Effects of Income and Urban Form on Urban NO$_2$: Global Evidence from Satellites

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**Supporting Information**

ABSTRACT: Urban air pollution is among the top 15 causes of death and disease worldwide, and a problem of growing importance with a majority of the global population living in cities. A important question for sustainable development is to what extent urban design can improve or degrade the environment and public health. We investigate relationships between satellite-derived estimates of nitrogen dioxide concentration (NO$_2$, a key component of urban air pollution) and urban form for 83 cities globally. We find a parsimonious yet powerful relationship (model $R^2 = 0.63$), using as predictors population, income, urban contiguity, and meteorology. Cities with highly contiguous built-up areas have, on average, lower urban NO$_2$ concentrations (a one standard deviation increase in contiguity is associated with a 24% decrease in average NO$_2$ concentration). More-populous cities tend to have worse air quality, but the increase in NO$_2$ associated with a population increase of 10% may be offset by a moderate increase (4%) in urban contiguity. Urban circularity (“compactness”) is not a statistically significant predictor of NO$_2$ concentration. Although many factors contribute to urban air pollution, our findings suggest that antileapfrogging policies may improve air quality. We find that urban NO$_2$ levels vary nonlinearly with income (Gross Domestic Product), following an “environmental Kuznets curve”; we estimate that if high-income countries followed urban pollution-per-income trends observed for low-income countries, NO$_2$ concentrations in high-income cities would be $\sim 10 \times$ larger than observed levels.

INTRODUCTION

Urban air pollution is responsible for an estimated 1 million deaths annually, or approximately 17% of environmentally related deaths in low- and middle-income countries and 81% in high-income countries. In 2008, for the first time in history, urban dwellers outnumbered rural dwellers; in coming decades, urban populations are expected to double while rural populations remain constant or decline. In recent decades, urban air quality has improved for many pollutants in developed countries, but declined in most developing countries for reasons that include rapid urban growth, strained transportation infrastructure, increased congestion and automobile ownership, and lack of effective emission control policies. Motor vehicles are a major contributor to urban air pollution. For instance, motor vehicles account for approximately half (53%) the emissions of nitrogen oxides (NO$_x = NO + NO_2$) in U.S. urban areas (based on the U.S. EPA National Emissions Inventory [http://www.epa.gov/ttn/chief/emch/index.html#2005] and urban area boundary files from the 2000 U.S. Census [http://www.census.gov/geo/www/ua/ua_bdfile.html]). Strategies for reducing vehicular emissions include changing vehicles, fuels, or vehicle activity level (e.g., annual average travel-distance per vehicle). Vehicle activity level is correlated with the size, shape, and layout of a neighborhood or city—i.e., its urban form. For example, evidence suggests that daily vehicle travel distances are less for residents of denser urban areas than for residents of less dense areas; in high-density areas, on average, origins and destinations are closer together, mass-transit is more available, and disincentives to driving, such as congestion and parking fees, are greater. This observation implies that increasing population density may decrease vehicle-kilometers traveled, reduce motor vehicle emissions, and consequently, improve air quality. More densely populated and geometrically compact and contiguous cities might therefore be expected to have reduced vehicle emissions and cleaner air.

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However, increasing population density with the aim of reducing vehicle emissions creates a counterintuitive potential hazard: even if emissions decline, air pollution concentrations and population exposure may worsen since people and their vehicles’ emissions are closer together. Shifts in urban form could thus reduce vehicle emissions yet increase primary pollutant concentrations. The net effect of high-versus low-density development on air quality is thus a balance of competing changes in emissions and atmospheric dilution.

In addition to the emission—dilution trade-off, the wealth of a city may influence its air quality. The environmental Kuznets curve (EKC) suggests that rising income increases pollution when per capita gross domestic product (GDP) is low, but decreases pollution when per capita GDP is high. This relationship is often attributed to the transition of a society from agrarian to industrialized and finally to a service economy. A related explanation involves the competing effects of scale and technology: as a developing economy experiences rapid growth, it increases output and consequently increases emissions; economic growth leads to technological progress, which allows cleaner new technologies to replace dirtier obsolete technologies, thus improving environmental quality. This phenomenon occurs over long periods of time for a single country, but it is also observed in multicountry cross-sectional analyses. The EKC hypothesis holds in many cases (especially for urban air pollution) but it is not universal.

Here we employ satellite measurements of nitrogen dioxide (NO₂, a key component of urban air pollution) from the Ozone Monitoring Instrument (OMI) and a global data set of 83 urban areas (Figure 1A) to explore the relationship between urban form and air pollution concentrations. We also examine relationships between income and satellite-estimated air pollution concentrations. Most prior investigations exploring the relationship between urban form and air quality have been modeling studies, relying on projected growth and land use scenarios to model air quality outcomes for specific cities. The few prior empirical studies generally focus on a single country and are limited to developed countries where high quality atmospheric and land use data are available. We present the first study using satellite measurements to explore the urban form–air pollution relationship for a stratified global sample of cities.

Although NO₂ is mainly produced in the atmosphere from photochemical oxidation of directly emitted nitric oxide (NO), the time scale for that transformation is short (minutes), so that NO₂ concentrations are essentially a marker for combustion-related emissions. Major sources of combustion-related emissions in urban areas are transportation, power generation, and industrial processes. Biomass burning can also contribute significantly to combustion emissions in nonurban regions (e.g., wildfires and human-initiated burning for land clearing) and developing countries (e.g., cooking and heating). NO₂ is linked to numerous adverse health effects including lung cancer, cardiopulmonary mortality, and type 2 diabetes. NO₂ is environmentally important as a marker for combustion emissions, as a precursor to the formation of ground-level ozone and particulate matter, because it has direct health effects, and as a cause of acid rain. NO₂ is a criteria pollutant regulated in the U.S. Clean Air Act. Here we show quantitatively that urban design can influence NO₂ concentrations, and demonstrate that urban NO₂ levels around the world track the wealth of the city in a nonlinear way and according to an EKC.

**METHODS**

While high quality, in situ measurements of urban air pollution are conducted regularly and are publicly available for many developed countries, such data are lacking for most developing countries. In contrast, satellite measurements offer near-global coverage using a uniform methodology. Data quality is consistent across cities, regions, and countries, and devoid of the political biases sometimes observed for in situ measurements. OMI provides daily measurements of NO₂ atmospheric column abundance. We derive daily surface concentrations using NO₂ surface-to-column ratios from a global chemical transport model.
Table 1. Summary Statistics among the 83 Cities

<table>
<thead>
<tr>
<th></th>
<th>mean</th>
<th>SD*</th>
<th>GM#</th>
<th>GSD$</th>
<th>interquartile range</th>
</tr>
</thead>
<tbody>
<tr>
<td>arithmetic mean NO₂ (ppb)</td>
<td>2.0</td>
<td>2.6</td>
<td>1.0</td>
<td>3.4</td>
<td>0.41–3.0</td>
</tr>
<tr>
<td>population (million)</td>
<td>2.7</td>
<td>3.8</td>
<td>1.3</td>
<td>3.0</td>
<td>0.56–2.8</td>
</tr>
<tr>
<td>income (US$)</td>
<td>$9,600</td>
<td>$10,000</td>
<td>$5,400</td>
<td>3.3</td>
<td>$2,300–$18,000</td>
</tr>
<tr>
<td>contiguity index</td>
<td>0.71</td>
<td>0.20</td>
<td>0.67</td>
<td>1.4</td>
<td>0.59–0.89</td>
</tr>
<tr>
<td>compactness index</td>
<td>0.35</td>
<td>0.10</td>
<td>0.33</td>
<td>1.4</td>
<td>0.27–0.43</td>
</tr>
<tr>
<td>harmonic mean dilution rate (m² s⁻¹)</td>
<td>2,600</td>
<td>2,600</td>
<td>1,500</td>
<td>3.1</td>
<td>520–4,300</td>
</tr>
</tbody>
</table>

* Standard deviation. # Geometric mean. $ Geometric standard deviation, unitless.

Table 2. Linear Regression Model for Logarithm of Mean Urban NO₂

|                          | coefficient | std. error | P < |t| | $Δ$ (1 – SD 1) | $Δ$ (1 – SD i) |
|--------------------------|-------------|------------|-----|---|----------------|----------------|
| _constant_               | –2.4        | 0.47       | <0.001 |   | --             | --             |
| income (US$)             | $6.5 \times 10^{-5}$ | $1.7 \times 10^{-5}$ | <0.001 |   | --             | --             |
| (income)                 | –1.1 \times 10^{-9} | 5.5 \times 10^{-10} | 0.05 | -22% | -22%          | -22%          |
| log (population)         | 0.41        | 0.074      | <0.001 | 62% | -38%          | -38%          |
| contiguity               | –0.58       | 0.19       | 0.004 | -24% | 31%           | 31%           |
| compactness              | 0.19        | 0.37       | 0.62 | 4.6% | -4.4%         | -4.4%         |
| harmonic mean dilution rate (m² s⁻¹) | –$4.6 \times 10^{-5}$ | $1.5 \times 10^{-5}$ | 0.003 | -24% | 31%           | 31%           |

* Change in surface NO₂ concentration for a one standard deviation increase/decrease from mean value while all other independent variables are held at mean values. For income: percent change for a one standard deviation increase/decrease from the peak NO₂ value (income = $29,600) while all other independent variables are held at mean values.

[GEOS-Chem, see Supporting Information (S1) for details] for a 3-h window (12:00–15:00 local time) corresponding to satellite overpass time. Figure 1A shows global NO₂ surface concentrations derived in this way from the OMI measurements, averaged over three years (2005–2007) and for visual display gridded to 0.1° × 0.1° (∼11 × 11 km² at the equator) resolution. OMI-derived NO₂ surface estimates are typically lower than 24-h average in situ measurements; reasons include spatial averaging from the satellite pixel and GEOS-Chem model, chemical interferences for certain in situ NO₂ measurements, and the diurnal cycle of NO₂ in surface air. Lamsl et al. demonstrated that the approach employed here to derive surface NO₂ concentrations from the satellite data gives values that are well-correlated with in situ observations.

To understand and quantify the impact of urban form and income on air pollution, we use data from the World Bank’s Urban Growth Management Initiative to define urban extent, calculated as the ratio of built-up area to total built-up area of a city. The compactness index is a measure of the circularity of the main built-up area of a city, calculated as the ratio of built-up area to total buildable area (areas without bodies of water or extreme slopes) within a circle surrounding the main built-up area of the city. The urban form characteristics we use from this data set represent a subset of the dimensions typically used to classify urban form; other urban form characteristics (e.g., land use mix, road network density, and centrality with respect to population and/or employment) are not included in this analysis because they are not available at a global scale. For a recent discussion of satellite-based estimates of land use, see Potere et al. Figure 1B illustrates contiguity and compactness using four cities in the study. We employ a meteorology metric (harmonic mean of the dilution rate at overpass time; dilution rate is the product of wind-speed and mixing height) to account for the influence of atmospheric dilution on pollution concentrations in each city.

Three-year annual-average surface mixing ratios for NO₂ derived from the OMI satellite measurements were interpolated to a 0.1° × 0.1 km² grid of built-up area for each city. We computed four measures (arithmetic mean, median, 90th percentile, and concentration-weighted mean) of NO₂ in each urban area; in each case, concentrations were log-normally distributed among cities. Arithmetic mean NO₂ mixing ratios vary from 0.07 to 16 ppb for the 83 cities, with an overall mean (standard deviation) of 2.0 (2.6) ppb and geometric mean (geometric standard deviation) of 1.0 ppb (3.4). Figure 1C illustrates built-up area and NO₂ concentrations for one of the 83 cities. Summary statistics for variables in the core model are provided in Table 1; summary statistics for all variables are provided in Table S1.

RESULTS AND DISCUSSION

We constructed a linear regression model (Table 2) for the logarithm of arithmetic mean NO₂ concentration in each city to determine its dependence on the urban characteristics. The resulting model captures more than 60% of the variability in the dependent variable ($R^2 = 0.63$, see Figure S1). Given the small number of parameters in the model and the variability in air pollution concentrations, the model provides a reasonable explanation for the observed variation in NO₂ concentrations.
pollution levels, the model offers a simple yet powerful description of underlying trends in the data. Figure 2 presents model-derived relationships between the dependent and independent variables. Employing mean values for all parameters (geometric mean for population) yields a concentration of 1.0 ppb.

We find that population has the single strongest effect on urban NO$_2$ levels and their differences among cities. Using mean values for the independent variables, a one geometric standard deviation population increase, 3.1 million people, would raise NO$_2$ concentrations by 62% (0.34-unit; on average, 48%) above baseline projected levels at the upper end of the income distribution. The NO$_2$–income curve in Figure 2A can also be interpreted to define, in a globally integrated sense, a transition point in advanced urban development when cities start to become less polluting with increased economic growth. The ~$30,000 peak, derived here based on NO$_2$ concentrations, is broadly consistent with reported transition points derived using per capita NO$_2$ emission estimates, but higher than for other air pollutants previously studied (see Table 3).

Figure 2F shows a linear projection based on the model relationship between income and surface NO$_2$ concentrations for the lowest 50th percentiles of cities by income. This finding suggests a nonlinear relationship between pollution concentrations and urban economic development. The NO$_2$–income curve in Figure 2A can also be interpreted to define, in a globally integrated sense, a transition point in advanced urban development when cities start to become less polluting with increased economic growth. The ~$30,000 peak, derived here based on NO$_2$ concentrations, is broadly consistent with reported transition points derived using per capita NO$_2$ emission estimates, but higher than for other air pollutants previously studied (see Table 3).

To explore further the differences between developed and developing countries, we create “dummy” variables to define two income groupings using the World Bank’s economic classification (based on GDP per capita): a four-level grouping (low, middle-low, middle-high, and high income) and a two-level grouping (high income; not high income). Neither grouping was selected using a backward stepwise multiple linear regression ($p < 0.1$) suggesting the most energy-efficient, or pollution-efficient, urban form. Contiguity and compactness are not well correlated (in our data set, $R^2 = 0.03$). Employing instead a multiple linear regression that excludes contiguity degrades the overall model performance ($R^2 = 0.59$) and the significance of the compactness index ($p = 0.09$), further indicating that compactness is not a proxy for contiguity. Likewise, population density was not identified in the model as statistically significant ($p = 0.12$), nor as providing an improvement to model performance ($R^2$).

We find a strong relation between income and air pollution across the 83 global cities (Figure 2A), consistent with the inverse “U” shape of the EKC. The peak occurs at approximately US $30,000 per capita GDP. Starting at this peak and employing mean values for all other independent variables, a 1-SD increase or decrease in per capita GDP yields a 22% reduction in NO$_2$ concentrations. This finding suggests a nonlinear relationship between pollution concentrations and urban economic development. The NO$_2$–income curve in Figure 2A can also be interpreted to define, in a globally integrated sense, a transition point in advanced urban development when cities start to become less polluting with increased economic growth. The ~$30,000 peak, derived here based on NO$_2$ concentrations, is broadly consistent with reported transition points derived using per capita NO$_2$ emission estimates, but higher than for other air pollutants previously studied (see Table 3).

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### Table 3. Transition Points for Air Pollution Environmental Kuznets Curve Studies

<table>
<thead>
<tr>
<th>Income Level</th>
<th>Suspension (sulfur dioxide)</th>
<th>Particulate (particulate matter)</th>
<th>Carbon (carbon monoxide)</th>
<th>Nitrogen (nitrogen oxides)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>ref 47 9,100</td>
<td>ref 48 14,200</td>
<td>ref 49 5,400</td>
<td>ref 50 6,600</td>
</tr>
<tr>
<td>Middle-low</td>
<td>ref 17 5,400</td>
<td>ref 49 5,400</td>
<td>ref 51 4,900</td>
<td>ref 51 4,900</td>
</tr>
<tr>
<td>Middle-high</td>
<td>ref 47 9,100</td>
<td>ref 48 14,200</td>
<td>ref 49 5,400</td>
<td>ref 50 6,600</td>
</tr>
<tr>
<td>High</td>
<td>ref 17 5,400</td>
<td>ref 49 5,400</td>
<td>ref 51 4,900</td>
<td>ref 51 4,900</td>
</tr>
<tr>
<td>This work</td>
<td>$29,600</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Adapted from Barbier.46 Values are in year-1995 US dollars using GDP implicit price deflator method.
that the income variable employed in the main results above provides a reasonable measure of income/development.

Daytime chemical removal of atmospheric NO2 is governed by sunlight, yielding a latitudinal gradient in NO2 concentrations. The absolute value of latitude is correlated with the logarithm of NO2 \( (R^2 = 0.37) \) for the cities in our analysis. However, the latitudinal dependence is complicated by the fact that the majority of developed countries are located in Northern midlatitudes. To explore the effect of latitude on our results we first calculate the NO2 latitudinal gradient over the open ocean (method: longitudinally averaged surface NO2 using the 0.1° gridded estimates, over oceans). This gradient reaches its peak in the Northern midlatitudes, with NO2 concentrations that are 0.3 ppb greater than in low latitudes. The standard deviation of NO2 concentrations for the cities in our analysis is almost an order of magnitude greater (2.6 ppb), suggesting that the NO2 differences seen among cities are much larger than those associated with latitude.

We consider three additional models using the logarithm of median, 90th percentile, and concentration-weighted mean NO2 concentrations for the dependent variable. Model R^2 and p-values for independent variables are similar to results for the core model (see Table S2) indicating that our results are robust to the method chosen to spatially summarize urban NO2 concentrations. Results using the 90th percentile of surface NO2 concentration imply that population and urban contiguity have slightly greater importance (by 5–10%) for extreme NO2 concentrations, i.e., pollution hot-spots, than for central-tendency NO2 concentrations (see Table S2).

As another sensitivity analysis, we evaluated a model similar to Table 2 but with the dependent variable as the logarithm of arithmetic mean column (rather than surface) NO2. Results are in Table S2. Model performance is good \( (R^2 = 0.70) \), and the unique effect of each independent variable (i.e., a plot analogous to Figure 2; not shown) is consistent with the core model. Thus, the modeled surface-to-column ratios do not appear to introduce differential bias into our core model.

Our findings indicate that cities with highly contiguous built-up areas have, on average, lower NO2 concentrations. All else being equal, urban areas with large amounts of development detached from main built-up areas will tend to have higher NO2 concentrations. The urban form metrics employed here do not allow us to distinguish among types of isolated development (e.g., residential-only subdivisions, versus satellite cities, versus business/industrial development) or their differential effect on NO2. It is possible, for example, that self-sufficient isolated satellite cities might reduce travel and/or NO2 concentrations. More work is needed in this regard. Overall our findings suggest that policies encouraging contiguous rather than isolated development may be an effective part of urban design strategies seeking to minimize NO2 air pollution.

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**REFERENCES**


