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Relationships between Changes in Urban Characteristics and Air Quality in East Asia from 2000 to 2010

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Abstract

Characteristics of urban areas, such as density and compactness, are associated with local air pollution concentrations. The potential for altering air pollution through changing urban characteristics, however, is less certain, especially for expanding cities within the developing world. We examined changes in urban characteristics from 2000 to 2010 for 830 cities in East Asia to evaluate associations with changes in nitrogen dioxide (NO_2) and fine particulate matter ($PM_{2.5}$) air pollution. Urban areas were stratified by population size into small (100,000–250,000), medium, (250,000–1,000,000) and large (>1,000,000). Multivariate regression models including urban baseline characteristics, meteorological variables, and change in urban characteristics explained 37%, 49%, and 54% of the change in NO_2 and 29%, 34%, and 37% of the change in $PM_{2.5}$ for small, medium and large cities, respectively. Change in lights at night strongly predicted change in NO_2 and $PM_{2.5}$, while urban area expansion was strongly associated with NO_2 but not $PM_{2.5}$. Important differences between changes in urban characteristics and pollutant levels were observed by city size, especially NO_2. Overall, changes in urban characteristics had a greater impact on NO_2 and $PM_{2.5}$ change than baseline characteristics, suggesting urban design and land use policies can have substantial impacts on local air pollution levels.

BACKGROUND

For the first time in human history more than 50% of the world's population resides in urban areas, with an expected increase to 66% by 2050.[1] Much of this growth is from, and will continue to occur in, rapidly urbanizing East Asia (China, Japan, Indonesia, Malaysia, Vietnam, Thailand, Korea, Philippines, Taiwan, Cambodia, Loa). In China alone the urban population grew from 191 million in 1980 to 622 million in 2009.[2] Only 36% of East Asia's

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SUPPORTING INFORMATION

Supporting tables include data sources and satruated regression models. Supproting figures include an overview of urban footprint calculations, variance-covariance matrices, compactness index examples, and maps of spatial distributions of several key varaibles.

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population currently lives in urban areas, suggesting substantial future urban growth in this region.[3] Important public health gains have resulted from urban growth, such as increased sanitation, safe drinking water, and access to education and healthcare; however, negative influences have also emerged, including increases in outdoor air pollution levels.

Global burden of disease estimates for 2013 include 2.9 million premature deaths and 70 million years of healthy life lost from exposure to outdoor fine particulate matter ($PM_{2.5}$) air pollution.[4] This places outdoor $PM_{2.5}$ air pollution ahead of such risk factors as physical inactivity, alcohol use, and high body-mass index in terms of disease burden in East Asia. Air pollution levels in this part of the world have also deteriorated from 2000–2010,[5] potentially due to rapid urbanization and accompanying air pollution emissions from energy production, industry, home heating and vehicles.

Planning of urban areas and land use policies can have important implications for local air pollution concentrations. A number of studies, primarily in developed countries, have documented that urban form characteristics, such as compactness (or alternatively sprawl),[6] green space[7], population density[8] and road density[9] can significantly improve or degrade local air pollution levels. For example, in 111 US urban areas, an interquartile range change in population density, centrality and transit supply was associated with 4–14% change in $PM_{2.5}$ air pollution concentrations; impacts equivalent in size to those from meteorological conditions.[10] However, studies examining urban characteristics and air pollution in rapidly developing countries are rare. One study conducted using 83 global cities in the World Bank's Urban Growth Management Initiative observed that, on average, cities with highly contiguous urban form had lower nitrogen dioxide (NO_2) air pollution (a marker for traffic-related air pollution), while urban compactness was not associated with NO_2 concentrations.[8] Importantly, no analyses have been conducted on the *change* in air pollution associated with urban expansion and changing urban characteristics – information vital to informing urban planning. Much of the existing literature also focuses on large urban areas, despite the fact that approximately 50% of the world's urban population reside in relatively small cities of less than 500,000 inhabitants,[1] and that small urban areas may be more amenable to policy and design changes that could reduce air pollution.

The degree to which urban growth increases air pollution is complex and an important policy question that has not been fully explored, especially in rapidly developing countries. Here we examined changes in NO_2 and $PM_{2.5}$ air pollution from 2000 to 2010 using satellite derived estimates for 830 cities in East Asia with 2010 populations' ≥100,000, and examine associations with urban expansion levels and changes in urban characteristics over this ten-year period.

METHODS

Study Region and Urban Areas

The geographical extent of our study region covers all of Eastern Asia, including Oceania island nations such as Marshall Islands and Micronesia (Figure 1). We used World Bank 2000 and 2010 East Asia urban area classifications[3] to define urban areas based on the extent of urban development rather than municipal boundaries. City footprints were

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esimated using a slight modification of an equation originally derived by Angel et al.[11] (Supplemental Figure 1)

$$\text{Footprint status}=\begin{cases}1 \text{ if classified as urban by the World Bank Urban Expansion dataset}\\ 1 \text{ if } 20\% \text{ or more of the area within a 1 km radius is classified as urban}\\ 0 \text{ otherwise}\end{cases}$$

Urban area population size was calculated by multiplying footprint size and mean population density from Gridded Population of the World population density estimates.[12] Urban areas with 2010 populations ≥100,000 were selected for analysis, which included 830 urban areas (Figure 1). Urban areas were stratified by 2010 population size based on US Census Bureau city size (by population) classification due to preliminary observations of differing typology-air pollution relationships and covariate correlations between urban areas with small (100,000–250,000), medium (250,000–1,000,000) and large (> 1,000,000) populations (Supplemental Figure 2)

Air Pollution Estimates

Ground-based air pollution monitoring data are not available for most urban areas in East Asia in 2010 and were extremely sparse in 2000. We therefore used satellite-derived estimates of NO_2 and $PM_{2.5}$ to determine changes from 2000 to 2010. Satellite data offer global coverage and a uniform approach to measuring air pollution concentrations. Estimates of NO_2 for 1999–2001 and 2009–2011 were derived from the GOME and SCIAMACHY satellite instruments, which provide measurements of NO_2 atmospheric column abundance with global coverage every three and six days respectively. Three-year averages were used to reduce the effects of inter-annual variability that may in part arise from random error. A global chemical transport model (GEOS-Chem) was used to relate the column observations to surface concentrations as described in Geddes et al.[13] In their approach, GOME observations were downscaled to achieve the finer resolution captured by SCIAMACHY by applying the mean spatial structure observed by SCIAMACHY at 0.1° × 0.1° over 2003–2005. There is no evidence of a systematic discontinuity, and a high correlation (r=0.89) between the two instruments was observed during a period of overlap.[13] $PM_{2.5}$ was estimated from retrievals of aerosol optical depth from three satellite instruments (MODIS, MISR, and SeaWIFS) with coincident aerosol vertical profiles from GEOS-Chem.[14] Three year average surfaces (at a 10×10 km resolution) were also created (1999–2001 and 2009–2011). These estimates have shown good agreement with ground-based measurements and have an expected 1-sigma uncertainty of 1 μg/m^3 +25%.[15] Similar satellite-derived $PM_{2.5}$ estimates have been used in recent global epidemiological studies,[16,17] and were the basis of the 2013 global disease burden estimates.[4,5]

Calculations of Change in Air Pollution and Urban Characteristics

Air pollution, urban expansion, and urban typology variables are listed in Table 1, with data sources listed in Supplemental Table 1. Variables are expressed as absolute rather than relative levels of change from 2000–2010. Air pollution variables include change in mean

$PM_{2.5}$ and NO_2 from 2000–2010. Urban expansion variables include change in population and urban footprint area from 2000–2010. Urban characteristic variables include changes in compactness index, a measure of urban sprawl (Supplemental Figure 3) and changes in mean and within-city-variation in population density, green space (calculated from the normalized difference vegetation index (NDVI)), impervious surface area (ISA), and percent lights at night, a satellite-based relative measure of global night time light emissions often used as an indirect measure of economic activity.[18] Measures of within-city-variation were calculated in addition to mean levels to evaluate the potential influence of spatial heterogeneity in urban typology on air pollution. For example, increased variation in population density is an indirect indicator of urban sprawl (low density suburban areas contrasting with high density urban centers).

Change in mean air pollution and urban typology variables were calculated as the difference in means for the corresponding 2000 and 2010 urban footprint:

$$\Delta\overline{X}_{ij}=\overline{X}_{i2010j2010}-\overline{X}_{i2000j2000} \quad \text{Eq. 1}$$

Where

$\Delta\bar{X}_{ij}$ denotes the change from 2000–2010 in the variable i mean for urban area j

$\bar{X}_{i2000j2000}$ denotes the year 2000 variable i mean for the area covered by the year 2000 footprint of urban area j

Similarly, changes in within-city-variation were calculated as the difference in standard deviation for the corresponding 2000 and 2010 urban footprint:

$$\Delta\sigma_{ij}=\sigma_{i2010j2010}-\sigma_{i2000j2000} \quad \text{Eq. 2}$$

Where

$\Delta\sigma_{ij}$ denotes the change from 2000–2010 in the standard deviation of variable i for urban area j

$\sigma_{i2000j2000}$ denotes the year 2000 variable i standard deviation for the area covered by the year 2000 footprint of urban area j

Cities with urban footprints smaller than $10km^2$ in area were assigned a within-city-variation value of zero due to the spatial resolution of several urban characteristic datasets.

Due to urban spillover there were several regions where a single 2010 urban footprint covered multiple distinct year 2000 urban areas. For these instances, changes in air pollution, urban expansion, and typology variables were calculated using an area-weighted average of corresponding 2000 urban areas.

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$$\Delta\overline{X}_{ij}=\overline{X}_{i2010j2010}-\frac{\sum_{k=1}^{n}\overline{X}_{i2000k2000}*\mathrm{Area}_{\mathrm{k2000}}}{\sum_{k=1}^{n}Area_{k2000}*n} \quad \text{Eq. 3}$$

Where

$\Delta\bar{X}_{ij}$ denotes the area-weighted change from 2000–2010 in the variable i mean for urban area j

$\bar{X}_{i2000k2000}$ denotes the year 2000 variable i mean for the area covered by the year 2000 footprint of urban area k

$\mathrm{Area}_{\mathrm{k2000}}$ denotes total area of year 2000 footprint for urban area k

And n is the number of year 2000 urban areas covered by the year 2010 urban area j

Statistical analysis

First, we tested for differences between 2000 and 2010 levels of independent variables using multiple paired t-tests with Bonferroni-adjusted confidence intervals. Second, linear regression models were developed for all univariate combinations of dependent variables (change in NO_2 and $PM_{2.5}$ air pollution) and independent variables (urban expansion and change in urban typology) stratified by small, medium, and large urban areas. Third, multiple, multivariate linear regression models were created with model structures consisting of 1) all of the independent variables, or 2) a subset of variables selected via bidirectional stepwise regression. Adjustment factors in the multivariate models include baseline (year 2000) urban characteristics, annual mean rainfall and temperature, and distance to coast.

RESULTS

Locations of the 830 urban areas in East Asia examined in our study are illustrated in Figure 1, along with the surface estimates for changes in NO_2 and $PM_{2.5}$ concentrations and an example of the urban expansion footprint for Beijing, China. Table 1 summarizes the air pollution concentrations, urban expansion levels, changes in urban characteristics (both in terms of average measures and within-area variability) and baseline (year 2000) characteristics by urban size category. On average the change in NO_2 and $PM_{2.5}$ levels ranged from 1.21 to 2.25 ppb and 10.54 to 11.02 μg/m^3 based on urban size. The size of urban expansion, in terms of geographic area and population, was large for all urban size categories. On average, the area of urban expansion for small, medium and large cities was 6.9, 49.3, and 379 km^2, while the population size expansion was 23,470, 342,400, and 2,178,000, respectively. Generally, urban expansion was associated with decreasing average compactness index and increasing population density, NDVI and lights at night. In small and medium cities, urban expansion was associated with decreases in the percent impervious surface (due to sprawl) but in large cities were associated with an increase. Change in variable heterogeneity showed similar patterns across urban size categories with the exception of lights at night that showed a decrease in heterogeneity with increasing urban size.

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Univariate associations between changes in NO_2 and $PM_{2.5}$, urban expansion, and changes in urban characteristics are shown in Table 2. For all urban areas the geographic size of expansion was associated with increased NO_2, but only in small urban areas was expansion size associated with increased $PM_{2.5}$. Population growth in small and medium urban areas was associated with increases in both NO_2 and $PM_{2.5}$, while no statistically significant association was seen for large cities. A number of significant associations were observed between changes in air pollution concentrations and urban characteristics that correspond to hypothesized effect directions. For example, NO_2 increased with increases in population density, % impervious surface, and lights at night, while NO_2 decreased with increasing compactness and NDVI.

Stepwise multivariate models of change in NO_2 and $PM_{2.5}$ are shown in Tables 3 and 4, respectively. Saturated multivariate models are shown in Supplemental Tables 3 and 4. The reduced stepwise model variables included urban expansion, change in urban characteristics (mean and variability measures), baseline (2000) urban characteristics, and other adjustment factors (distance to coast and meteorological variables). For change in NO_2, the overall model explained 37%, 49% and 54% for small, medium and large urban areas. The largest predictors were lights at night (R2=0.20) and annual rainfall (R2=0.16) for small urban areas; lights at night (R2=0.13) and the annual rainfall (R2=0.13) for medium urban areas; and heterogeneity in population density (R2=0.12) and annual rainfall (R2=0.12) for large urban areas.

Models of $PM_{2.5}$ change generally had lower performance than NO_2 models. The overall models explained 29%, 34% and 37% of change in $PM_{2.5}$ for small, medium and large urban areas. The largest predictors were annual rainfall (R2=0.10) and baseline urban area (R2=0.07) for small urban areas; lights at night (R2=0.10) and baseline impervious surface area (R2=0.05) for medium urban areas; and lights at night (R2=0.08) and population density heterogeneity (R2=0.11) for large urban areas. The change in urban characteristics and urban characteristic heterogeneity explained 14.7–28.8% and 4.0–20.5% of the decadal change in NO_2 and $PM_{2.5}$, respectively, compared to 3–13% and 4–14% explained by baseline urban characteristics.

Sensitivity Analyses

We presented models stratified by urban population size due to differences in the rate of urban expansion, change in urban characteristics and observed differences in the associations between these urban characteristics and NO_2 and $PM_{2.5}$ change. In a model including all urban areas, the percent variance explained in the NO_2 and $PM_{2.5}$ multivariate model was 40.3% and 24.9%, respectively (Supplemental Table 2). For the NO_2 model the strongest predictors were change in lights at night (R2=0.10) and change in NDVI (R2=0.05) and for $PM_{2.5}$ were change in lights at night (R2=0.10) and change in population heterogeneity (R2=0.03). We also examined models including baseline (2000) NO_2 and $PM_{2.5}$ concentrations. Including baseline concentrations greatly increased model predictions (R2=0.53 and 0.42 for change in NO_2 and $PM_{2.5}$, respectively) but did not influence direction or relative contribution of significant predictor variables. Approximately 3.6% (n=30) of the cities in our analysis exhibited negative population growth (located in both

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developing (Indonesia, Vietnam) and developed (South Korea, Japan) countries. We tested the influence of these cities on model predictions using an indicator variable and observed no statistically significant associations for all city stratification levels.

To assess model structure and multicollinearity, we compared multivariate bidirectional stepwise linear regression models to multivariate linear regression models with all covariates included in the model structure (Supplemental Tables 3 and 4). Coefficients and relative contributions to percent variance explained by urban characteristics are similar, increasing confidence in identified relationships between urban characteristics and air pollution change. We also assessed the explanatory variable covariance for each proposed model using hierarchical clustering (Supplemental Figure 2). During stepwise variable selection, clusters of highly correlated variables were reduced to one or two explanatory variables.

DISCUSSION

We examined associations between NO_2 and $PM_{2.5}$ air pollution change and urban expansion and urban characteristic change from 2000 to 2010 for 830 cities in East Asia. Geographic expansion of urban areas was associated with increases in NO_2 air pollution only, although several urban characteristics were also associated with differential changes in both NO_2 and $PM_{2.5}$ air pollution. Multivariate models were able to predict up to 54% of the change in NO_2 and 37% of the change for $PM_{2.5}$, of which baseline urban conditions had less influence compared to changes in urban characteristics. Associations between urban characteristics and air pollution change also varied by city size. Overall, this study demonstrates that policies to change urban design and land use can have a substantial impact on urban air pollution levels in East Asia, especially for NO_2.

Urban expansion, in term of geographic area and population growth, was associated with increased NO_2 concentrations. Geographic expansion of urban areas was positively associated with change in NO_2 for all city sizes, but was not significantly associated with change in $PM_{2.5}$. This is not necessarily surprising, as $PM_{2.5}$ concentrations in East Asia are influenced by more diverse sources that are less exclusive to urban development, including coal-fired power plants, industrial processes, and biofuel burning in personal homes for cooking and heating.[19,20,21]

Increasing urban populations from 2000 to 2010 were also associated with both NO_2 and $PM_{2.5}$ concentration changes. Change in population coefficients were positive for small and medium cities and negative for medium large cities for NO_2, while change in population density was non-significant for small and medium cities and negatively associated with change in NO_2 for large cities. These results suggest that increasing population while controlling geographic expansion leads to attenuation and perhaps even decrease in per capita emissions. Relationships between population and air quality are further complicated by heterogeneity in population density. Increased heterogeneity, often associated with resource inequity and suburban expansion, explained 11.5% and 10.5% of the change in NO_2 and $PM_{2.5}$ in large cities, respectively, suggesting urban areas with greater suburban population growth have greater increases in air pollution compared to cities with similar population size.

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Changes in a number of different urban characteristics were associated with changes in air pollution levels over this ten year study period. Lights at night (a measure of economic activity) and impervious surface area were strong predictors of change in NO_2 and $PM_{2.5}$ for all urban sizes, with the exception of $PM_{2.5}$ for small urban areas. Percent change in impervious surface area was negatively associated with change in NO_2 and $PM_{2.5}$, suggesting that urban areas that decrease concentrations of impervious surface areas (i.e. greater expansion of suburban areas) are prone to increased levels of air pollution.

Rainfall explained a surprisingly large percentage of NO_2 and $PM_{2.5}$ variation across all city sizes. Although rainfall is widely known to reduce air particulate concentrations, rainfall in our study is also strongly associated with green space (r=0.66, 0.82, and 0.81 for small, medium, and large cities, respectively), and latitude in Eastern Asia (Supplemental Figures 4–7). Our rainfall regression models may be under- or over-estimating the association between rainfall, temperature and change in NO_2 and $PM_{2.5}$, depending on the East Asia variability in meteorological conditions.

Multivariate models indicated that the change in NO_2 and $PM_{2.5}$ concentrations were more strongly associated with the change in urban characteristics compared to baseline (2000) urban characteristics. For example, the change in urban characteristics between 2000 and 2010 explained up to 28% and 22% of the change in NO_2 and $PM_{2.5}$ respectively, compared to 13% and 14% by baseline urban characteristics. Some baseline urban characteristics were important, but these impacts were generally small in magnitude and explained a small percentage of change in NO_2 and $PM_{2.5}$ in large cities.

Urban growth and associated air pollution is a major policy issue in many parts of East Asian that has prompted actions to improve air quality. Urban development, particularly in developed countries, has been characterized by low density, and low transport connectivity and automobile dependence, leading to increased air pollution emissions. Our study suggests that urban development in East Asia from 2000–2010 suffered from similar urban expansion characteristics and associated increased air pollution levels, exacerbated by unprecedented levels of economic growth. Although economic growth and urban development in the past has led to increased energy consumption and air pollution, economic growth can also facilitate deliberate and planned development towards sustainable infrastructure and reduction of location air pollution. Compared to much of the rapidly developing world, China is in a unique situation to implement such sustainable development as much of their urban development is planned. For example, the China Development Bank, a state-owned financial institution, lent US$168 billion to projects related to urbanization in 2013.[3] Our study suggests that urban characteristics can influence air pollution levels but that ideal urban typologies also differ depending on the city size. When considering urban development impacts on air pollution, future changes in urban characteristics appear to be just as significant if not more significant than current urban characteristics for predicting future air pollution levels. Responsible urban development therefore needs to be proactive, considering future development concerns such as zoning and neighboring city expansion. Although NO_2 and $PM_{2.5}$ were correlated in East Asia, there were substantial differences in their associations with urban expansion and urban characteristics. NO_2 is influenced primarily by vehicle emissions and will therefore be most amenable to changes in urban characteristics (as demonstrated in this analysis) while $PM_{2.5}$ is strongly (although not exclusively) influenced by regional emission sources (e.g. power plants) that are not easily changed through urban planning and land use policies.

There are several limitations to inferences derived from our model predictions. Satellite estimates allow for consistent monitoring of pollution in regions without air monitoring stations, but may include increased uncertainty compared to ground-based measurements and were limited to a spatial resolution of ~10 km × 10 km in these datasets. Associations between urban characteristics and air pollution therefore may not represent associations at finer scales levels. Some changes in NO_2 from 2000–2010 could be underestimated due to the inherent assumption of persistent NO_x sources in the approach to downscale GOME observations to match the resolution of SCIAMACHY, but this assumption was in general shown to be valid for most regions over this time period.[13] While satellite-derived NO_2 surface estimates were not evaluated over East Asia due to a lack of long-term ground-based observations, the estimates are highly spatially correlated (r=0.80) with ground-based monitoring measurements for North America.[15] Likewise, the changes in ground-level NO_2 derived from satellite observations were consistent with regional trends inferred from ground-station monitoring networks (within 0.7% yr^{-1}). Absolute satellite-derived ground-level NO_2 is often lower than ground-based in-situ measurements, due to a combination of several factors, including location-specific overestimates in the ground-based monitoring instruments that are known to suffer NO_2 interferences[22], and the placement of ground level monitors near large NO_x sources to monitor air quality compliance[23].

In this paper we did not distinguish between cities that changed size classifications from and cities that remained within the same size classification. Cities in transition may exhibit different urban typology-air pollution relationships. Large urban areas with multiple municipalities were not distinguished in this study from regions with a single urban area. Further studies are needed to evaluate spillover cities, which are becoming increasingly prevalent in Eastern Asia.

We demonstrated that urban expansion and changes in urban area characteristics are associated with NO_2 and $PM_{2.5}$ change from 2000 to 2010 for 830 cities in East Asia. The importance of urban characteristics on air pollution change differed with respect to the population size of a city; however, changes in urban characteristics were consistently more important than baseline urban characteristics for predicting air pollution change. Overall, this study demonstrates that policies to change urban design and land use can have a substantial impact on air pollution levels in rapidly developing cities in East Asia.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

1. World urbanization prospects (2014 revision). United Nations Department of Economic and Social Affairs; New York: 2014. http://esa.un.org/unpd/wup/
2. Gong P, Liang S, Carlton EJ, Wu J, Wang L, Remais JV. Urbanisation and health in China. The Lancet. 2012; 379(9818):843–852. DOI: 10.1016/S0140-6736(11)61878-3
3. East Asia's changing urban landscape: measuring a decade of spatial growth. The World Bank; Washington, DC: 2013. http://elibrary.worldbank.org/doi/book/10.1596/978-1-4648-0363-5
4. Forouzanfar MH, Alexander L, Anderson HR, et al. Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks in 188 countries, 1990–2013: a systematic analysis for the Global Burden of Disease Study 2013. The Lancet. 2015; 386:2287–323. DOI: 10.1016/S0140-6736(15)00128-2
5. Brauer M, Amann M, Burnett RT, Cohen A, Dentener F, Ezzati M, Henderson SB, Kryzanowski M, Martin RV, van Dingenen R, van Donelaar A, Thurston GD. Exposure assessment for estimation of the global burden of disease attributable to outdoor air pollution. Environ Sci Technol. 2012; 46(2): 652–660. DOI: 10.1021/es2025752 [PubMed: 22148428]
6. McCarty J, Kaza N. Urban form and air quality in the United States. Landsc Urban Plan. 2015; 139:168–179. DOI: 10.1016/j.landurbplan.2015.03.008
7. De Ridder K, Adamec V, Bañuelos A, Bruse M, Burger M, Damsgaard O, Dufek J, Hirsch J, Lefebre F, Perez-Lacorzana JM, Thierry A, Weber C. An integrated methodology to assess the benefits of urban green space. Sci Total Environ. 2004; 334–335:489–497. DOI: 10.1016/j.scitotenv. 2004.04.054
8. Lamsal LN, Martin RV, Parish DD, Krotkov NA. Scaling relationship for NO2 pollution and population size: A satellite perspective. Environ Sci. Technol De Ridder K, Adamec V, Bañuelos A, Bruse M, Burger M, Damsgaard O, Dufek J, Hirsch J, Lefebre F, Perez-Lacorzana JM, Thierry A, Weber C. An integrated methodology to assess the benefits of urban green space. Sci Total Environ. 2013; 47:7855–7861. DOI: 10.1021/es4000744g
9. Hoek G, Beelen R, de Hoogh K, Viennaue D, Gulliver J, Fischer P, Briggs D. A review of land-use regression models to assess spatial variation of outdoor air pollution. Atmos Environ. 2008; 42(33): 7561–7578. DOI: 10.1016/j.atmosenv.2008.05.057
10. Clark LP, Millet DB, Marshall JD. Air quality and urban form in U.S. urban areas: evidence from regulatory monitors. Environ Sci Technol. 2011; 45(16):7028–7035. DOI: 10.1021/es2006786 [PubMed: 21766846]
11. Angel, SJ., Parent, DL., Civco, DL., Blei, AM. Atlas of Urban Expansion 2010. Lincoln Institute of Land Policy; Cambridge: 2010.
12. The Global distribution of population: evaluating the gains in resolution refinement. Center for International Earth Science Information Network, Columbia University; Palisades: 2004. http://sedac.ciesin.columbia.edu/downloads/docs/gpw-v3/gpw3_documentation_final.pdf
13. Geddes JA, Martin RV, Boys BL, Van Donkelaar A. Long-term trends in worldwide ambient NO2 concentrations inferred from satellite observations. Environ Health Persp. 2016; 124(3):281.
14. Van Donkelaar A, Martin RV, Brauer M, Boys BL. Use of Satellite Observations for Long=Term Exposure Assessment of Global Concentrations of Fine Particulate Matter. Environ Health Perspec. 2015; 123(2):135–143.
15. Van Donkelaar A, Martin RV, Spurr RJ, Drury E, Remember LA, Levy RC, Wang J. Optimal estimation for global ground-level fine particulate matter concentrations. J Geophys Res Atmospheres. 2013; 118(11):5621–5636. DOI: 10.1002/jgrd.50479
16. Anderson HR, Butland BK, van Donkelaar A, Brauer M, Strachan DP, Clayton T, van Dingenen R, Amann M, Brunekreef B, Cohen A, Dentener F, Lai C, Lamsal LN, Martin RV, One IP. Satellite-based estimates of ambient air pollution and global variations in childhood asthma prevalence. Environ Health Perspect. 2012; 120(9):1333–1339. DOI: 10.1289/ehp.1104724 [PubMed: 22548921]
17. Fleischer NL, Merialdi M, van Donkelaar A, Vadillo-Ortega F, Martin RV, Betran AP, Souza JP. Outdoor air pollution, preterm birth, and low birth weight: analysis of the world health

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organization global survey on maternal and perinatal health. Environ Health Perspect. 2014; 122(4):425–430. DOI: 10.1289/ehp.1306837 [PubMed: 24508912]

18. Keola S, Andersson M, Hall O. Monitoring economic development from space: using night time light and land cover data to measure economic growth. World Dev. 2015; 66:322–334. DOI: 10.1016/j.worlddev.2014.08.017
19. Shao M, Tang X, Zhang Y, Li W. City clusters in china: air and surface water pollution. Frontiers in Ecology and the Environment. 2006; 4(7):353–361. DOI: 10.1890/1540-9295(2006)004[0353;CCICAA]2.0.CO;2
20. Aunan K, Wang S. Internal migration and urbanization in China: Impacts on population exposure to household air pollution (2000–2010). Science of the Total Environment. 2014; 481(15):186–195. DOI: 10.10/16/j.scitoenv.2014.02.073 [PubMed: 24598149]
21. Zheng M, Salmon LG, Schauer JJ, Zeng L, Kiang CS, Zhang Y, Cass GR. Seasonal trends in PM2. 5 source contributions in Beijing, China. Atmos Environ. 2005; 39(22):3967–3976.
22. Dunlea EJ, Herndon SC, Nelson DD, Volkamer RM, San Martini F, Sheehy PM, Zahniser MS, Shorter JH, Wormhoudt JC, Lamb BK, et al. Evaluation of nitrogen dioxide chemiluminescence monitors in a polluted urban environment. Atmospheric Chem Phys. 2007; 7(10):2691–2704.
23. Kharol SK, Martin RV, Philip S, Boys B, Lamsal LN, Jerrett M, Brauer M, Crouse DL, McLinden C, Burnett RT. Assessment of the magnitude and recent trends in satellite-derived ground-level nitrogen dioxide over North America. Atmos Environ. 2015; 118:236–245.

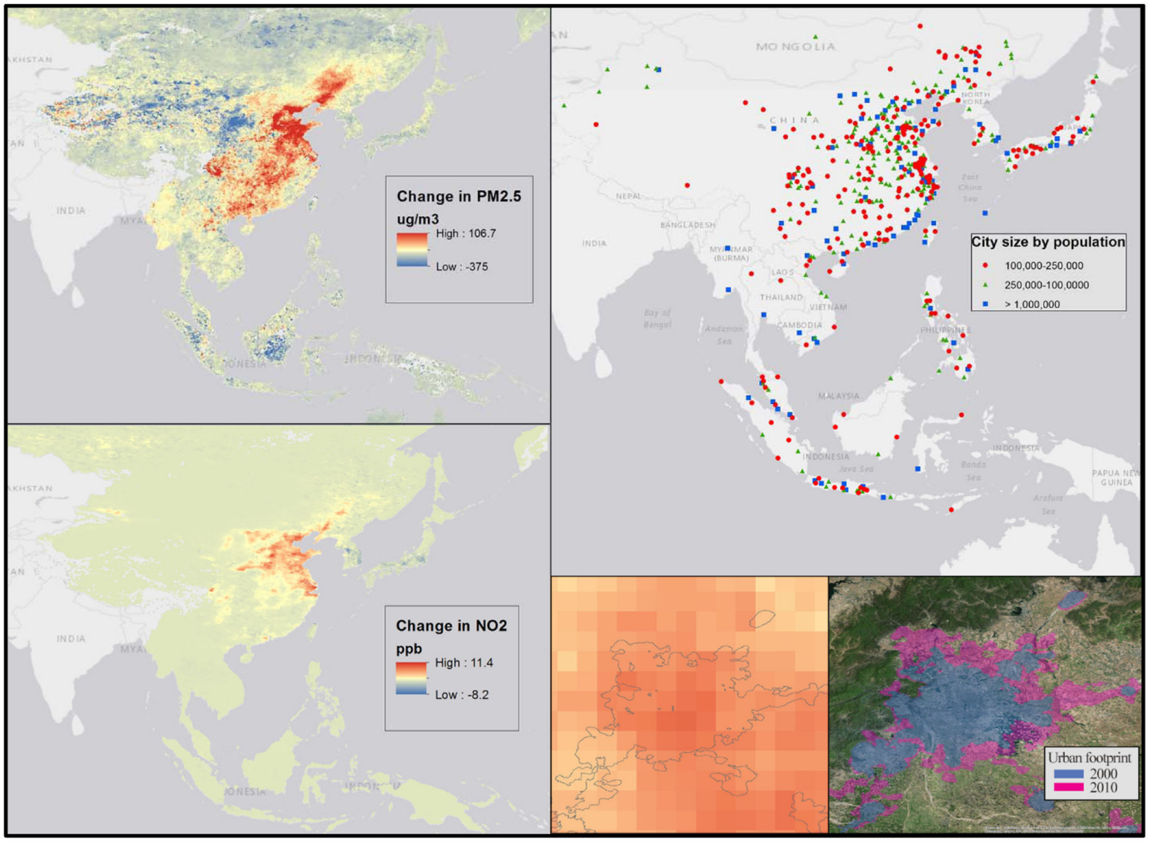

Figure 1.
Study region, urban area classification and air pollution change. Change in annual PM2.5 and NO2 concentrations from 2000 to 2010 are shown in the top and bottom left, respectively.

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Table 1

Descriptive statistics of change in NO_2 and $PM_{2.5}$, urban expansion and urban characteristic variables from 2000–2010 stratified by urban population

	Urban Size					
	100,000–250,000 (n=235)		250,000–1,000,000 (n=340)		> 1,000,000 (n=255)	
	Mean	Std dev	Mean	Std dev	Mean	Std dev
Change in Air Pollution						
NO_2 (ppb)	1.21	1.75 ***	2.07	2.15 ***	2.25	3.03 ***
$PM_{2.5}$ (μg/m^3)	10.54	10.19 ***	12.53	10.91 ***	11.02	12.42 ***
Urban Expansion						
Area (sq km)	6.93	7.67 ***	49.27	63.86 ***	3.79×10^{2}	8.72×10^{2} ***
Population (1,000s)	23.47	32.29	3.42×10^{2}	2.25×10^{2} ***	2.18×10^{3}	1.96×10^{4} ***
Change in Urban Characteristics						
Compactness Index (0–1)	-1.72×10^{-2}	4.65×10^{-2} ***	-2.87×10^{-2}	8.43×10^{-2} ***	-2.35×10^{-2}	9.09×10^{-2} ***
Population Density (pop/km^2)	7.72×10^{2}	1.12×10^{3} ***	2.76×10^{3}	2.94×10^{3} ***	4.56×10^{4}	2.93×10^{5}
NDVI (-1-1)	0.35	0.10 ***	0.33	0.11 ***	0.31	0.12 ***
Impervious Surface Area (%)	−0.10	10.96 ***	−0.13	11.10 ***	10.16	11.15 ***
Lights at Night (%)	12.09	7.83 ***	10.62	6.26 ***	8.79	7.11 ***
Change in Urban Characteristic Heterogeneity						
Population Density	5.21×10^{2}	1.03×10^{3} ***	3.31×10^{3}	2.76×10^{3} ***	6.33×10^{3}	5.13×10^{3} ***
NDVI (-1-1)	8.24×10^{-2}	2.83×10^{2} ***	8.32×10^{2}	3.57×10^{-2} ***	9.05×10^{-2}	3.77×10^{-2} ***
Impervious Surface Area (%)	−15.96	8.92 ***	−16.82	7.92 ***	−13.43	7.13 ***
Lights at Night (%)	0.69	2.84 **	−1.47	3.34	−3.20	3.81 ***
Baseline (2000) Urban Characteristics						
NO_2 (ppb)	1.58	1.27	1.77	1.28	2.51	1.27
$PM_{2.5}$ (μg/m^3)	28.05	19.15	31.42	21.07	23.86	17.81
Area (sq km)	53.54	43.90	1.14×10^{2}	93.51	5.50×10^{2}	43.90
Population (1000s)	52.18	73.05	1.41×10^{2}	2.17×10^{2}	1.68×10^{3}	7.31
NDVI (-1-1)	1.41×10^{-2}	3.06×10^{-3}	1.33×10^{-2}	2.88×10^{-3}	1.28×10^{-2}	3.06×10^{-3}
Impervious Surface Area (%)	24.46	9.35	28.27	11.21	33.14	9.35
Lights at Night (%)	35.49	11.00	37.75	11.31	11.16	11.00

* p-value < 0.05,

** p-value < 0.01,

*** p-value < 0.001.

Differences between 2000 and 2010 levels were tested for significance using multiple paired t-tests with Bonferroni-adjusted confidence intervals.

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Table 2

Univariate associations between NO_2 and $PM_{2.5}$ change, urban expansion, and change in urban characteristics

	Urban Size					
	100,000–250,000		250,000–1,000,000		> 1,000,000	
	Coefficient	**Std Error**	**Coefficient**	**Std Error**	**Coefficient**	**Std Error**
NO_2						
Urban Expansion						
Area (sq km)	3.82×10^{-2}	9.56×10^{-3} ***	9.32×10^{-3}	2.37×10^{-3} ***	1.24×10^{-3}	3.45×10^{-4} ***
Population (1000s)	2.02×10^{-2}	2.14×10^{-3} *	2.78×10^{-3}	6.70×10^{-4} *	-2.50×10^{-7}	1.62×10^{-7}
Change in Urban Characteristics						
Compactness Index (0–1)	−2.86	1.60	−4.58	1.84 *	−1.26	3.55
Population Density	4.08×10^{-4}	6.42×10^{-5} ***	-1.06×10^{-5}	5.37×10^{-5}	-1.91×10^{-6}	1.08×10^{-6}
NDVI (-1-1)	−3.97	0.71 ***	−3.47	1.38 *	−2.74	2.68
Impervious Surface Area (%)	2.09×10^{-2}	6.73×10^{-3} **	2.85×10^{-2}	1.41×10^{-2} *	4.81×10^{-2}	2.85×10^{-2}
Lights at Night (%)	9.76×10^{-2}	8.54×10^{-3} ***	8.00×10^{-2}	2.45×10^{-2} **	0. 24	3.79×10^{-2} ***
Change in Urban Characteristic Heterogeneity						
Population Density	2.64×10^{-4}	7.12×10^{-5} ***	2.35×10^{-4}	5.45×10^{-5} ***	2.48×10^{-4}	5.71×10^{-5} ***
NDVI (-1-1)	-1.21×10^{-3}	2.58×10^{-4} ***	-1.46×10^{-3}	4.29×10^{-4} ***	-2.47×10^{-3}	8.15×10^{-4} **
Impervious Surface Area (%)	3.21×10^{-2}	8.22×10^{-3} ***	6.60×10^{-2}	1.93×10^{-2} ***	4.77×10^{-2}	4.50×10^{-2}
Lights at Night (%)	-6.25×10^{-2}	2.61×10^{-2} *	−0.13	4.62×10^{-2} **	−0.3.1	7.80×10^{-2} ***
$PM_{2.5}$						
Urban Expansion						
Area (sq km)	0.12	5.64×10^{-2} *	2.28×10^{-2}	1.24×10^{-2}	9.85×10^{-4}	1.51×10^{-3}
Population (1000s)	0.10	1.27×10^{-2} ***	1.53×10^{-2}	3.38×10^{-2} ***	-7.00×10^{-6}	6.66×10^{-6}
Change in Urban Characteristics						
Compactness Index (0–1)	−23.35	9.29 *	−8.44	9.50	9.78	14.45
Population Density	3.24×10^{-3}	3.63×10^{-4} ***	3.53×10^{-4}	2.72×10^{-4}	5.90×10^{-6}	4.44×10^{-6}
NDVI (-1-1)	-1.25×10^{-3}	4.20×10^{-4} **	-1.43×10^{-3}	7.05×10^{-4} *	-8.01×10^{-4}	1.09×10^{-3}
Impervious Surface Area (%)	2.91×10^{-2}	3.96×10^{-2}	7.11×10^{-2}	7.201×10^{-2}	0.13	0.12
Lights at Night (%)	0.421	5.25×10^{-2} ***	0.56	0.12 ***	0.83	0.17 ***
Change in Urban Characteristic Heterogeneity						
Population Density	1.624×10^{-3}	4.15×10^{-4} ***	1.53×10^{-3}	2.68×10^{-4} ***	9.77×10^{-4}	2.35×10^{-4} ***
NDVI (-1-1)	-6.10×10^{-3}	1.52×10^{-3} ***	-6.65×10^{-3}	2.20×10^{-3} **	-1.01×10^{-2}	3.32×10^{-3} **
Impervious Surface Area (%)	4.61×10^{-2}	4.86×10^{-2}	0.17	0.10	0.20	0.18
Lights at Night (%)	0.20	0.15	0.52	0.24 *	−0.78	0.34 *

* p-value < 0.05,

** p-value < 0.01,

*** p-value < 0.001.

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Table 3

Multivariate associations between NO_2 change and urban expansion and urban characteristics – reduced model

	Urban Size								
	100,000–250,000 (n=235)			**250,000–1,000,000 (n=340)**			**> 1,000,000 (n=255)**		
	Coefficient	**Std Error**	**R2**	**Coefficient**	**Std Error**	**R2**	**Coefficient**	**Std Error**	**R2**
Urban Expansion									
Area (sq km)	3.84×10^{-2}	1.23×10^{-2}**	0.02	1.38×10^{-2}	4.72×10^{-3}**	<0.01	2.10×10^{-3}	5.66×10^{-4}***	0.07
Population (1000s)	4.92×10^{-6}	1.95×10^{-6}*	<0.01	9.89×10^{-7}	5.91×10^{-7}	0.02	-5.26×10^{-8}	3.02×10^{-8}	0.04
R2			0.02			0.03			0.12
Change in Urban Characteristics									
Compactness Index (0–1)							−2.27	1.36	<0.01
Population Density									
NDVI (-1-1)									
Impervious Surface Area (%)	-7.57×10^{-2}	1.95×10^{-2}***	0.03	-7.67×10^{-2}	1.83×10^{-2}***	0.01	-9.21×10^{-2}	2.22×10^{-2}***	0.03
Lights at Night (%)	8.19×10^{-2}	1.34×10^{-2}***	0.20	8.60×10^{-2}	1.98×10^{-2}***	0.13	7.05×10^{-2}	2.88×10^{-2}*	0.05
R2			0.22			0.14			0.08
Change in Urban Characteristic Heterogeneity									
Population Density				-6.92×10^{-5}	3.99×10^{-5}	<0.01	1.41×10^{-4}	3.46×10^{-5}***	0.12
NDVI (-1-1)									
Impervious Surface Area (%)	4.94×10^{-2}	1.78×10^{-2}	0.06				5.42×10^{-2}	2.65×10^{-2}*	0.02
Lights at Night (%)				-6.69×10^{-2}	4.08×10^{-2}	0.01	-8.57×10^{-2}	4.73×10^{-2}	0.01
R2			0.06			0.01			0.15
Baseline (2000) Urban Characteristics									
Area (sq km)	-9.78×10^{-3}	5.02×10^{-3}	0.01	-2.07×10^{-2}	3.14×10^{-3}***	0.06			
Population (1000s)				2.11×10^{-6}	6.23×10^{-7}***	<0.01			
NDVI (-1-1)				2.51×10^{-2}	5.75×10^{-3}***	0.02			
Impervious Surface Area (%)	-6.68×10^{-2}	1.41×10^{-2}***	0.02	−0.11	1.98×10^{-2}***	0.03	-6.4×10^{-2}	1.85×10^{-2}***	0.02
Lights at Night (%)	4.77×10^{-2}	1.16×10^{-2}***	0.03	5.66×10^{-2}	1.76×10^{-2}**	0.02	3.99×10^{-2}	2.31×10^{-2}	0.01
R2			0.06			0.13			0.03
Adjustment Factors									
Distance to Coast (km)	-9.21×10^{-4}	3.24×10^{-4}**	<0.01	-2.25*10^{-3}	3.30×10^{-4}***	0.01	-1.70×10^{-3}	3.23×10^{-4}***	<0.01
Annual Rainfall (mm)	-3.06×10^{-2}	3.39×10^{-3}***	0.16	-5.66×10^{-2}	7.46×10^{-3}***	0.13	-4.15×10^{-2}	5.98×10^{-3}***	0.12
Annual Temperature (°C)				-1.71×10^{-2}	6.73×10^{-3}*	0.05	-1.59×10^{-2}	8.17×10^{-3}	0.05
R2			0.16			0.19			0.17
Full Model R2			0.37			0.49			0.54

*p-value < 0.05,

** p-value < 0.01,

*** p-value < 0.001.

Blank spaces correspond to variables not selected during stepwise regression

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Table 4

Multivariate associations between $PM_{2.5}$ change and urban expansion and urban characteristics – reduced model

	Urban Size								
	100,000–250,000 (n=235)			250,000–1,000,000 (n=340)			> 1,000,000 (n=255)		
	Coefficient	**Std Error**	**R2**	**Coefficient**	**Std Error**	**R2**	**Coefficient**	**Std Error**	**R2**
Urban Expansion									
Area (sq km)									
Population (1000s)									
R2									
Change in Urban Characteristics									
Compactness Index (0–1)				−12.98	7.54	<0.01			
Population Density							-9.49×10^{-6}	5.49×10^{-6}	0.01
NDVI (-1-1)				-1.06×10^{-3}	6.41×10^{-4}	0.03			
Impervious Surface Area (%)	−0.21	7.87×10^{-2}**	<0.01	−0.22	8.97×10^{-2}*	0.02	−0.24	6.72×10^{-2}***	0.01
Lights at Night (%)				0.21	8.49×10^{-2}*	0.10	0.37	0.11***	0.08
R2			<0.01			0.15			0.10
Change in Urban Characteristic Heterogeneity									
Population Density				3.25×10^{-4}	1.98×10^{-4}	0.02	8.56×10^{-4}	1.82×10^{-4}***	0.11
NDVI (-1-1)	-2.80×10^{-3}	1.96×10^{-3}	0.04						
Impervious Surface Area (%)									
Lights at Night (%)	−0.41	0.23	<0.01	−0.39	0.19*	<0.01			
R2			0.04			0.02			0.11
Baseline (2000) Urban Characteristics									
Area (sq km)	−9.86×10–2	3.05×10^{-2}***	0.07	-6.67×10^{-2}	1.63×10^{-2}***	0.04			
Population (1000s)				6.90×10^{-6}	2.46×10^{-6}**	<0.01	2.27×10^{-7}	1.07×10^{-7}*	<0.01
NDVI (-1-1)				0.12	3.29×10^{-2}***	0.02			
Impervious Surface Area (%)	−0.38	7.98×10^{-2}***	0.07	−0.41	8.11×10^{-2}***	0.05	−0.24	6.19×10^{-2}***	0.03
Lights at Night (%)									
R2			0.14			0.11			0.04
Adjustment Factors									
Distance to Coast (km)				-7.46×10^{-3}	1.72×10^{-3}***	<0.01	-9.18×10^{-3}	1.66×10^{-3}***	0.02
Annual Rainfall (mm)	−0.11	3.00×10^{-2}***	0.10	−0.19	3.97×10^{-2}***	0.05	−1.3	3.16×10^{-2}***	0.06
Annual Temperature (°C)				-6.85×10^{-2}	3.74×10^{-2}	0.01	−0.10	4.42×10^{-2}*	0.04
R2			0.10			0.06			0.12
Full Model R2			0.29			0.34			0.37

* p-value < 0.05,

** p-value < 0.01,

*** p-value < 0.001.

Blank spaces correspond to variables not selected during stepwise regression.

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