, therefore, take both sets of models into account in interpreting our findings.

The number of households and average household size clearly appear to be important factors. The number of households had a positive and significant effect in the basic models on all pollutants. Similarly, average household size had a positive significant effect in the basic models on all pollutants except CO. In the saturated models, the coefficients for both household variables remained positive and broadly similar in value to those in the basic models for all four pollutants. However, in the CO and NMVOC models neither household coefficient is significant, and in the NO_x model the coefficients are only significant at the .05 level with one-tailed tests. The reduced effects of the household variables in the saturated models are likely due in good part to the multicollinearity problems introduced with the additional variables, since the sign of the coefficients remains the same as in the basic models. Furthermore, the magnitude of the household coefficients is still substantial in the saturated models, except for average household size in the NMVOC model. The change in the size of some of the coefficients of the household variables between the basic and the saturated models also suggests that part of their effects apparent in the basic models is due to the association of household size and number with factors added in the saturated models. However, we note that for SO₂, none of the variables added in the saturated models was significant and that the size and significance of the coefficients for both household variables is very similar between the basic and saturated models, suggesting that for this pollutant the basic model accurately captures the relationship between households and emissions. The basic (Table 3) and saturated (Table 4) models point to the same general conclusions about the effect of number of households and average household size; namely that the number of households and average household size have clear effects on SO₂ and NO_x emissions, but their effects on the other pollutants are less certain.

Our choice of splitting the population variable into the number of households and average household size was based on the presumption that the split would allow us to assess whether the distribution of population over households has an effect on air pollution emissions. Overall the results suggest that the number of household has a more substantial effect on pollution emissions than the average number of people per household. This is clear when comparing the average difference between the coefficients for number of households with those of average household size. If pollution emissions are not dependent on how the population is distributed over households (e.g., many households with few inhabitants versus a few households with many inhabitants) the coefficients for number of households and average household size should be approximately equal, indicating that population growth has the same effect on emissions regardless of whether it occurs primarily due to changes in number of households or average household size. Alternatively, significantly different coefficients suggest that the way that population is distributed over households matters for pollution emissions.

To assess these alternatives required a test of the entire collection of retained coefficients, to determine if there is a pattern across all eight models. The coefficient for number of households was larger than average household size in 7 of the 8 models. A result this extreme (larger coefficient in 7 of 8 models) would occur by chance only once in approximately 28 instances and the average difference between the coefficients of .436 is statistically significant.⁵ The difference is particularly striking for SO₂ emissions (3.356 versus 2.197 in the basic model), a significant difference indicated by an *F*-test ($p = .020$). Thus, it is reasonable to conclude that SO₂ emissions, and perhaps emissions of other pollutants, are affected by how population is distributed across

5. This is based on a calculation from the binomial distribution, where the null hypothesis is that the likelihood one coefficient will be larger than the other is .50 (i.e., equally likely to go either way). The likelihood that in seven or more out of eight models the number of households would have a larger coefficient than average household size by chance is .035 (i.e., approximately 1 out of 28), statistically significant at the .05 level (one-tailed test). We also used a paired *t*-test to assess the

households, where a change in the number of households has a somewhat greater effect on pollution emissions than a change in average household size.

To appreciate the importance of this finding, consider the coefficients from the basic model for SO₂, where the coefficient for number of households is 3.356 and for average household size 2.197 (see Table 3). Based on these coefficients we would expect that if in a hypothetical nation population grew by 1 percent, but this growth was due to a 1 percent increase in the number of households, with average household size remaining unchanged, SO₂ emissions would be expected to increase by 3.356 percent, all else being equal. In contrast, if this 1 percent population growth occurred entirely due to a 1 percent increase in average household size while the number of households remained constant, SO₂ emissions would be expected to increase by only 2.197 percent, all else being equal. Clearly, the different effects of changes in the number of households and average household size have important implications for pollution emissions.

Another variable of particular interest is GDP per capita, since the effects of economic growth on the environment have been subject to intense debate. As found in the basic models, GDP per capita has a consistently positive effect on the emissions of all pollutants examined here except CO, for which we found an environmental Kuznets curve. However, in the saturated models, while the coefficient is positive for all pollutants, it is only significant for NO_x. This suggests that the association between economic growth and pollution is not singularly due to economic growth itself, but in part to various features associated with economic growth that are to some degree captured by the additional control variables.

One other issue to address is the general fit of the models. Variance in SO₂ and NO_x emissions is explained reasonably well by the factors we identify, with the household variables consistently having significant effects. The models fit less well for NMVOCs and fairly poorly for CO. This is perhaps not entirely surprising since SO₂ and NO_x emissions are closely tied to fossil fuel consumption and industrial processes, which have been shown to be closely connected with demographic and economic factors (York 2007a, 2007b). In contrast, while CO emissions stem in part from industrial processes and fossil fuel combustion, they also are generated in substantial quantities by natural processes, such as forest fires (which, of course, may also be affected by humans). Thus, the multiple sources, some of which are natural, for CO emissions will add noise to the models, reducing the fit.

To test the robustness of our results, we have also estimated these models using a variety of other methods. We have estimated models assessing whether there is an interaction effect between time period and GDP per capita but we found no evidence for a significant effect. We also estimated random-effects versions of all models, finding results broadly similar to the fixed-effects results. The coefficient for the number of households is significant for all eight models (the basic and saturated models for all four pollutants) and the average household size variable is significant for all models except the saturated model for CO. The greater number of significant findings is unsurprising since random-effects models have more statistical power than fixed-effects models. However, the difference between the coefficients for number of households and average household size is less pronounced in the random-effects models than in the fixed-effects models.

Since, as explained above, we imputed the number of households for 1990 and 1995 based on values for 1985 and 2000 and trends in the growth rate, we estimated other models to assess whether our results are dependent on these imputations. First, we estimated a cross-sectional version of all models for the year 2000, for which none of the data are imputed. Regarding households, the results of these models are fairly similar to the random-effects models. The coefficient for number of households is significant in every model and the coefficient for average household size is significant in all models except the basic model for NMVOCs and the saturated models for SO₂ and CO. As with the random-effects models, the difference in magnitude between the coefficients for number of households and average household size is not as pronounced as in the fixed-effects

average difference in the eight pairs of household coefficients from the models. The coefficient for number of households was on average .436 larger than the coefficient for household size (1.568 versus 1.132), and this difference was significant at the .01 level (one-tailed test).

models. However, the overall pattern of significant findings, where the coefficient for number of households is significant in all models, whereas the coefficient for average household size is significant for only 5 out of the 8 models, is consistent with the pattern in the fixed-effects models where number of households appears to have a more pronounced influence on pollution emissions than average household size. To further assess the effects of imputing the household variables for some years, we estimated fixed-effects models that included only the years 1990 and 2000, thereby using only one year with imputed values, which is close to the first year of measured values (1985). The results from these models are very similar to those presented in Tables 3 and 4.

Based on these various assessments, we believe our principal finding regarding the importance of the number of households as a key factor influencing air pollution emissions, particularly those of SO₂, is robust and not an artifact of our methods or imputation of data.

Discussion and Conclusion

Our results suggest that demographic factors, particularly household number and size, influence air pollution emissions at the national level. Consistent with the fundamental predictions of structural human ecology, population is clearly an important factor producing environmental impacts. However, what we have been able to show here is a deepening of our understanding of that relationship with a more nuanced measure of population. We found that changes in the number of households generally have a greater effect on pollution emissions, particularly those of SO₂, than changes in average household size. In short, population growth is an important force behind pollution emissions, but the way it is distributed across households matters.

It is important to recognize that nations where population growth rates are the highest are not necessarily the nations where air pollution emissions are increasing most rapidly. Two points are worth stressing. First, there is a great disparity in rates of consumption and production, and consequent pollution emissions, per household and per capita across nations. Since pollution emissions per household are generally much higher in affluent nations than in poor nations, a modest growth rate in number of households in rich nations may lead to more pollution emissions in absolute terms than a high growth rate in number of households in less affluent nations. This is because total emissions are the multiplicative product of the number of households and pollution emissions per household. This functional relationship is captured well with the multiplicative structure of the STIRPAT model.

To illustrate this point we can look at the year 2000 where per household emissions in the United States for SO₂, NO_x, CO, and NMVOCs were respectively approximately 2, 5, 3, and 5 times those in China and 18, 10, 2, and 4 times those in Bangladesh. This disparity is all the more striking when we take into account that the average number of people per household is greater in China (3.50) and especially in Bangladesh (5.35) than in the United States (2.64). Therefore, the effect of household growth patterns on the *absolute* quantity of pollution emissions depends on the level of affluence in nations where growth occurs.

Second, although population growth rates are low in more affluent nations, the number of households is growing much faster in them than is total population, since household size is declining rapidly in these nations. In fact, from 1985 to 2000, the average annual growth rate in the number of households in affluent nations was more than three times higher than the growth rate in population (1.3 percent versus .4 percent). Thus, while between 1985 and 2000 the annual population growth rate in less developed nations was more than four times higher than in more developed nations (1.8 percent versus .4 percent), the annual growth rate in number of households was only two times higher (2.7 percent versus 1.3 percent) (UN Centre for Human Settlements 2001:268, 274). Since growth in number of households has a somewhat greater effect on pollution emissions, most notably SO₂ emissions, than growth in average household size, the growing number of households in rich nations may have greater impacts on the global environment than

population growth in poor ones. In sum, our analysis points to the importance of the distribution of population across households over total population in examining environmental effects.

We also analyzed several other factors examined in the sociological literature. However, since these were not our focus, our analysis is not definitive on these issues. Economic growth is clearly associated with pollution emissions, although this association is less pronounced when controlling for other factors, suggesting that GDP per capita is an indicator of processes that are not reducible to economic production and consumption alone. In all cases this association is a consistently positive one, except in the case of CO emissions where there are suggestions of an environmental Kuznets curve. Although we included a variety of other factors in our models, most do not appear to have clear effects on pollution emissions. However, some measures of the structure of the economy do appear to matter. The share of national GDP from agriculture and manufacturing, as well as government consumption expenditures, are positively associated with NO_x emissions, and manufacturing is also positively associated with NMVOC emissions.

Overall, our results support the fundamental conceptualization underpinning the structural human ecology perspective: demographic and economic factors are the primary direct forces behind anthropogenic environmental change. Changes in number of households, average household size, and the economy account for much of the change in pollution levels over time. However, our models, aimed at explaining how demographic and economic factors influence the environment, do not address the factors that drive demographic and economic change. Political factors and the structure of the world system are likely forces influencing the economy and demographic patterns, including the structure of households (Dunaway 2001). Likewise, gender relations have clear and substantial effects on household structure and fertility rates (Cohen 1995; Dunaway 2001), as well as exerting considerable influence on the economy. Democracy also influences demography and economics. Thus, our results do not suggest that political economy, democracy, and other factors are unimportant to the environment, since there are good reasons to believe that they are. But, insofar as political, social, and cultural factors influence environmental conditions, for the most part, they do so indirectly, through their connection with demographic and economic processes. It is unlikely that environmental sustainability can be achieved without addressing this larger sequence of relationships.

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