National Patterns in Environmental Injustice and Inequality: Outdoor NO_2 Air Pollution in the United States

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Abstract

We describe spatial patterns in environmental injustice and inequality for residential outdoor nitrogen dioxide (NO_2) concentrations in the contiguous United States. Our approach employs Census demographic data and a recently published high-resolution dataset of outdoor NO_2 concentrations. Nationally, population-weighted mean NO_2 concentrations are 4.6 ppb (38%, $p<0.01$) higher for nonwhites than for whites. The environmental health implications of that concentration disparity are compelling. For example, we estimate that reducing nonwhites' NO_2 concentrations to levels experienced by whites would reduce Ischemic Heart Disease (IHD) mortality by ~7,000 deaths per year, which is equivalent to 16 million people increasing their physical activity level from inactive (0 hours/week of physical activity) to sufficiently active (>2.5 hours/week of physical activity). Inequality for NO_2 concentration is greater than inequality for income (Atkinson Index: 0.11 versus 0.08). Low-income nonwhite young children and elderly people are disproportionately exposed to residential outdoor NO_2. Our findings establish a national context for previous work that has documented air pollution environmental injustice and inequality within individual US metropolitan areas and regions. Results given here can aid policy-makers in identifying locations with high environmental injustice and inequality. For example, states with both high injustice and high inequality (top quintile) for outdoor residential NO_2 include New York, Michigan, and Wisconsin.

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Introduction

Environmental injustice often places disproportionate health risks on people who are already the most vulnerable or susceptible to those risks. Since the earliest US environmental justice studies [1–6] in the 1960s–1980s, disparities in exposures to environmental risks (e.g., landfills, hazardous waste sites, polluting industries, vehicle traffic) by socioeconomic status (SES) have been widely documented [7–9]. Air pollution is a priority environmental risk in the United States (US): urban outdoor air pollution is one of the top ten causes of death in high-income nations [10]. Low-SES communities are often disproportionately exposed to air pollution [11] and also may be more susceptible to air pollution owing to other underlying disparities in, for example, access to health care [12].

Although relationships between air pollution exposure and SES have been documented in certain US cities, little is known about the broader patterns in ambient air pollution environmental justice within and across US geographies (cities, regions, states, urban versus rural areas). This previous lack of understanding is largely because of the limited coverage and spatial resolution of ambient air pollution data. Recent work exploring air pollution environmental justice in US cities or regions has been based on industrial emissions-based air pollution concentration estimates [13–16], or has focused on people living near regulatory monitor locations [17–19]. Those multi-city and national studies reported differences in environmental injustice by US region [18], metropolitan area [13] and urban form characteristics of metropolitan areas [15–17].

Here, we employ a recently developed ambient air pollution dataset [20] to explore patterns in environmental justice within and across US geographies, including rural and urban populations. The work applies a national land use regression with high spatial resolution (~0.1 km) to examine residential outdoor nitrogen dioxide (NO_2) air pollution in the US. NO_2, which is one of the six US Environmental Protection Agency criteria pollutants, in the US is mainly emitted (as NO_x) from combustion in vehicles and power plants [21]; it is a marker for traffic emissions [22] and has high within-urban variability [23,24]. NO_2 and other traffic emissions are linked to asthma [25] and decreased lung function [26] in children, low birth-weights [27], and cardiovascular and respiratory mortality (e.g., ischemic heart disease mortality) [28,29]. Previous work in specific US cities suggests that ambient NO_2 (and/or NO_x) concentrations tend to be higher in low- than in high-SES communities [30–33].

This paper applies a national-scale analysis to quantify US-wide NO_2 concentration patterns by SES characteristics. It provides quantitative information for understanding how environmental equality and justice for air pollution vary among communities and regions across the US. A goal of this study is to identify US locations with highest priority environmental justice and equality concerns attributable to NO_2 and co-emitted air pollutants.

Methods

1. Data

Our analysis covers the year-2000 population of the contiguous US (280 million people). The spatial unit of analysis is the Census Block Group (BG), which is the smallest Census geography with demographic data (race-ethnicity, household income, poverty status, education status, and age) reported in the 2000 Census. Of all BGs ($n = 207{,}492$), 64% are urban, 14% are rural, and 21% are mixed urban-rural (i.e., contain both urban and rural Census Blocks). The mean BG sizes are 1.1 km^2 (urban), 185 km^2 (rural), and 45 km^2 (mixed); the mean (standard deviation) BG population is 1,350 (890) people.

Air pollution data are year-2006 annual average ground-level NO_2 concentration estimates from a recently published national land use regression (LUR) [20]. This LUR predicts NO_2 concentrations at the Census Block level for the contiguous US based on satellite- and ground-based measurements of NO_2, combined with land use data (e.g., road locations, elevation, tree cover, impervious-surface coverage, population density). To match the Census BG level demographic data, we calculate the mean concentration among all Blocks in each BG. Nationally, the mean NO_2 concentration for all BGs is 11.4 ppb.

2. Statistical Analyses

We calculate population-weighted mean NO_2 concentrations by race-ethnicity, poverty status, household income, education status, and age, using annual mean BG concentrations (from year-2006 LUR data) and population estimates (from year-2000 Census data). For example, the national population-weighted mean NO_2 concentration for nonwhites is the mean of BG mean concentrations weighted by the population of nonwhites in each BG. We then calculate environmental injustice and inequality metrics by US region, state, county, and Urban Area (UA), and rural versus urban location.

Our primary comparison metric for environmental injustice is the difference (ppb) in population-weighted mean NO_2 concentration between lower-income nonwhites (LIN; nonwhites in the lowest annual household income quintile [<$20,000]) and higher-income whites (HIW; whites in the highest annual household income quintile [>$75,000]). Our primary comparison metric for environmental inequality is the Atkinson Index ($\varepsilon = 0.75$ [34–38]), which measures the extent to which NO_2 concentrations are evenly distributed across the population: Atkinson Index = 0 indicates perfect equality (i.e., concentrations are equal for all people); higher values indicate greater inequality (maximum = 1). The US Census information about race covers 100% of the population, whereas combined race-income categories (e.g., whites with income >$75,000) are only available for 38% of the population (one person per household; "householders"). Our injustice metric includes 10% of the total Census population (26% of householders): lower-income nonwhite householders are 2.9% of the total Census population; higher-income white householders are 7.0%. In contrast, the inequality metric and straightforward white/nonwhite comparisons include 100% of the total Census population. See Supporting Information (**Figures S1–S2** and **Table S1** in **File S1**) for sensitivity analyses regarding metric selection.

Results and Discussion

Our results reveal significant disparities in NO_2 concentrations for specific socioeconomic groups (**Table 1; Table 2**). For example, average NO_2 concentrations are 4.6 ppb (38%, $p<0.01$) higher for nonwhites than for whites, 1.2 ppb (10%, $p<0.01$) higher for people below versus above poverty level, and 3.4 ppb (27%, $p<0.01$) higher for lower-income nonwhites than for higher-income whites. Likewise, NO_2 concentrations are higher for residents with less than a high school education compared to those with a high school education or above (difference: 0.9 ppb [8%], $p<0.01$). Among urban residents, NO_2 concentrations for Black Hispanics (the most exposed race-ethnicity group) are 6.1 ppb (38%, $p<0.01$) higher than for American Indians (the least exposed race-ethnicity group) and 4.7 ppb (28%, $p<0.01$) higher than for the total urban population. Urban-rural differences abound: in urban areas, NO_2 concentrations are higher for nonwhites than for whites, and higher for low- than for high-income groups; in contrast, NO_2 concentrations in rural areas are similar for nonwhites and for whites but are slightly lower for low- than for high-income groups. Urban areas exhibit more low- than high-income communities in NO_2-polluted areas (e.g., adjacent to busy roadways), whereas the same trend does not emerge in rural areas. Among race-ethnicity groups, American Indians have the lowest NO_2 exposures in urban areas, but the second highest NO_2 exposures (after Hispanics) in rural areas. Overall, for seven of the eight nonwhite race-ethnicity groups considered (upper portion of **Table 1**), NO_2 concentrations are higher for that group than for whites.

Young children and the elderly are especially vulnerable to air pollution. We find that NO_2 concentrations for these groups correlate with SES. Population-weighted mean NO_2 concentrations are similar (within 3% [0.3 ppb]) for those two subpopulations (elderly: greater than 65 years; young: less than 5 years) as for other age groups (5 to 65 years). However, for below-poverty level nonwhite individuals, NO_2 concentrations are notably higher for young children (3.0 ppb; 23%, $p<0.01$) and elderly people (3.1 ppb; 24%, $p<0.01$) than for the rest of the population (age 5 to 65 years, including whites and nonwhites).

An important issue is whether the NO_2 disparities described above are relevant to public health. To investigate that question, we consider here one illustrative example: ischemic heart disease (IHD) annual deaths associated with NO_2 concentration disparities between nonwhites and whites. Assuming a 6.6% change in IHD mortality rate per 4.1 ppb NO_2 [39] and US-average IHD annual mortality rates (109 deaths per 100,000 people [40]), reducing NO_2 concentrations to levels experienced by whites (a 4.6 ppb [38%] reduction) for all nonwhites (87 million people) would be associated with a decrease of ~7,000 IHD deaths per year. For comparison, interventions with a similar benefit (a decrease in ~7,000 IHD deaths per year) include: 16 million people increasing physical activity level from inactive (0 h/wk) to sufficiently active (>2.5 h/wk)[41]; 25 million people increasing physical activity level from insufficiently active (<2.5 h/wk) to sufficiently active (>2.5 h/wk); or, 3.2 million fewer adults (age 30–44) beginning smoking [42]. Calculations in this paragraph (details in **Table S2** in **File S1**) may underestimate true health impacts because we ignore here differences in vulnerability and susceptibility to air pollution and differences in underlying IHD mortality rates; also, the analysis above considers only one health outcome (IHD mortality) and one pollutant (outdoor NO_2).

Within individual urban areas, even after controlling for urban area size and household income group, nonwhites are generally more exposed to residential outdoor NO_2 air pollution than

Table 1. Population-weighted mean NO_2 concentration in ppb (percent of total population[1]).

	Total	Urban	Mixed	Rural
Total	11.3 (100%)	14.2 (63%)	7.3 (25%)	4.4 (12%)
Race-ethnicity[2]				
White	9.9 (69%)	12.9 (38%)	7.1 (20%)	4.4 (11%)
Nonwhite	14.5 (31%)	16.4 (24%)	8.1 (4.6%)	4.5 (1.6%)
Hispanic	15.6 (13%)	17.2 (10%)	8.6 (1.8%)	5.8 (0.4%)
Black	13.3 (12%)	15.3 (9.4%)	7.4 (1.9%)	3.7 (0.8%)
Asian	16.5 (3.4%)	17.5 (3.0%)	9.7 (0.4%)	4.8 (0.03%)
Two or more races	13.1 (1.6%)	15.3 (1.2%)	7.9 (0.3%)	4.5 (0.1%)
Amer. Indian/Alaska Native	8.8 (0.7%)	12.8 (0.3%)	7.2 (0.2%)	5.4 (0.2%)
Black Hispanic	17.4 (0.3%)	18.9 (0.2%)	9.0 (0.03%)	4.2 (0.01%)
Other race	15.0 (0.2%)	16.9 (0.1%)	8.3 (0.03%)	4.7 (0.01%)
Nat. Hawaiian/Pacific Islander	14.2 (0.1%)	15.7 (0.1%)	8.4 (0.01%)	4.7 (0.003%)
Poverty status				
Below poverty level	12.4 (12%)	15.3 (8.2%)	7.3 (2.3%)	4.3 (1.5%)
Above poverty level	11.2 (85%)	14.1 (53%)	7.3 (22%)	4.5 (10%)
Household income quintile				
<$20,000	11.4 (8.3%)	14.4 (5.3%)	7.3 (1.8%)	4.3 (1.2%)
$20,000–$35,000	11.0 (7.3%)	13.9 (4.6%)	7.2 (1.7%)	4.4 (1.0%)
$35,000–$50,000	10.9 (6.2%)	13.9 (3.8%)	7.2 (1.5%)	4.4 (0.8%)
$50,000–$75,000	11.0 (7.3%)	13.9 (4.5%)	7.3 (1.9%)	4.5 (0.9%)
>$75,000	11.7 (8.4%)	14.2 (5.5%)	7.7 (2.3%)	4.6 (0.6%)
Education level for population >25 years old				
Less than high school degree	12.0 (13%)	15.5 (8.0%)	7.2 (2.8%)	4.3 (1.9%)
High school degree	10.5 (19%)	13.9 (10%)	7.1 (5.0%)	4.4 (3.1%)
Some post-secondary	11.0 (18%)	13.8 (11%)	7.3 (4.6%)	4.5 (2.0%)
Bachelor's degree	11.7 (10%)	14.0 (6.8%)	7.6 (2.5%)	4.5 (0.7%)
Graduate degree	12.1 (5.7%)	14.3 (4.0%)	7.7 (1.4%)	4.5 (0.4%)
Age				
<5 years	11.6 (6.8%)	14.4 (4.4%)	7.4 (1.7%)	4.5 (0.8%)
5 to 18 years	11.2 (19%)	14.2 (12%)	7.2 (4.8%)	4.5 (2.4%)
18 to 40 years	11.8 (32%)	14.5 (21%)	7.4 (7.4%)	4.4 (3.3%)
40 to 65 years	11.0 (30%)	14.1 (18%)	7.2 (7.9%)	4.4 (4.0%)
>65 years	11.0 (12%)	13.9 (7.7%)	7.3 (3.1%)	4.4 (1.7%)
Children (<5 years) below poverty level				
White	9.1 (0.4%)	12.5 (0.2%)	6.9 (0.1%)	4.3 (0.1%)
Nonwhite	14.3 (0.8%)	16.1 (0.6%)	7.9 (0.1%)	4.7 (0.1%)
Elderly (>65 years) below poverty level				
White	9.9 (0.8%)	13.5 (0.4%)	7.1 (0.2%)	4.2 (0.2%)
Nonwhite	14.5 (0.2%)	16.9 (0.2%)	7.7 (0.03%)	4.3 (0.02%)

[1]Population totals may be less than 100% because of rounding, nonresponses in Census data, and category definitions (e.g., population >25 years old is 66% of total population).
[2]Each race-ethnicity category in **Table 1** includes people who reported a single race category and non-Hispanic ethnicity (i.e., ''White'' category is ''White alone; non-Hispanic''), except for the ''Hispanic'' category, which includes people who reported any race(s) and Hispanic ethnicity, and the ''Black Hispanic'' category, which includes people who reported Black race alone and Hispanic ethnicity.
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whites. **Figure 1** presents regression models predicting population-weighted mean NO_2 concentration as a function of household income for all 16 Census-defined household income categories and for the 4 largest race-ethnicity groups (Whites, Hispanics, Blacks, Asians) by urban area size (small; medium; large; defined by urban population tertiles). Each within-urban model reveals an inverse relationship between population-weighted NO_2 concentration and household income with high statistical significance ($R^2>0.86$; model p-value<0.01; **Tables S3–S18** in **File S1**). Across household income groups, urban NO_2 concentrations are often highest for Asians or Hispanics and lowest for Whites.

Table 2. Comparisons between population-weighted mean NO_2 concentrations for specific populations.

Group 1 (concentration in ppb)	Group 2 (concentration in ppb)	Difference[1] (ppb)	Relative Difference (%)
National comparisons			
Nonwhites (14.5)	Whites (9.9)	4.6	38
Below poverty (12.4)	At or above poverty (11.2)	1.2	10
Low-income nonwhites (14.4)	High-income whites (11.0)	3.4	27
Less than high school degree (12.0)	High school degree or above (11.1)	0.9	8
Children<5 years (11.6)	Age 5 to 65 years (11.3)	0.2	2
Nonwhite children below poverty level (14.3) poverty	Age 5 to 65 years (11.3)	3.0	23
Elderly>65 years (11.0)	Age 5 to 65 years (11.3)	−0.3	−3
Nonwhite elderly below poverty level (14.5)	Age 5 to 65 years (11.3)	3.1	24
Urban comparisons			
Black Hispanics (18.9)	American Indians (12.8)	6.1	38
Black Hispanics (18.9)	Total (14.2)	4.7	28

[1]Difference in population-weighted mean concentration [Group 1 - Group 2]. For all rows, differences are statistically significant with $p<0.001$.
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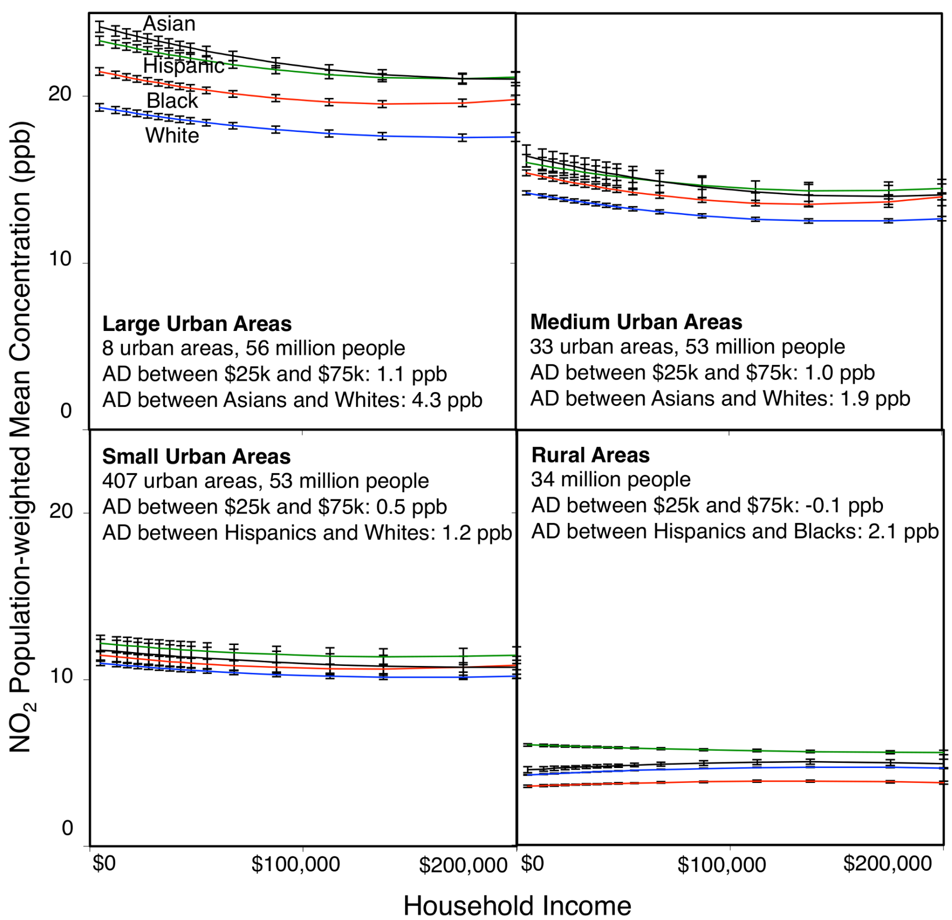

Figure 1. Within-urban and within-rural population-weighted mean NO_2 concentrations (105 million householders) by Census household income category, race, and urban category (large UA population tertile, medium UA population tertile, small UA population tertile, or rural). Concentrations shown are modeled by UA population tertile (linear regressions: $R^2>0.98$ [large UAs], >0.96 [medium UAs], >0.86 [small UAs], >0.47 [rural]; all models are statistically significant at $p<0.01$; see **Tables S3–S18** in **File S1**). For visual display, plots use the population-weighted mean UA-specific dummy variable for each UA population tertile. Error bars show the 95% confidence intervals on linear regression model predictions. AD = average difference, UA = Urban Area. AD values shown are for interquartile range incomes ($25k, $75k) and for race-ethnicity groups with highest and lowest concentrations for that panel.
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Within individual urban areas, on average, NO_2 concentration disparities by race (after controlling for income) are more than 2 times greater than NO_2 concentration disparities by income (after controlling for race). The relative importance of race versus income for environmental injustice increases with urban area size. For each urban area size category, we compared average differences in NO_2 concentrations between the race group (of the 4 largest race groups) with the highest versus the lowest NO_2 concentrations (controlling for household income group) to the average differences in NO_2 concentrations between the $25,000 versus $75,000 income groups (approximate income interquartile range; controlling for race group; **Figure 1**). In large urban areas, disparities by race are ~4 times greater than by income. In medium and small urban areas, disparities by race are ~2 times greater than by income. For rural residents, differences by race are ~20 times greater than by income (despite significantly lower average concentrations for rural versus urban residents: 4.4 ppb [rural population-weighted mean] versus 14.2 ppb [urban population-weighted mean]). For rural areas, differences by income are small (0.1 ppb) and in the opposite direction as for the US as a whole (i.e., in rural areas, concentrations are higher for higher- than for lower-income groups).

As an alternative analysis, we developed NO_2 regression models for which each observation is a Block Group concentration rather than population-weighted concentration (by location, income and race category; **Tables S19–S30** in **File S1**). Results for the Block Group and population-weighted analyses cannot be compared directly. Block Group analyses indicate a more varied relationship with race and with income, but in general suggest that NO_2 concentrations are higher for nonwhites than for whites and are higher for lower-income than for higher-income communities; and, on average, disparities are greater by race (percent white) than by income.

Inequality metrics are presented in **Table 3**. On a national scale, we find that inequality levels are higher for NO_2 (Atkinson Index = 0.11) than for income (Atkinson Index = 0.08), despite the fact that the US has a high degree of income inequality compared to most developed nations [43].

Figure 2. shows national spatial patterns in environmental injustice and inequality in outdoor NO_2 air pollution. States with high levels (top quintile) of both injustice and inequality include New York, Michigan, and Wisconsin. Given previous work documenting inequality and injustice in NO_2 concentrations (among other environmental hazards) it is not surprising that we observe injustice and inequality in NO_2 concentrations on a national basis. What is unexpected, however, are the spatial patterns in **Figure 2**. Environmental injustice and inequality do not exhibit clear spatial coherence with respect to regional race or income characteristics. For example, among urban areas, environmental inequality (Atkinson Index) has a low correlation with race (percent nonwhite) and average income [Pearson's $r<0.2$]. Understanding the processes driving these spatial distributions of environmental injustice and inequality is thus a priority need for future research.

Inequality and injustice metrics vary by location. NO_2 inequality (Atkinson Index) is slightly higher among rural residents than among urban residents, but environmental injustice may be higher for urban residents: NO_2 concentration differences between lower-income nonwhites and higher-income whites are an order of magnitude higher and in the opposite direction for urban residents as for rural residents (2.8 ppb versus −0.3 ppb; see **Table 1**). Across the 448 urban areas in the US, there is variation in injustice (difference range [ppb]: −1.1 to 6.0) and inequality (Atkinson Index range: 0.00008 to 0.04) for NO_2 air pollution, consistent with a previous multi-city study [13]. In 426 of 448 urban areas (accounting for 99% of the total US urban population), NO_2 concentrations are higher for the lower-income nonwhite group than for the higher-income white group, with injustice and inequality tending to be higher in large urban areas. Supporting Information (**File S2**) provides environmental injustice and inequality rankings by urban area, county, and state.

A contribution of this work is that it covers the entire contiguous US population, including both urban and rural populations, with

Table 3. Environmental injustice and inequality metric mean (population-weighted mean) [range].

	Environmental Injustice	Environmental Inequality
	Difference[1] between low-income nonwhites and high-income whites (ppb)	Atkinson Index[2]
National	3.4	0.11
Urban	2.8	0.059
Mixed	0.4	0.062
Rural	−0.3	0.080
Regions (n = 10)	3.6 (3.7) [1.1 to 7.1]	0.083 (0.083) [0.064 to 0.12]
States (n = 49)	2.5 (3.5) [−0.6 to 7.2]	0.068 (0.073) [0.006 to 0.14]
Counties[3] (n = 3,109)	0.8 (1.9) [−2.6 to 7.0]	0.031 (0.027) [0.000006 to 0.17]
Urban Areas (n = 448)	1.3 (2.8) [−1.1 to 6.0]	0.009 (0.016) [0.00008 to 0.040]
Large Urban Areas (n = 8)	3.6 (4.0) [0.8 to 6.0]	0.018 (0.020) [0.009 to 0.031]
Medium Urban Areas (n = 33)	2.6 (2.7) [1.1 to 5.0]	0.015 (0.015) [0.005 to 0.039]
Small Urban Areas (n = 407)	1.1 (1.7) [−1.1 to 4.7]	0.009 (0.012) [0.0001 to 0.040]

[1]Larger positive differences indicate greater injustice (concentrations are higher for low-income nonwhites than for high-income whites). A negative value denotes concentrations being lower for low-income nonwhites than for high-income whites.
[2]Larger Atkinson Indices indicate greater inequality. Inequality aversion coefficient: $\varepsilon = 0.75$.
[3]This analysis excludes counties that consist of 1 Block Group (n = 29; total population = 21,500 people) or contain 0 low-income nonwhites and/or 0 high-income whites (n = 16; total population = 65,800 people).
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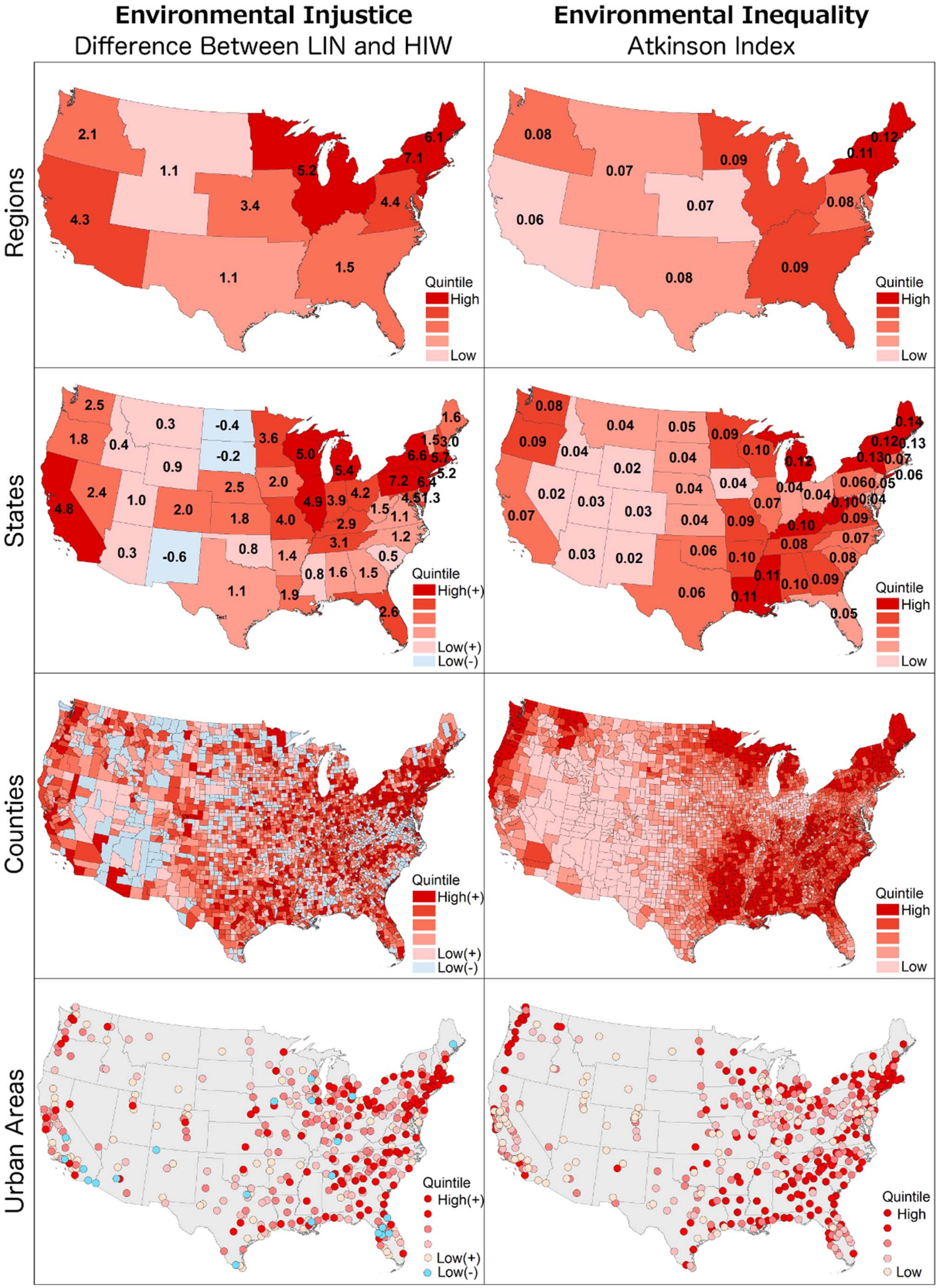
Environmental Injustice
Difference Between LIN and HIW
Environmental Inequality
Atkinson Index
Regions
States
Counties
Urban Areas
Quintile
High
Low
High(+)
Low(+)
Low(-)

Figure 2. Environmental injustice and inequality in residential outdoor NO_2 concentrations for US regions, states, counties and urban areas. The left column shows differences in population-weighted mean NO_2 concentrations between low-income nonwhites (LIN) and high-income whites (HIW), with larger positive differences (red colors) indicating higher injustice (larger concentration difference between LIN and HIW). The right column shows the Atkinson Index, with higher values indicating greater inequality.
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higher spatial precision in urban areas (urban BG-scale: ~1-km; LUR scale: ~0.1-km) relative to previous regional or multi-city air quality environmental equality and/or justice studies (typical air quality model-scale: ~12-km grid or coarser). Although the spatial resolution is higher than in previous work, resolution is still a limitation: because we are using Census demographic data, we are unable to study within-BG variations. As a second limitation, we measure inequality for one pollutant (NO_2); inequality may differ for other pollutants (e.g., ozone [44]) or for multi-pollutant cumulative exposure [32]. As a third limitation, we study only ambient pollution; disparities may also exist for indoor NO_2 emissions (e.g., owing to indoor sources such as natural gas combustion), for indoor-outdoor pollution relationships (e.g., because low-income households may live in comparatively older, leakier buildings), and for occupational and commute exposures. As a fourth limitation, there is a temporal mismatch between the year-2000 Census data and year-2006 air pollution data. We expect demographic changes during that time to be small compared to the cross-sectional differences explored here.

We investigated environmental injustice and inequality in residential outdoor NO_2 air pollution for the contiguous US population. Nationally, inequality in average NO_2 concentration is greater than inequality in average income. Nonwhites experience 4.6 ppb (38%) higher residential outdoor NO_2 concentrations than whites – an exposure gap that has potentially large impacts to public health. Within individual urban areas, after controlling for income, nonwhites are on average exposed to higher outdoor residential NO_2 concentrations than whites; and, after controlling for race, lower-income populations are exposed to higher outdoor residential average NO_2 concentrations than higher-income populations. The spatial patterns observed for inequality and injustice nationally (**Figure 2**) are not predicted by region, race, or income. Our results highlight a need for future work exploring the reasons behind these spatial distributions of environmental injustice and inequality. Results given here provide strong US-wide evidence of ambient NO_2 air pollution injustice and inequality, establish a national context for studies of individual metropolitan areas and regions, and enable comprehensive tracking over time. Hopefully results given here will usefully allow policy-makers to identify counties and urban areas with highest priority NO_2 air pollution environmental justice and equality concerns.

Supporting Information

File S1
(PDF)

File S2
(XLSX)

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Matthew Bechle calculated Block Group mean NO_2 concentrations. The Minnesota Supercomputing Institute provided computational resources.

Author Contributions

Conceived and designed the experiments: LPC DBM JDM. Analyzed the data: LPC DBM JDM. Wrote the paper: LPC DBM JDM.

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Supporting Information

Title: National patterns in environmental injustice and inequality: outdoor NO_2 air pollution in the United States

Authors: Lara P. Clark, Dylan B. Millet, Julian D. Marshall

Filse S1 Contents:
42 pages (.pdf)
Figures S1-S2
Tables S1-S30

File S2 Contents:
Spreadsheet of environmental injustice and inequality rankings for states, counties, and urban areas (.xls)

Supporting information for environmental injustice and inequality metrics

Equation S1 presents the calculation of population-weighted NO_2 concentration (C), where i indexes the Block Groups, c_i is the mean concentration for each Block Group i; p_i is the population of Block Group i; and n is the number of Block Groups. As an example, for calculating the population-weighted NO_2 concentration for urban whites, c_i is the mean concentration for each urban Block Group i; p_i is the white population of urban Block Group i; and n is the number of urban Block Groups

(Equation S1)

$$C = \frac{\sum_{i=1}^{n} c_i p_i}{\sum_{i=1}^{n} p_i}$$

Equations S2-S3 present the calculation of the Atkinson Index (A) for grouped Census data [1,2], under two conditions for the inequality aversion parameter (ε): ε = 1 (**Equation S2**) or ε ≠ 1 (**Equation S3**). Here, i indexes the Block Groups within the geographical unit of interest (e.g., a specific state, county, or urban area), c is the mean concentration in Block Group i; f_i is the fraction of total population of the geographical unit of interest in Block Group i; c_i is the mean concentration in Block Group i; and w is the population-weighted mean concentration among Block Groups in the geographical unit of interest.

(Equation S2)

$$A = 1 - \exp\left(\left[\frac{1}{n}\right]\sum_{i=1}^{n} f_i \log\left(\frac{c_i}{w}\right)\right)$$

(Equation S3)

$$A=1-\left(\left[\frac{1}{n}\right]\sum_{i=1}^{n} f_i\left(\frac{c_i}{w}\right)^{(1-\varepsilon)}\right)^{\left(\frac{1}{1-\varepsilon}\right)}$$

Figure S1 presents a sensitivity analysis on the selection of the Atkinson Index (with inequality aversion parameter, $\varepsilon = 0.75$) as the core environmental inequality metric presented in the main text. This core environmental inequality metric is highly correlated (Pearson's correlation coefficients > |0.96| and Spearman's rank coefficients > |0.98|) with the alternate environmental inequality metrics we considered (Atkinson Indices with $\varepsilon = \{0.25, 0.5, 1, 1.25, 1.5, 2\}$), Gini coefficient, and Gini coefficents on modified and inverse NO_2 datasets) among the 448 urban areas. Thus, the conclusions presented in the main text are not highly sensitive to the core metric selection for environmental inequality.

As a supplement to **Figure 2** and **Table 3** in the main text, **Figure S2** and **Table S1** present alternate metrics for environmental injustice (relative percent difference between lower-income nonwhites and higher-income whites) and inequality (Gini coefficient) for US regions, states, counties and urban areas.

Supporting information for health impact estimates

Table S2 provides details for the public health impacts (reductions in Ischemic Heart Disease mortality) associated with disparities in NO_2 concentration differences observed between nonwhites and whites.

Supporting information for regression models

Tables S3-S18 present linear regression model details for **Figure 1** in the main text. The dependent variable in each model is the population-weighted NO_2 concentration for Census householders. The independent variables are income, income-squared, and, for urban models, a dummy variable to control for specific urban area. We developed separate regression models for each of the 4 largest race-ethnicity categories (white, black, hispanic, asian) in 4 location categories (large urban areas, medium urban areas, small urban areas, rural areas), yielding 16 total regression models.

As an alternative analysis to **Figure 1** in the main text, **Tables S19-S30** present NO_2 regression models for which each observation is a Block Group concentration rather than population-weighted concentration. The dependent variable for each model is the Block Group mean NO_2 concentration. The independent variables are Block Group average income, Block Group average income-squared, and Block Group percent white population. We developed separate regression models for each of the 3 Block Group percent white population tertiles and for each of 4 location categories (large urban areas, medium urban areas, small urban areas, and rural areas), yielding 12 total regression models. Compared to the population-weighted concentration analyses (**Figure 1**; **Tables S3-S18**), Block Group analyses indicate a more varied relationship with race and with income, but in general suggest that NO_2 concentration disparities are greater by race (percent white tertile) than by income.

Supporting information references

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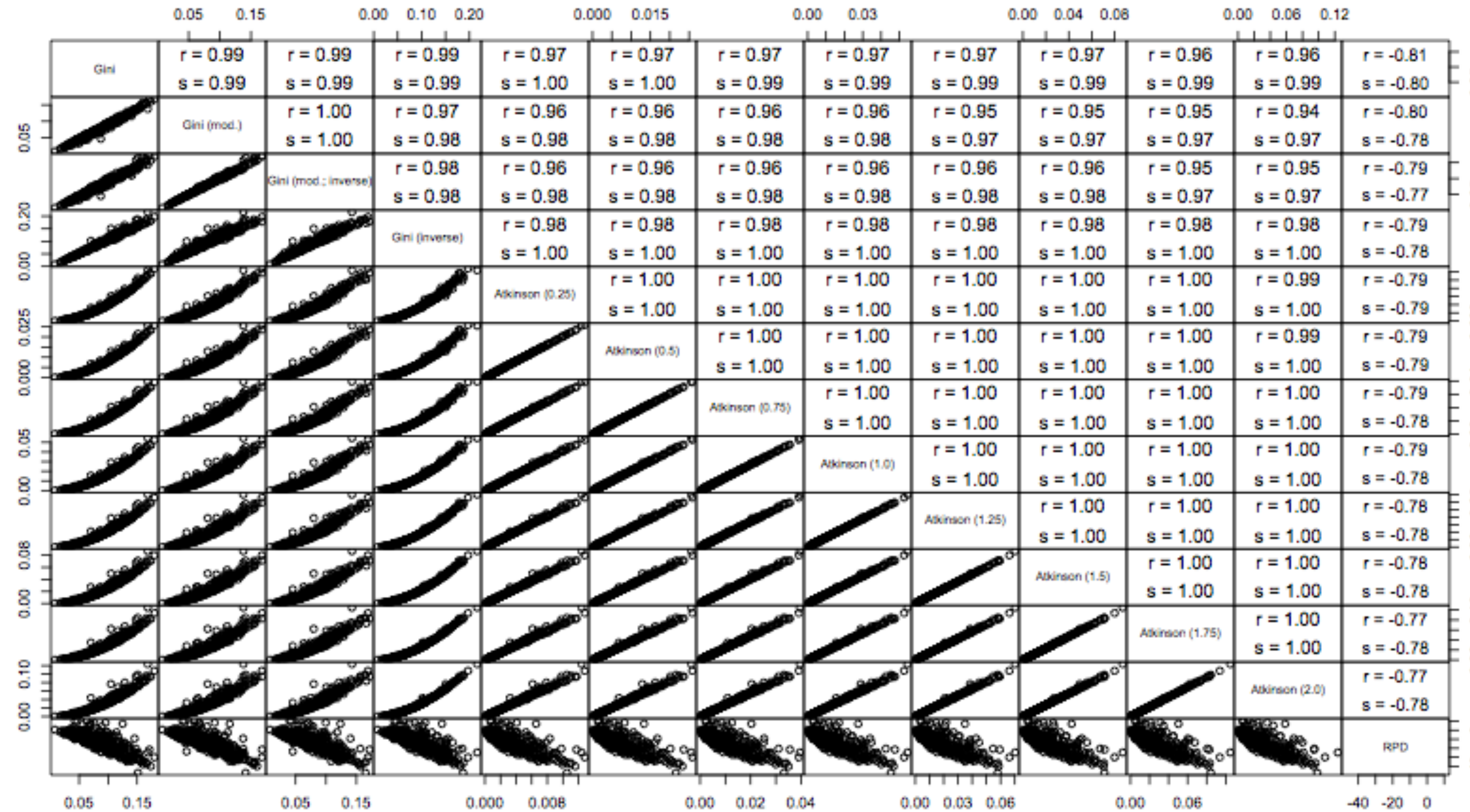

Figure S1. Correlations among environmental injustice and inequality metrics (Pearson's correlation coefficient, r; Spearman's rank correlation coefficient, s) for urban areas (*n*=448). "Atkinson (0.75)" indicates Atkinson Index calculated with the inequality aversion parameter (ε) = 0.75. "Gini (mod.)" indicates the Gini Coefficient calculated on a modified NO_2 dataset in which the BGs with the lowest 10% of NO_2 concentrations in each UA are clipped to the 10th percentile concentration in the UA. "Gini (inverse)" indicates the Gini Coefficient calculated using the inverse of concentration (ppb^{-1}) for all BGs.

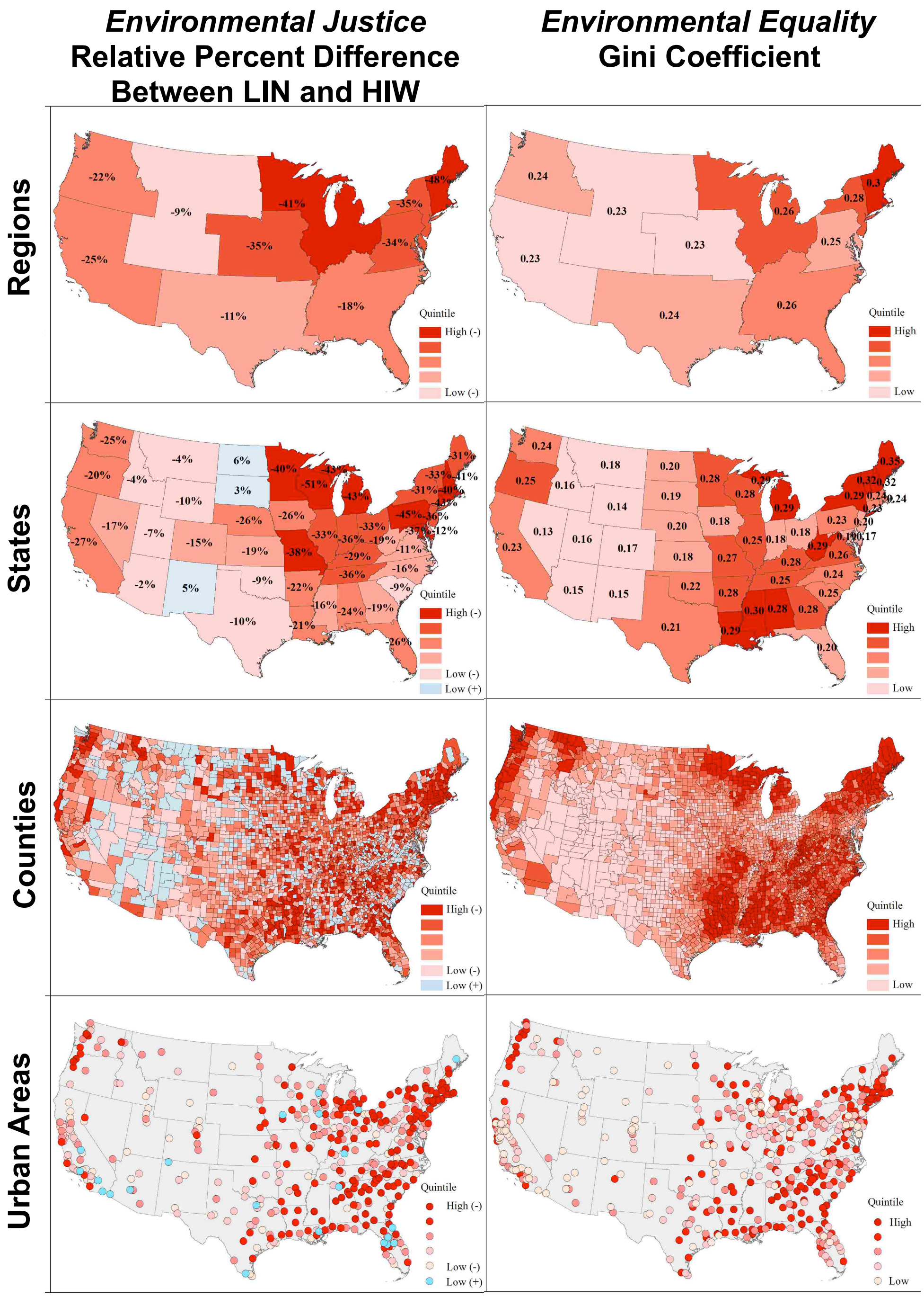

Figure S2. Supplemental environmental injustice and inequality in residential outdoor NO_2 concentrations for US regions, states, counties and urban areas. The left column shows relative difference in population-weighted mean NO_2 concentration between low-income nonwhites and high-income whites, with larger positive differences (red colors) indicating higher injustice (larger relative percent difference between lower-income nonwhites and higher-income whites). The right column shows the Gini Coefficient, with higher values indicating greater inequality.

Table S1. Supplemental environmental injustice and inequality metric means (ranges)

	Environmental Injustice Difference[2] in population-weighted concentration between low-income nonwhites and high-income whites (%)	Environmental Inequality Gini Coefficient[1]
National	27%	0.30
Urban	19%	0.23
Mixed	5%	0.22
Rural	-7%	0.26
Regions (*n* =10)	28% (9% to 48%)	0.25 (0.23 to 0.30)
States (*n* = 49)	23% (6% to 51%)	0.23 (0.08 to 0.35)
Counties[3] (*n* = 3,109)	11% (-52% to 67%)	0.14 (0.0008 to 0.38)
Urban Areas (*n* = 448)	12% (11% to 47%)	0.08 (0.008 to 0.18)

[1]Larger Gini Coefficients indicate greater inequality.
[2]Larger positive percent differences indicate greater injustice (low-income nonwhites more exposed relative to high-income whites). Negative differences indicate that high-income whites are more exposed relative to low-income nonwhites.
[3]This analysis excludes counties that consist of 1 Block Group (*n*=29; total population = 21,500 people) or contain 0 low-income nonwhites and/or 0 high-income whites (*n*=16; total population = 65,800 people).

Table S2. Public health impact data and calculations

Data for calculations	Value	Source
NO_2 population-weighted concentrations		
Nonwhites	14.5 ppb	Table 1
Whites	9.9 ppb	Table 1
Difference	4.6 ppb	Table 1
Relative risks in Ischemic Heart Disease mortality		
Increasing NO_2 concentrations by 4.1 ppb	1.066	Jerrett et al., 2013 [3]
NO_2 concentrations experienced by nonwhites (14.5 ppb)	1.254[a]	Table S2[a]
NO_2 concentrations experienced by whites (9.9 ppb)	1.167[a]	Table S2[a]
Increasing physical activity level from inactive (0 h/wk) to sufficiently active (>2.5 h/wk)	1.47[b]	WHO 2004 [4]
Increasing physical activity level from insufficient (<2.5 h/wk) to sufficiently active (>2.5 h/wk)	1.31[b]	WHO 2004 [4]
Nonsmoking versus smoking status (adults age 30-44 years)	3.9[c]	Danaei et al., 2009 [5]
Population data		
Nonwhite population	87 million	Census 2000 [6]
Ischemic Heart Disease mortality rate	109 deaths per 100,000 people	CDC 2013 [7]

[a]Relative risks (RR) for NO_2 concentrations experienced by nonwhites and whites calculated using: RR = $exp(\beta c)$, where c is the NO_2 concentration (units: ppb), and $\beta = ln(1.066)/(4.1 \text{ ppb}) = 0.0156 \text{ ppb}^{-1}$.

[b]Since ~29% of the US adult population is physically inactive, ~45% is insufficiently physically active, and ~26% is sufficiently physically active [4], based on an overall IHD annual mortality of 109 (units: deaths per 100,000 people), IHD annual mortality would be 125.6 for physically inactive adults, 111.9 for insufficiently active adults, and 85.4 for sufficiently active adults. Thus, the annual risk difference attributable to increasing physical activity level from inactive to sufficiently active is 125.6 - 85.4 = **40.2 IHD deaths per 100,000 people**; and, the annual risk difference attributable to increasing physical activity level from insufficiently to sufficiently active is 111.9 - 85.4 = **26.5 IHD deaths per 100,000 people**.

[c]Relative risk (RR) for IHD mortality for smoking versus non-smoking adults age 30-44 years: 5.5 (men); 2.3 (women). Thus, the average RR (for both men and women) is 3.9. Since ~18% of the US adult population smokes [8], based on an overall IHD annual mortality of 109 (units: deaths per 100,000 people), IHD annual mortality would be 279.3 for smokers, 71.6 for nonsmokers; the annual risk difference attributable to changing smoking status is 279.3 – 71.6 = **207.7 IHD deaths per 100,000 people**.

Ischemic Heart Disease (IHD) mortality reduction per year associated with reducing annual NO_2 concentrations for all nonwhites to levels experienced by whites:

$$87{,}000{,}000 \text{ people} \times \frac{109 \text{ IHD deaths}}{100{,}000 \text{ people}} \times \frac{1.254 - 1.0}{1.254} = 19{,}208 \text{ IHD deaths}$$

$$87{,}000{,}000 \text{ people} \times \frac{109 \text{ IHD deaths}}{100{,}000 \text{ people}} \times \frac{1.167 - 1.0}{1.254} = 12{,}629 \text{ IHD deaths}$$

Difference =19,208 - 12,629 = **6,579 IHD deaths per year**

Number of people changing from smoking to nonsmoking status associated with a reduction of 6,579 IHD deaths per year:

$$6{,}579 \text{ IHD deaths} \times \frac{100{,}000 \text{ people}}{207.7 \text{ IHD deaths}} = \mathbf{3.2\ million\ people}$$

Number of people changing physical activity status from inactive to sufficiently active associated with a reduction of 6,579 IHD deaths per year:

$$6{,}579 \text{ IHD deaths} \times \frac{100{,}000 \text{ people}}{40.2 \text{ IHD deaths}} = \mathbf{16\ million\ people}$$

Number of people changing physical activity status from insufficiently active to sufficiently active associated with a reduction of 6,579 IHD deaths per year:

$$6{,}579 \text{ IHD deaths} \times \frac{100{,}000 \text{ people}}{26.5 \text{ IHD deaths}} = \mathbf{25\ million\ people}$$

Table S3. **Linear regression model results for population-weighted concentrations for White householders in large Urban Areas**

Variable	Coefficient	*p*-value
(Intercept)	15.62	0.0000***
Income[a]	-1.35E-05	0.0000***
Income[a]-squared	6.36E-11	0.0000***
Urban Area-specific dummy variables[b]		
Dallas--Fort Worth--Arlington, TX Urbanized Area	-2.24	0.0000***
Detroit, MI Urbanized Area	-1.00	0.0000***
Los Angeles--Long Beach--Santa Ana, CA Urbanized Area	7.36	0.0000***
Miami, FL Urbanized Area	-4.11	0.0000***
New York--Newark, NY--NJ--CT Urbanized Area	5.98	0.0000***
Philadelphia, PA--NJ--DE--MD Urbanized Area	0.48	0.0004***
Washington, DC--VA--MD Urbanized Area	-2.50	0.0000***
Model adjusted R^2 = 0.98		
Model *p*-value = 0.0000***		
n = 128		

[a]Income is the mid-point of the Census household income category, transformed by subtracting the mean household income.
[b]The reference UA (for which the UA specific dummy variable = 0) is Chicago, IL.

Statistical significance: *p<0.1; **p<0.05; ***p<0.01

Table S4. Linear regression model results for population-weighted concentrations for Black householders in large Urban Areas

Variable	Coefficient	*p*-value
(Intercept)	17.46	0.0000***
Income[a]	-1.54E-05	0.0000***
Income[a]-squared	9.60E-11	0.0000***
Urban Area-specific dummy variables[b]		
Dallas--Fort Worth--Arlington, TX Urbanized Area	-4.35	0.0000***
Detroit, MI Urbanized Area	0.10	0.47
Los Angeles--Long Beach--Santa Ana, CA Urbanized Area	8.18	0.0000***
Miami, FL Urbanized Area	-4.60	0.0000***
New York--Newark, NY--NJ--CT Urbanized Area	7.59	0.0000***
Philadelphia, PA--NJ--DE--MD Urbanized Area	1.53	0.0000***
Washington, DC--VA--MD Urbanized Area	-3.67	0.0000***

Model adjusted $R^2 = 0.99$

Model p-value = 0.0000***

$n = 128$

[a]Income is the mid-point of the Census household income category, transformed by subtracting the mean household income.
[b]The reference UA (for which the UA specific dummy variable = 0) is Chicago, IL.

Statistical significance: *p<0.1; **p<0.05; ***p<0.01

Table S5. Linear regression model results for population-weighted concentrations for Hispanic householders in large Urban Areas

Variable	Coefficient	*p*-value
(Intercept)	17.85	0.0000***
Income[a]	-1.73E-05	0.0000***
Income[a]-squared	8.71E-11	0.0000***
Urban Area-specific dummy variables[b]		
Dallas--Fort Worth--Arlington, TX Urbanized Area	-4.09	0.0000***
Detroit, MI Urbanized Area	-2.22	0.0000***
Los Angeles--Long Beach--Santa Ana, CA Urbanized Area	7.98	0.0000***
Miami, FL Urbanized Area	-5.22	0.0000***
New York--Newark, NY--NJ--CT Urbanized Area	6.98	0.0000***
Philadelphia, PA--NJ--DE--MD Urbanized Area	0.87	0.0000***
Washington, DC--VA--MD Urbanized Area	-4.00	0.0000***

Model adjusted R^2 = 0.99

Model *p*-value = 0.0000***

n = 128

[a]Income is the mid-point of the Census household income category, transformed by subtracting the mean household income.
[b]The reference UA (for which the UA specific dummy variable = 0) is Chicago, IL.

Statistical significance: *$p<0.1$; **$p<0.05$; ***$p<0.01$

Table S6. Linear regression model results for population-weighted concentrations for Asian householders in large Urban Areas

Variable	Coefficient	*p*-value
(Intercept)	16.78	0.0000***
Income[a]	-2.23E-05	0.0000***
Income[a]-squared	8.94E-11	0.0000***
Urban Area-specific dummy variables[b]		
Dallas--Fort Worth--Arlington, TX Urbanized Area	-3.06	0.0000***
Detroit, MI Urbanized Area	-1.78	0.0000***
Los Angeles--Long Beach--Santa Ana, CA Urbanized Area	8.09	0.0000***
Miami, FL Urbanized Area	-4.94	0.0000***
New York--Newark, NY--NJ--CT Urbanized Area	7.91	0.0000***
Philadelphia, PA--NJ--DE--MD Urbanized Area	0.82	0.0000***
Washington, DC--VA--MD Urbanized Area	-3.64	0.0000***
Model adjusted $R^2 = 0.99$		
Model p-value = 0.0000***		
$n = 128$		

[a]Income is the mid-point of the Census household income category, transformed by subtracting the mean household income.
[b]The reference UA (for which the UA specific dummy variable = 0) is Chicago, IL.

Statistical significance: *p<0.1; **p<0.05; ***p<0.01

Table S7. Linear regression model results for population-weighted concentrations for White householders in medium Urban Areas

Variable	Coefficient	*p*-value
(Intercept)	10.51	0.0000***
Income[a]	-1.33E-05	0.0000***
Income[a]-squared	7.70E-11	0.0000***
Urban Area-specific dummy variables[b]		
Austin, TX Urbanized Area	0.54	0.0000***
Baltimore, MD Urbanized Area	2.58	0.0000***
Boston, MA--NH--RI Urbanized Area	4.05	0.0000***
Buffalo, NY Urbanized Area	1.15	0.0000***
Cincinnati, OH--KY--IN Urbanized Area	1.80	0.0000***
Cleveland, OH Urbanized Area	3.56	0.0000***
Columbus, OH Urbanized Area	2.86	0.0000***
Denver--Aurora, CO Urbanized Area	5.82	0.0000***
Houston, TX Urbanized Area	2.70	0.0000***
Indianapolis, IN Urbanized Area	1.87	0.0000***
Kansas City, MO--KS Urbanized Area	0.80	0.0000***
Las Vegas, NV Urbanized Area	4.61	0.0000***
Louisville, KY--IN Urbanized Area	1.94	0.0000***
Memphis, TN--MS--AR Urbanized Area	-0.36	0.0000***
Milwaukee, WI Urbanized Area	0.88	0.0000***
Minneapolis--St. Paul, MN Urbanized Area	-0.46	0.0000***
New Orleans, LA Urbanized Area	2.52	0.0000***
Orlando, FL Urbanized Area	-0.25	0.0047***
Phoenix--Mesa, AZ Urbanized Area	3.75	0.0000***
Pittsburgh, PA Urbanized Area	5.02	0.0000***
Portland, OR--WA Urbanized Area	0.77	0.0000***
Providence, RI--MA Urbanized Area	2.32	0.0000***
Riverside--San Bernardino, CA Urbanized Area	8.55	0.0000***
Sacramento, CA Urbanized Area	3.33	0.0000***

St. Louis, MO--IL Urbanized Area	0.59	0.0000***
San Antonio, TX Urbanized Area	1.34	0.0000***
San Diego, CA Urbanized Area	3.58	0.0000***
San Francisco--Oakland, CA Urbanized Area	5.47	0.0000***
San Jose, CA Urbanized Area	7.42	0.0000***
Seattle, WA Urbanized Area	1.01	0.0000***
Tampa--St. Petersburg, FL Urbanized Area	0.05	0.5599
Virginia Beach, VA Urbanized Area	0.39	0.0000***
Model adjusted $R^2 = 0.99$		
Model *p*-value = 0.0000***		
n = 528		

[a]Income is the mid-point of the Census household income category, transformed by subtracting the mean household income.
[b]The reference UA (for which the UA specific dummy variable = 0) is Atlanta, GA.

Statistical significance: *p<0.1; **p<0.05; ***p<0.01

Table S8. **Linear regression model results for population-weighted concentrations for Black householders in medium Urban Areas**

Variable	Coefficient	*p*-value
(Intercept)	11.47	0.0000***
Income[a]	-1.50E-05	0.0000***
Income[a]-squared	1.08E-10	0.0000***
Urban Area-specific dummy variables[b]		
Austin, TX Urbanized Area	-0.30	0.0080**
Baltimore, MD Urbanized Area	3.23	0.0000***
Boston, MA--NH--RI Urbanized Area	6.05	0.0000***
Buffalo, NY Urbanized Area	2.50	0.0000***
Cincinnati, OH--KY--IN Urbanized Area	2.54	0.0000***
Cleveland, OH Urbanized Area	4.60	0.0000***
Columbus, OH Urbanized Area	3.22	0.0000***
Denver--Aurora, CO Urbanized Area	5.17	0.0000***
Houston, TX Urbanized Area	2.30	0.0000***
Indianapolis, IN Urbanized Area	1.98	0.0000***
Kansas City, MO--KS Urbanized Area	0.80	0.0000***
Las Vegas, NV Urbanized Area	3.77	0.0000***
Louisville, KY--IN Urbanized Area	2.19	0.0000***
Memphis, TN--MS--AR Urbanized Area	-0.68	0.0000***
Milwaukee, WI Urbanized Area	2.26	0.0000***
Minneapolis--St. Paul, MN Urbanized Area	0.08	0.4947
New Orleans, LA Urbanized Area	1.97	0.0000***
Orlando, FL Urbanized Area	-0.69	0.0047****
Phoenix--Mesa, AZ Urbanized Area	3.09	0.0000***
Pittsburgh, PA Urbanized Area	6.49	0.0000***
Portland, OR--WA Urbanized Area	1.60	0.0000***
Providence, RI--MA Urbanized Area	3.92	0.0000***
Riverside--San Bernardino, CA Urbanized Area	8.27	0.0000***
Sacramento, CA Urbanized Area	2.80	0.0000***

St. Louis, MO--IL Urbanized Area	1.24	0.0000***
San Antonio, TX Urbanized Area	0.22	0.0574*
San Diego, CA Urbanized Area	4.06	0.0000***
San Francisco--Oakland, CA Urbanized Area	5.50	0.0000***
San Jose, CA Urbanized Area	6.67	0.0000***
Seattle, WA Urbanized Area	1.57	0.0000***
Tampa--St. Petersburg, FL Urbanized Area	-0.10	0.3770
Virginia Beach, VA Urbanized Area	0.73	0.0000***
Model adjusted $R^2 = 0.98$		
Model *p*-value = 0.0000***		
n = 528		

[a]Income is the mid-point of the Census household income category, transformed by subtracting the mean household income.
[b]The reference UA (for which the UA specific dummy variable = 0) is Atlanta, GA.

Statistical significance: *$p<0.1$; **$p<0.05$; ***$p<0.01$

Table S9. Linear regression model results for population-weighted concentrations for Hispanic householders in medium Urban Areas

Variable	Coefficient	*p*-value
(Intercept)	11.66	0.0000***
Income[a]	-1.33E-05	0.0000***
Income[a]-squared	7.71E-11	0.0000***
Urban Area-specific dummy variables[b]		
Austin, TX Urbanized Area	-0.38	0.0042**
Baltimore, MD Urbanized Area	1.48	0.0000***
Boston, MA--NH--RI Urbanized Area	5.89	0.0000***
Buffalo, NY Urbanized Area	1.00	0.0000***
Cincinnati, OH--KY--IN Urbanized Area	1.35	0.0000***
Cleveland, OH Urbanized Area	4.71	0.0000***
Columbus, OH Urbanized Area	2.08	0.0000***
Denver--Aurora, CO Urbanized Area	5.68	0.0000***
Houston, TX Urbanized Area	2.70	0.0000***
Indianapolis, IN Urbanized Area	1.57	0.0000***
Kansas City, MO--KS Urbanized Area	1.09	0.0000***
Las Vegas, NV Urbanized Area	4.10	0.0000***
Louisville, KY--IN Urbanized Area	1.08	0.0000***
Memphis, TN--MS--AR Urbanized Area	-0.54	0.0000***
Milwaukee, WI Urbanized Area	1.50	0.0000***
Minneapolis--St. Paul, MN Urbanized Area	-0.27	0.0383**
New Orleans, LA Urbanized Area	1.34	0.0000***
Orlando, FL Urbanized Area	-1.13	0.0047****
Phoenix--Mesa, AZ Urbanized Area	3.44	0.0000***
Pittsburgh, PA Urbanized Area	5.00	0.0000***
Portland, OR--WA Urbanized Area	-0.42	0.0000***
Providence, RI--MA Urbanized Area	4.34	0.0000***
Riverside--San Bernardino, CA Urbanized Area	8.59	0.0000***
Sacramento, CA Urbanized Area	2.72	0.0000***

St. Louis, MO--IL Urbanized Area	0.12	0.3674
San Antonio, TX Urbanized Area	0.98	0.0000***
San Diego, CA Urbanized Area	3.09	0.0000***
San Francisco--Oakland, CA Urbanized Area	4.91	0.0000***
San Jose, CA Urbanized Area	6.83	0.0000***
Seattle, WA Urbanized Area	0.64	0.0000***
Tampa--St. Petersburg, FL Urbanized Area	-0.55	0.0000***
Virginia Beach, VA Urbanized Area	-0.50	0.0000***
Model adjusted R^2 = 0.98		
Model p-value = 0.0000***		
n = 528		

[a]Income is the mid-point of the Census household income category, transformed by subtracting the mean household income.
[b]The reference UA (for which the UA specific dummy variable = 0) is Atlanta, GA.

Statistical significance: *p<0.1; **p<0.05; ***p<0.01

Table S10. Linear regression model results for population-weighted concentrations for Asian householders in medium Urban Areas

Variable	Coefficient	*p*-value
(Intercept)	11.26	0.0000***
Income[a]	-1.84E-05	0.0000***
Income[a]-squared	9.34E-11	0.0000***
Urban Area-specific dummy variables[b]		
Austin, TX Urbanized Area	0.09	0.6063
Baltimore, MD Urbanized Area	1.62	0.0000***
Boston, MA--NH--RI Urbanized Area	5.97	0.0000***
Buffalo, NY Urbanized Area	0.88	0.0000***
Cincinnati, OH--KY--IN Urbanized Area	1.69	0.0000***
Cleveland, OH Urbanized Area	3.51	0.0000***
Columbus, OH Urbanized Area	2.21	0.0000***
Denver--Aurora, CO Urbanized Area	4.97	0.0000***
Houston, TX Urbanized Area	2.44	0.0000***
Indianapolis, IN Urbanized Area	1.20	0.0000***
Kansas City, MO--KS Urbanized Area	0.75	0.0000***
Las Vegas, NV Urbanized Area	4.19	0.0000***
Louisville, KY--IN Urbanized Area	1.60	0.0000***
Memphis, TN--MS--AR Urbanized Area	-0.41	0.0176**
Milwaukee, WI Urbanized Area	1.11	0.0000***
Minneapolis--St. Paul, MN Urbanized Area	-0.30	0.0858*
New Orleans, LA Urbanized Area	1.07	0.0000***
Orlando, FL Urbanized Area	-0.98	0.0047****
Phoenix--Mesa, AZ Urbanized Area	3.30	0.0000***
Pittsburgh, PA Urbanized Area	5.64	0.0000***
Portland, OR--WA Urbanized Area	0.25	0.1510
Providence, RI--MA Urbanized Area	3.44	0.0000***
Riverside--San Bernardino, CA Urbanized Area	8.15	0.0000***
Sacramento, CA Urbanized Area	2.76	0.0000***

St. Louis, MO--IL Urbanized Area	0.67	0.0000***
San Antonio, TX Urbanized Area	0.33	0.0537*
San Diego, CA Urbanized Area	3.40	0.0000***
San Francisco--Oakland, CA Urbanized Area	4.87	0.0000***
San Jose, CA Urbanized Area	6.78	0.0000***
Seattle, WA Urbanized Area	1.20	0.0000***
Tampa--St. Petersburg, FL Urbanized Area	-0.46	0.0072***
Virginia Beach, VA Urbanized Area	0.17	0.3362
Model adjusted $R^2 = 0.96$		
Model *p*-value = 0.0000***		
n = 528		

[a]Income is the mid-point of the Census household income category, transformed by subtracting the mean household income.
[b]The reference UA (for which the UA specific dummy variable = 0) is Atlanta, GA.

Statistical significance: *$p<0.1$; **$p<0.05$; ***$p<0.01$

Table S11. Linear regression model results for population-weighted concentrations for White householders in small Urban Areas

Variable	Coefficient	*p*-value
(Intercept)	9.81	0.0000***
Income[a]	-6.59E-06	0.0000***
Income[a]-squared	3.75E-11	0.0000***
Urban Area-specific dummy variables[b]		
Abilene, TX Urbanized Area	0.49	0.0000***
Akron, OH Urbanized Area	3.22	0.0000***
Albany, GA Urbanized Area	-2.86	0.0000***
Albany, NY Urbanized Area	0.77	0.0000***
Albuquerque, NM Urbanized Area	4.67	0.0000***
Alexandria, LA Urbanized Area	-1.59	0.0000***
Allentown--Bethlehem, PA--NJ Urbanized Area	3.98	0.0000***
Alton, IL Urbanized Area	-0.51	0.0000***
Altoona, PA Urbanized Area	2.78	0.0000***
Amarillo, TX Urbanized Area	1.88	0.0000***
Ames, IA Urbanized Area	-2.95	0.0000***
Anderson, IN Urbanized Area	0.05	0.5850
Anderson, SC Urbanized Area	-1.73	0.0000***
Ann Arbor, MI Urbanized Area	1.17	0.0000***
Anniston, AL Urbanized Area	-3.28	0.0000***
Antioch, CA Urbanized Area	2.71	0.0000***
Appleton, WI Urbanized Area	-0.19	0.0456
[*Continued; 407 total small Urban Areas*]		
Model adjusted $R^2 = 0.98$		
Model p-value = 0.0000***		
$n = 6512$		

[a] Income is the mid-point of the Census household income category, transformed by subtracting the mean household income.
[b]The reference UA (for which the UA specific dummy variable = 0) is Aberdeen, MD.

Statistical significance: *p<0.1; **p<0.05; ***p<0.01

Table S12. Linear regression model results for population-weighted concentrations for Black householders in small Urban Areas

Variable	Coefficient	*p*-value
(Intercept)	10.15	0.0000***
Income[a]	-6.56E-06	0.0000***
Income[a]-squared	5.13E-11	0.0000***
Urban Area-specific dummy variables[b]		
Abilene, TX Urbanized Area	0.38	0.0611*
Akron, OH Urbanized Area	4.65	0.0000***
Albany, GA Urbanized Area	-2.29	0.0000***
Albany, NY Urbanized Area	2.38	0.0000***
Albuquerque, NM Urbanized Area	4.17	0.0000***
Alexandria, LA Urbanized Area	-0.93	0.0000***
Allentown--Bethlehem, PA--NJ Urbanized Area	5.01	0.0000***
Alton, IL Urbanized Area	-1.04	0.0000***
Altoona, PA Urbanized Area	3.14	0.0000***
Amarillo, TX Urbanized Area	1.90	0.0000***
Ames, IA Urbanized Area	-3.51	0.0000***
Anderson, IN Urbanized Area	0.14	0.4763
Anderson, SC Urbanized Area	-1.52	0.0000***
Ann Arbor, MI Urbanized Area	1.01	0.0000***
Anniston, AL Urbanized Area	-2.26	0.0000***
Antioch, CA Urbanized Area	2.47	0.0000***
Appleton, WI Urbanized Area	-0.63	0.0030**
[*Continued; 407 total small Urban Areas*]		
Model adjusted R^2 = 0.93		
Model *p*-value = 0.0000***		
n = 5776		

[a]Income is the mid-point of the Census household income category, transformed by subtracting the mean household income.
[b]The reference UA (for which the UA specific dummy variable = 0) is Aberdeen, MD.

Statistical significance: *p<0.1; **p<0.05; ***p<0.01

Table S13. Linear regression model results for population-weighted concentrations for Hispanic householders in small Urban Areas

Variable	Coefficient	*p*-value
(Intercept)	10.07	0.0000***
Income[a]	-6.37E-06	0.0000***
Income[a]-squared	3.90E-11	0.0000***
Urban Area-specific dummy variables[b]		
Abilene, TX Urbanized Area	0.76	0.0029*
Akron, OH Urbanized Area	4.01	0.0000***
Albany, GA Urbanized Area	-2.32	0.0000***
Albany, NY Urbanized Area	1.34	0.0000***
Albuquerque, NM Urbanized Area	3.98	0.0000***
Alexandria, LA Urbanized Area	-1.31	0.0000***
Allentown--Bethlehem, PA--NJ Urbanized Area	5.31	0.0000***
Alton, IL Urbanized Area	-0.53	0.0589*
Altoona, PA Urbanized Area	3.26	0.0000***
Amarillo, TX Urbanized Area	1.78	0.0000***
Ames, IA Urbanized Area	-3.34	0.0000***
Anderson, IN Urbanized Area	-0.15	0.5795
Anderson, SC Urbanized Area	-1.93	0.0000***
Ann Arbor, MI Urbanized Area	1.11	0.0000***
Anniston, AL Urbanized Area	-2.85	0.0000***
Antioch, CA Urbanized Area	2.33	0.0000***
Appleton, WI Urbanized Area	-0.50	0.0585*
[*Continued; 407 total small Urban Areas*]		
Model adjusted R^2 = 0.90		
Model *p*-value = 0.0000***		
n = 5769		

[a]Income is the mid-point of the Census household income category, transformed by subtracting the mean household income.
[b]The reference UA (for which the UA specific dummy variable = 0) is Aberdeen, MD.

Statistical significance: *$p<0.1$; **$p<0.05$; ***$p<0.01$

Table S14. Linear regression model results for population-weighted concentrations for Asian householders in small Urban Areas

Variable	Coefficient	*p*-value
(Intercept)	9.80	0.0000***
Income[a]	-7.55E-06	0.0000***
Income[a]-squared	3.22E-11	0.0000***
Urban Area-specific dummy variables[b]		
Abilene, TX Urbanized Area	0.21	0.4886
Akron, OH Urbanized Area	3.99	0.0000***
Albany, GA Urbanized Area	-2.61	0.0000***
Albany, NY Urbanized Area	1.19	0.0000***
Albuquerque, NM Urbanized Area	4.95	0.0000***
Alexandria, LA Urbanized Area	-0.97	0.0019**
Allentown--Bethlehem, PA--NJ Urbanized Area	4.40	0.0000***
Alton, IL Urbanized Area	-0.08	0.8418
Altoona, PA Urbanized Area	2.67	0.0000***
Amarillo, TX Urbanized Area	0.98	0.0000***
Ames, IA Urbanized Area	-3.34	0.0000***
Anderson, IN Urbanized Area	0.19	0.6219
Anderson, SC Urbanized Area	-1.48	0.0000***
Ann Arbor, MI Urbanized Area	1.34	0.0000***
Anniston, AL Urbanized Area	-3.52	0.0000***
Antioch, CA Urbanized Area	2.65	0.0000***
Appleton, WI Urbanized Area	0.20	0.4798
[*Continued; 407 total small Urban Areas*]		
Model adjusted R^2 = 0.86		
Model *p*-value = 0.0000***		
n = 5192		

[a]Income is the mid-point of the Census household income category, transformed by subtracting the mean household income.
[b]The reference UA (for which the UA specific dummy variable = 0) is Aberdeen, MD.

Statistical significance: **p*<0.1; ***p*<0.05; ****p*<0.01

Table S15. Linear regression model results for population-weighted concentrations for White householders in rural areas

Variable	Coefficient	p-value
(Intercept)	4.54	0.0000***
Income[a]	3.74E-06	0.0000***
Income[a]-squared	-2.35E-11	0.0000***
Model adjusted R^2 = 0.98		
Model p-value = 0.0000***		
n = 16		

[a]Income is the mid-point of the Census household income category, transformed by subtracting the mean household income.

Statistical significance: *p<0.1; **p<0.05; ***p<0.01

Table S16. Linear regression model results for population-weighted concentrations for Black householders in rural areas

Variable	Coefficient	p-value
(Intercept)	3.76	0.0000***
Income[a]	2.47E-06	0.0000***
Income[a]-squared	-1.92E-11	0.0017**
Model adjusted $R^2 = 0.73$		
Model p-value = 0.0000***		
$n = 16$		

[a]Income is the mid-point of the Census household income category, transformed by subtracting the mean household income.

Statistical significance: *$p<0.1$; **$p<0.05$; ***$p<0.01$

Table S17. Linear regression model results for population-weighted concentrations for Hispanic householders in rural areas

Variable	Coefficient	*p*-value
(Intercept)	5.79	0.0000***
Income[a]	-3.06E-06	0.0000***
Income[a]-squared	1.02E-11	0.1280
Model adjusted R^2 = 0.79		
Model *p*-value = 0.0000***		
n = 16		

[a]Income is the mid-point of the Census household income category, transformed by subtracting the mean household income.

Statistical significance: *p<0.1; **p<0.05; ***p<0.01

Table S18. Linear regression model results for population-weighted concentrations for Asian householders in rural areas

Variable	Coefficient	*p*-value
(Intercept)	4.865	0.0000***
Income[a]	3.77E-06	0.0029**
Income[a]-squared	-2.62E-11	0.0638*
Model adjusted R^2 = 0.46		
Model *p*-value = 0.0072***		
n = 16		

[a]Income is the mid-point of the Census household income category, transformed by subtracting the mean household income.

Statistical significance: *p<0.1; **p<0.05; ***p<0.01

Table S19. Linear regression model results for mean Block group concentrations for the high percent White tertile in large Urban Areas

Variable	Coefficient	*p*-value
(Intercept)	31.80	0.0000***
Income[a]	1.56E-06	0.0000***
Income[a]-squared	2.33E-10	0.0000***
Percent White	-0.17	0.0000***
Model adjusted $R^2 = 0.03$		
Model *p*-value = 0.0000***		
n = 13,632		

[a]Income is the mean Block Group income, transformed by subtracting the mean household income.

Statistical significance: *p<0.1; **p<0.05; ***p<0.01

Table S20. **Linear regression model results for mean Block Group concentrations for the medium percent White tertile in large Urban Areas**

Variable	Coefficient	*p*-value
(Intercept)	23.69	0.0000***
Income[a]	2.89E-05	0.0000***
Income[a]-squared	-1.03E-11	0.0000***
Percent White	-0.07	0.0000***
Model adjusted R^2 = 0.03		
Model *p*-value = 0.0000***		
n = 13,633		

[a]Income is the mean Block Group income, transformed by subtracting the mean household income.

Statistical significance: *p<0.1; **p<0.05; ***p<0.01

Table S21. Linear regression model results for mean Block Group concentrations for the low percent White tertile in large Urban Areas

Variable	Coefficient	*p*-value
(Intercept)	23.22	0.0000***
Income[a]	-9.61E-05	0.0000***
Income[a]-squared	4.28E-10	0.0000***
Percent White	-0.07955	0.0000***
Model adjusted R^2 = 0.02		
Model *p*-value = 0.0000***		
n = 13,632		

[a]Income is the mean Block Group income, transformed by subtracting the mean household income.

Statistical significance: *p<0.1; **p<0.05; ***p<0.01

Table S22. Linear regression model results for Block Group concentrations for the high percent White tertile in medium Urban Areas

Variable	Coefficient	*p*-value
(Intercept)	19.53	0.0000***
Income[a]	-3.70E-05	0.0000***
Income[a]-squared	8.01E-10	0.0000***
Percent White	-0.08	0.0000***

Model adjusted R^2 = 0.02

Model *p*-value = 0.0000***

n = 12,787

[a]Income is the mean Block Group income, transformed by subtracting the mean household income.

Statistical significance: *p<0.1; **p<0.05; ***p<0.01

Table S23. Linear regression model results for Block Group concentrations for the medium percent White tertile in medium Urban Areas

Variable	Coefficient	*p*-value
(Intercept)	18.99	0.0000***
Income[a]	3.45E-05	0.0000***
Income[a]-squared	1.90E-11	0.7670
Percent White	-0.07	0.0000***
Model adjusted R^2 = 0.04		
Model *p*-value = 0.0000***		
n = 12,787		

[a]Income is the mean Block Group income, transformed by subtracting the mean household income.

Statistical significance: **p*<0.1; ***p*<0.05; ****p*<0.01

Table S24. **Linear regression model results for Block Group concentrations for the low percent White tertile in medium Urban Areas**

Variable	Coefficient	*p*-value
(Intercept)	15.60	0.0000***
Income[a]	-5.16E-05	0.0000***
Income[a]-squared	3.61E-09	0.0000***
Percent White	-0.01	0.0000***
Model adjusted R^2 = 0.01		
Model *p*-value = 0.0000***		
n = 12,787		

[a]Income is the mean Block Group income, transformed by subtracting the mean household income.

Statistical significance: *p<0.1; **p<0.05; ***p<0.01

Table S25. Linear regression model results for Block Group concentrations for the high percent White tertile in small Urban Areas

Variable	Coefficient	*p*-value
(Intercept)	15.51	0.0000***
Income[a]	-8.02E-06	0.0002***
Income[a]-squared	4.82E-11	0.0019***
Percent White	-0.06	0.0000***
Model adjusted R^2 = 0.005		
Model *p*-value = 0.0000***		
n = 13,372		

[a]Income is the mean Block Group income, transformed by subtracting the mean household income.

Statistical significance: *p<0.1; **p<0.05; ***p<0.01

Table S26. Linear regression model results for Block Group concentrations for the medium percent White tertile in small Urban Areas

Variable	Coefficient	*p*-value
(Intercept)	15.40	0.0000***
Income[a]	1.68E-05	0.0000***
Income[a]-squared	3.58E-10	0.0039***
Percent White	-0.06	0.0000***
Model adjusted R^2 = 0.02		
Model *p*-value = 0.0000***		
n = 13,371		

[a]Income is the mean Block Group income, transformed by subtracting the mean household income.

Statistical significance: *p<0.1; **p<0.05; ***p<0.01

Table S27. Linear regression model results for Block Group concentrations for the low percent White tertile in small Urban Areas

Variable	Coefficient	*p*-value
(Intercept)	12.20	0.0000***
Income[a]	-4.99E-06	0.3671
Income[a]-squared	4.00E-10	0.0522*
Percent White	-0.01	0.0000***
Model adjusted R^2 = 0.02		
Model *p*-value = 0.0000***		
n = 13,372		

[a]Income is the mean Block Group income, transformed by subtracting the mean household income.

Statistical significance: *p<0.1; **p<0.05; ***p<0.01

Table S28. Linear regression model results for Block Group concentrations for the high percent White tertile in rural areas

Variable	Coefficient	*p*-value
(Intercept)	1.68	0.3600
Income[a]	9.74E-05	0.0000***
Income[a]-squared	-8.08E-10	0.0000***
Percent White	0.04	0.0475**
Model adjusted R^2 = 0.005		
Model *p*-value = 0.0000***		
n = 24,588		

[a]Income is the mean Block Group income, transformed by subtracting the mean household income.

Statistical significance: *p<0.1; **p<0.05; ***p<0.01

Table S29. Linear regression model results for Block Group concentrations for the medium percent White tertile in rural areas

Variable	Coefficient	*p*-value
(Intercept)	15.07	0.0000***
Income[a]	1.02E-04	0.0000***
Income[a]-squared	-5.66E-10	0.0000***
Percent White	-0.09	0.0000***
Model adjusted R^2 = 0.11		
Model *p*-value = 0.0000***		
n = 24,588		

[a]Income is the mean Block Group income, transformed by subtracting the mean household income.

Statistical significance: *$p<0.1$; **$p<0.05$; ***$p<0.01$

Table S30. **Linear regression model results for Block Group concentrations for the low percent White tertile in rural areas**

Variable	Coefficient	*p*-value
(Intercept)	9.44	0.0000***
Income[a]	1.45E-04	0.0000***
Income[a]-squared	-5.30E-10	0.0000***
Percent White	-0.04	0.0000***
Model adjusted R^2 = 0.08		
Model *p*-value = 0.0000***		
n = 24,588		

[a]Income is the mean Block Group income, transformed by subtracting the mean household income.

Statistical significance: *p<0.1; **p<0.05; ***p<0.01