

Changes in Transportation-Related Air Pollution Exposures by Race-Ethnicity and Socioeconomic Status: Outdoor Nitrogen Dioxide in the United States in 2000 and 2010

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BACKGROUND: Disparities in exposure to air pollution by race-ethnicity and by socioeconomic status have been documented in the United States, but the impacts of declining transportation-related air pollutant emissions on disparities in exposure have not been studied in detail.

OBJECTIVE: This study was designed to estimate changes over time (2000 to 2010) in disparities in exposure to outdoor concentrations of a transportation-related air pollutant, nitrogen dioxide (NO₂), in the United States.

METHODS: We combined annual average NO₂ concentration estimates from a temporal land use regression model with Census demographic data to estimate outdoor exposures by race-ethnicity, socioeconomic characteristics (income, age, education), and by location (region, state, county, urban area) for the contiguous United States in 2000 and 2010.

RESULTS: Estimated annual average NO₂ concentrations decreased from 2000 to 2010 for all of the race-ethnicity and socioeconomic status groups, including a decrease from 17.6 ppb to 10.7 ppb (–6.9 ppb) in nonwhite [non-(white alone, non-Hispanic)] populations, and 12.6 ppb to 7.8 ppb (–4.7 ppb) in white (white alone, non-Hispanic) populations. In 2000 and 2010, disparities in NO₂ concentrations were larger by race-ethnicity than by income. Although the national nonwhite–white mean NO₂ concentration disparity decreased from a difference of 5.0 ppb in 2000 to 2.9 ppb in 2010, estimated mean NO₂ concentrations remained 37% higher for nonwhites than whites in 2010 (40% higher in 2000), and nonwhites were 2.5 times more likely than whites to live in a block group with an average NO₂ concentration above the WHO annual guideline in 2010 (3.0 times more likely in 2000).

CONCLUSIONS: Findings suggest that absolute NO₂ exposure disparities by race-ethnicity decreased from 2000 to 2010, but relative NO₂ exposure disparities persisted, with higher NO₂ concentrations for nonwhites than whites in 2010. <https://doi.org/10.1289/EHP959>

Introduction

Environmental injustice describes conditions in which more vulnerable communities experience disproportionate burdens of environmental health risks, such as exposure to air pollution. Environmental injustice in air pollution has been widely documented in the United States: many (>140) studies, covering a range of pollutants and U.S. locations, found higher air pollution exposures for lower-income groups and/or for race-ethnicity minority groups (Marshall et al. 2014). A key knowledge gap is whether environmental injustice has changed over time in the United States (Mohai and Saha 2015; Hajat et al. 2015). Longitudinal studies are needed to evaluate impacts of environmental policies on equity (Bento et al. 2015; Post et al. 2011), to explore the underlying causes of environmental injustice (Pastor et al. 2001), to enable tracking of environmental justice outcomes over time (Payne-Sturges and Gee 2006), and to test relationships between health disparities and exposure disparities over time (Mohai et al. 2009).

The goal of the present study was to estimate changes over time in environmental injustice in exposure to outdoor concentrations of a transportation-related air pollutant (TRAP) for

the contiguous United States. Previous studies explored environmental injustice aspects of distributions of benefits (e.g., accessibility) and costs (e.g., noise) of transportation (Schweitzer and Valenzuela 2004). We focused on exposure to air pollution as a cost of transportation emissions that often differs by race-ethnicity and/or socioeconomic status in the United States. Racial minorities and low-income households are disproportionately likely to live near a major road [e.g., 27% of racial minorities vs. 19% of the total population lived near high traffic volume roads in the United States in 2010 (based on an analysis of national census and traffic data; Rowangould 2013)], where TRAP concentrations are typically highest (e.g., nitrogen dioxide concentrations were on average 2.9 times higher near major roads than urban background levels [based on a synthesis of monitoring studies in multiple cities; Karner et al. 2010]).

Previous U.S.-based longitudinal air pollution environmental justice studies have focused on exposure to industrial air pollution or proximity to polluting industrial facilities. Ard (2015) studied annual average concentrations of industrial air pollution nationwide during 1995–2004 and found that exposures decreased for all race-ethnicity groups over time, but African Americans remained more exposed than whites and Hispanics (by a factor of ~50%). Longitudinal case studies on residential proximity to polluting industrial facilities [e.g., Seattle, 1990–2007 (Abel and White 2011); southern California, 1990–2000 (Hipp and Lakon 2010); in a national cohort, 1990–2007 (Pais et al. 2014)] found that race-ethnicity minority groups and/or lower socioeconomic status groups experienced closer average proximity to industrial facilities compared with other groups, and this pattern persisted over time. Few U.S.-based studies have explored temporal trends in environmental injustice for ambient air pollution or for transportation-related air pollution. Brajer and Hall (2005), studying ozone and coarse particulate matter in southern California during 1990–1999, found that on average, as air pollution decreased over time, Asians and Hispanics

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experienced larger reductions in ozone concentrations but smaller reductions in coarse particulate matter concentrations, compared with other groups. Kravitz-Wirtz et al. (2016), studying nitrogen dioxide and particulate matter exposures in the United States for a cohort of ~9,000 families during 1990–2009, found that as exposures decreased over time, exposures remained higher for blacks and Hispanics than for whites.

We focused on nitrogen dioxide (NO₂) as a TRAP. Transportation sources accounted for an estimated 60% of anthropogenic NO_x emissions in the United States in 2010 (U.S. EPA 2016), and NO₂ is an indicator of local transportation-related emissions (Brook et al. 2007; Burnett et al. 2004; Levy et al. 2014) with high within-urban spatial variability (Hewitt 1991; Apte et al. 2017). The U.S. EPA regulates outdoor annual NO₂ as one of six criteria pollutants, in part because exposure to NO₂ (together with other co-emitted TRAPs) is associated with health impacts, including low birth weight (Brauer et al. 2008), asthma in children (Takenoue et al. 2012), and cardiovascular mortality (Jerrett et al. 2013).

Air quality improved substantially in the United States after the 1990 Clean Air Act Amendments (Clean Air Act Amendments of 1990). From 2000 to 2010, estimated annual anthropogenic NO_x emissions in the United States decreased by ~50% (U.S. EPA 2016). It is unknown to what extent these estimated emission-reductions impacted NO₂ exposure disparities by race-ethnicity and by socioeconomic status. To investigate, we combined NO₂ air pollution data from a spatially precise (Census block scale) temporal land use regression model (Bechle et al. 2015) with Census demographic data (MPC 2011) and then estimated changes in TRAP environmental injustice over a decade (2000 to 2010) for the contiguous United States.

Methods

Study Area and Time Points

Analyses covered the contiguous United States (48 states plus the District of Columbia; selected based on availability of air pollution data) for two time points (selected based on availability of decennial Census demographic data): year 2000 (population: 280 million) and year 2010 (population: 306 million).

Datasets

Air pollution data. Air pollution estimates were annual average NO₂ concentrations for 2000 and 2010. These values were from a monthly land use regression (LUR) model incorporating satellite-based and ground-based observations (Bechle et al. 2015) for Census blocks [in 2010, $n = 8.2$ million; mean area = 0.97 km² (total), 0.048 km² (urban), 1.8 km² (rural)].

Demographic data. Demographic data were population estimates from the Census by race-ethnicity, socioeconomic status, language, and age. Demographic data included race (seven categories: white alone, black or African American alone, Asian alone, Native Hawaiian or other Pacific Islander alone, American Indian or Alaska Native alone, other race alone, two or more races), ethnicity (two categories: Hispanic, non-Hispanic), per capita income (continuous variable), household income [five categories (approximate annual household income quintiles): <\$20,000, \$20,000–\$35,000, \$35,000–\$50,000, \$50,000–\$75,000, >\$75,000], poverty (two categories: below poverty level, at or above poverty level), highest level of education for population >25 y (five categories: less than high school degree, high school degree, some college, college degree, graduate degree), employment for population >16 y (two categories: employed, unemployed), household language (five categories: English only, Spanish, other Indo-European

language, Asian language, other language), household linguistic isolation [two categories: linguistically isolated (no one >14 y speaks English “well” or “very well”), not linguistically isolated], and age [four categories: younger children (<5 y), older children (5–18 y), younger adults (18–65 y), older adults (>65 y)]. Demographic data for 2000 were from the Decennial Census (2000 estimated populations for all demographic characteristics) and for 2010 were from the decennial Census (2010 estimated populations by race-ethnicity and by age) and the American Community Survey (2008–2012 five-year estimated populations for all other demographic characteristics not reported in the 2010 decennial Census) at the Census block group level [in 2010, $n = 210,000$ (total); area mean (interquartile range) = 36 km² (0.49 km²–9.1 km²) (total); 1.1 km² (0.34 km²–1.3 km²) (urban); 200 km² (32 km²–150 km²) (rural)], the finest spatial scale for which detailed Census data are publicly available.

Spatial and Temporal Matching of Air Pollution and Demographic Data

To match the air pollution data (block level) with demographic data (block group level), we calculated population-weighted mean annual NO₂ concentrations for all block centroids within each block group boundary, for 2000 and 2010. Boundaries for Census urban areas (defined based on population, population density, land cover, and other criteria; U.S. Census Bureau 2011) and boundaries for smaller Census geographies (blocks and block groups) changed during 2000 to 2010. For analyses comparing consistent block group boundaries over time, we applied the National Historic Geographic Information System time-series data: estimates of 2000 population counts and race-ethnicity within 2010 block group boundaries (MPC 2011). To match urban area data over time, we applied the 2010 urban area definitions to both 2000 and 2010 block groups, including block groups for which all blocks were inside the urban area boundary.

Urban and Rural Block Group Definitions

For urban versus rural comparisons, we applied the following definitions based on 2010 Census urban definitions: urban block groups contain only urban blocks (65%; $n = 140,000$ in 2010), rural block groups contain only rural blocks (13%; $n = 28,000$ in 2010), and mixed block groups contain both urban and rural blocks (22%; $n = 47,000$ in 2010).

Exposure Assessment

Exposure assessment was based on residential block group LUR estimates of outdoor annual average NO₂ concentrations.

Analyses Estimating Changes in NO₂ Environmental Injustice over Time

We applied three related approaches to estimating changes in NO₂ environmental injustice over time: *a*) we estimated and compared NO₂ concentrations for populations defined by demographic characteristics (e.g., race-ethnicity groups); *b*) we estimated and compared NO₂ concentrations for block groups (as proxies for “neighborhoods” or “local areas”) by demographic characteristics (e.g., per capita income); and *c*) we estimated and compared NO₂ environmental injustice metrics on a national basis and for regions, states, counties, and urban areas.

Estimated changes in NO₂ concentrations by demographic groups. Our analyses by demographic groups focused on categories of race-ethnicity (14 groups), age (4 groups), household income (5 groups), and educational attainment (5 groups). We

also performed analyses with race-ethnicity dichotomized as “white” or “nonwhite,” where the white population was defined as the race-ethnicity majority group (i.e., the “white alone, non-Hispanic” population; 69% of population in 2000, 64% in 2010), and the nonwhite population included all other race-ethnicity minority groups combined (i.e., the non-“white alone, non-Hispanic” population). In addition, we performed supplemental analyses of populations by household primary language and linguistic isolation (combined, 13 groups), employment status (unemployed, employed), and poverty (below or above poverty level). For all analyses by demographic groups, we conducted analyses for the total population, and separately for the urban and rural populations.

We estimated the population-weighted mean annual NO₂ concentration C for each demographic group j in each year t (2000 or 2010) as

$$C_j = \frac{\sum_{i=1}^n c_i p_{ij}}{\sum_{i=1}^n p_{ij}} \quad [1]$$

where c_i is the annual mean NO₂ concentration for block group i , p_{ij} is the population of demographic group j in block group i , and n is the total number of block groups.

To compare population-weighted mean NO₂ concentrations between demographic groups j_1 and j_2 in year t (cross-sectional comparisons), we estimated absolute differences as $C_{j_1} - C_{j_2}$, and relative percent differences as $\{100(C_{j_1} - C_{j_2}) / [(C_{j_1} + C_{j_2}) / 2]\}$. To compare population-weighted mean NO₂ concentrations between 2000 (t_1) and 2010 (t_2) for group j (temporal comparisons), we estimated the absolute change as $C_{t_2} - C_{t_1}$, and the relative percent change as $\{100(C_{t_2} - C_{t_1}) / [(C_{t_2} + C_{t_1}) / 2]\}$. Changes were calculated such that negative values indicate a decrease in NO₂ concentration over time.

Estimated changes in NO₂ concentrations by block group demographic characteristics. To quantify differences by local (i.e., block group) demographic characteristics, we compared estimated mean NO₂ concentrations in each year between block groups with proportions of nonwhite residents in the highest and lowest 5% of the distribution for all block groups in the United States in each year. We analyzed data for all block groups combined and separately for urban and rural block groups.

To explore block group differences in NO₂ concentrations by race-ethnicity, income, and size of urban area, we categorized urban block groups by percent nonwhite in each year (quintiles), average per capita income in 2010 (20 equal groups), and total urban area population in 2010 (tertiles; large: 4.2 million to 18 million residents, $n=8$, total population = 61 million; medium: 830,000 to 3.8 million residents, $n=35$, total population = 63 million; and small: 14,000 to 800,000 residents, $n=438$, total population = 61 million). We then compared estimated mean NO₂ concentrations according to average per capita income (by approximate interquartile range in 2010 per capita income: \$18,000 to \$33,000) between urban block groups with percent nonwhite populations in the highest and lowest quintile of the national distribution for each year, after stratifying by small, medium, or large urban area population size.

Estimated changes in NO₂ environmental injustice metrics. To quantify how environmental injustice has changed over time on a national basis and for different U.S. geographies, we calculated and compared environmental injustice metrics in 2000 and 2010 on a national basis and by region, state, county, and urban area. Our core environmental injustice metric is the difference in estimated population-weighted mean NO₂ concentration (Equation 1) for nonwhites versus whites [i.e., (population-weighted mean NO₂ concentration for nonwhites) – (population-weighted mean NO₂ concentration for whites)],

hereafter referred to as the “nonwhite–white NO₂ disparity.” As supplements to the nonwhite–white NO₂ disparity, we calculated alternate environmental injustice metrics by race-ethnicity {for the three largest minority race-ethnicity groups: black–white NO₂ disparity [difference in estimated population-weighted mean NO₂ concentration for non-Hispanic blacks and non-Hispanic whites], Hispanic–white NO₂ disparity [difference in estimated population-weighted mean NO₂ concentration for Hispanics of any race(s) and non-Hispanic whites], and Asian–white NO₂ disparity [difference in estimated population-weighted mean NO₂ concentration for non-Hispanic Asians and non-Hispanic whites]} and by income (difference in estimated population-weighted mean NO₂ concentration for the population with income below the poverty level and the population with income two times the poverty level). We calculated correlations (Pearson’s correlation coefficient; Spearman’s rank coefficient) among the changes in the alternate environmental injustice metrics for states, counties, and urban areas.

Potential Influence of Changes in NO₂ Emissions and Changes in Demographic Patterns to Changes in Environmental Injustice over Time

As a preliminary step in understanding underlying mechanisms for changes over time in TRAP environmental injustice, we explored potential contributions of two factors: emission-reductions and residential demographic patterns. To estimate the potential extent to which each factor separately contributed to changes in NO₂ environmental injustice, we considered two counterfactual scenarios with the following assumptions: *a*) NO₂ concentrations changed as observed (from 2000 to 2010), but residential demographic patterns remained constant (at year-2000 values); and *b*) residential demographic patterns changed as observed (from 2000 to 2010), but NO₂ concentrations remained constant (at year-2000 values). We then calculated the core national environmental injustice metric (nonwhite–white NO₂ disparity) for each scenario. To estimate the contribution of changes in NO₂ concentrations alone, we divided the predicted change in the national nonwhite–white NO₂ disparity calculated under counterfactual scenario *a* by the observed change in the national nonwhite–white NO₂ disparity. To estimate the contribution of changes in residential demographic patterns alone, we divided the change in national nonwhite–white NO₂ disparity calculated under counterfactual scenario *b* by the observed change in the nonwhite–white NO₂ disparity.

Potential Relevance of Changes in Environmental Injustice for Public Health

As a preliminary step to explore the potential health relevance of the observed gaps in NO₂ exposures, we *a*) compared estimated exposures to health-based air quality guidelines and *b*) conducted an illustrative (“back-of-the-envelope”) health impact calculation. We compared the proportion of nonwhites versus whites living in block groups with NO₂ concentrations above the WHO annual guideline [$>40 \mu\text{g}/\text{m}^3$ (corresponds approximately to >21 ppb) NO₂; WHO 2005] and below 50% of the WHO guideline (<11 ppb). [All block groups were below the U.S. EPA annual standard for NO₂ (53 ppb) in 2000 and 2010.] We estimated potential health impacts for one outcome [ischemic heart disease (IHD) mortality, the most common cause of death in the United States (CDC 2015)] attributable to the difference in national mean NO₂ concentration for nonwhites and whites in 2000 and 2010. We assumed the relative risk (RR) of IHD mortality associated with outdoor annual average NO₂ concentration was 1.066 [95% confidence interval (CI): 1.015, 1.119] per 4.1 ppb NO₂ (based on a cohort of 74,000 adults in California during 1982–2000; Jerrett et al. 2013).

Relative risks (RR) for NO₂ concentrations experienced by nonwhites and whites were calculated using: $RR = \exp(\beta C)$, where C is the population-weighted mean NO₂ concentration (Equation 1), and $\beta = \ln(1.066)/(4.1 \text{ ppb}) = 0.0156 \text{ ppb}^{-1}$. To obtain a simplified estimate that reflects only the estimated potential impact of changes in NO₂ exposure over time experienced on average by nonwhites and whites (all else equal), our health risk calculations assumed that the underlying IHD mortality rate was constant over time [using the year-2011 estimate: 109 deaths per 100,000 (CDC 2012), although IHD mortality rates decreased during this time period in the United States (Finegold et al. 2013; WHO 2016)], and that the underlying mortality rate was the same for nonwhites and whites and the same by U.S. location [although IHD mortality rates differed by race-ethnicity and by U.S. location during this time period (CDC 2016)].

Sensitivity Analyses on Uncertainty in NO₂ LUR Model Estimates

To assess the potential impact of exposure misclassification on our findings, we tested whether NO₂ LUR model residuals showed systematic bias with respect to demographic characteristics. We compared annual average NO₂ concentrations based on measurements from 366 U.S. EPA monitors in 2006 (the base year for the temporal LUR model; Bechle et al. 2015) with the LUR-based estimates for each block group in which a monitor was located. We then compared the distributions of the LUR model residuals (i.e., the measured – predicted values) among block groups categorized by tertiles of percent nonwhite residents and tertiles of average per capita income in 2010. In addition, we compared the nonwhite–white NO₂ disparity (core environmental injustice metric) based on U.S. EPA monitor data versus LUR model estimates for the 366 block groups with U.S. EPA monitors.

Results

Estimated Changes in NO₂ Concentrations by Demographic Groups

Consistent with national trends, outdoor annual average NO₂ concentrations decreased substantially across all race-ethnicity, income, education, and age groups during 2000 to 2010. Overall, on a national basis, the estimated population-weighted mean NO₂ concentration decreased from 14.1 ppb in 2000 to 8.9 ppb in 2010, an absolute change of –5.2 ppb and a relative change of –37% (Table 1). Estimated changes among groups defined by race-ethnicity, income, age, and education ranged from –3.5 ppb to –8.6 ppb (–33% to –42%).

In general, the groups with the highest estimated NO₂ exposures in 2000 experienced the largest reductions in NO₂ concentrations from year 2000 to year 2010 (see Figures S1 and S2). As an example, the Hispanic black group, the group with the highest estimated mean NO₂ exposure in 2000 [20.8 ppb; 6.6 ppb (38%) higher than the national mean] experienced the largest estimated reduction in NO₂ exposure from 2000 to 2010 [–8.6 ppb, a 3.3 ppb (48%) greater concentration reduction than the national mean reduction].

In 2000 and 2010, disparities in estimated mean NO₂ concentrations were larger by race-ethnicity group than by income, education, or age group (Table 1). For example, in 2000, mean NO₂ concentrations for race-ethnicity groups ranged from 10.1 ppb (non-Hispanic American Indian group) to 20.8 ppb (black Hispanic group), a maximum difference of 10.7 ppb, compared with maximum differences of 1.7 ppb, 0.9 ppb, and 0.7 ppb between the education, income, and age groups with the highest and lowest mean exposures, respectively. In 2010, mean NO₂

concentrations for race-ethnicity groups ranged from 6.6 ppb to 12.2 ppb (a maximum difference of 6.5 ppb), whereas mean values for all individual education, income, and age subgroups were within 1.0 ppb of the national average.

On a national basis, rankings (most to least exposed groups) remained fairly consistent over time (Figure 1). For the six largest race-ethnicity groups, rank-order by estimated population-weighted mean NO₂ concentration remained constant with time: the non-Hispanic Asian group was most exposed and the non-Hispanic American Indian group was least exposed over time. Differences by age, income, and education were small compared with differences by race-ethnicity in both time periods.

After controlling for urban versus rural location (see Figures S3 and S4, Table S1), disparities in NO₂ concentrations by race-ethnicity persisted (with higher concentrations and higher disparities in urban than in rural locations), with some differences in exposure patterns for demographic groups by urban versus rural location in each year. For example, estimated population-weighted mean NO₂ concentrations were lower for non-Hispanic American Indians than non-Hispanic whites in rural locations (–1.3 ppb in 2000; –0.5 in 2010) but higher in urban locations (+0.2 ppb 2000; +0.1 ppb in 2010).

Results for supplemental measures of socioeconomic status (poverty, employment) and language (see Table S2) were generally consistent with the core demographic characteristics (race-ethnicity, income, education, and age). NO₂ concentrations were higher for people below the poverty level than above the poverty level, for households with a language other than English than households with only English, and for linguistically isolated than nonlinguistically isolated households. NO₂ concentrations were higher for employed than for unemployed populations.

Estimated Changes in NO₂ Concentrations by Block Group Demographic Characteristics

Consistent with population-based results, block groups with a higher proportion of race-ethnicity minority residents tended to have higher concentrations of NO₂, and this pattern was consistent over time (Figure 2). In 2000, the 5% of block groups with the highest proportion of nonwhite residents had 2.5 times higher [+13.2 ppb (22.1 ppb vs. 8.9 ppb)] estimated mean NO₂ concentrations than the 5% of block groups with the lowest proportion of nonwhite residents; in 2010, the 2.5-fold gap had increased slightly, to 2.7-fold [+8.9 ppb (14.1 ppb vs. 5.2 ppb)]. Considering urban versus rural block groups separately (see Figure S5), urban results were consistent with national results [the 5% of urban block groups with the highest versus lowest proportion of nonwhite residents had 1.8 times higher [+10.3 ppb (23.6 ppb vs. 13.3 ppb)] mean NO₂ concentration in 2000 and 1.8 times higher [+6.9 ppb (15.0 ppb vs. 8.1 ppb)] mean NO₂ concentration in 2010), whereas rural results had the reverse pattern to a minor extent: NO₂ concentrations were lower in block groups with a higher proportion of nonwhite residents (the 5% of rural block groups with the highest vs. lowest proportion of nonwhite residents had 0.7 times lower [–1.9 ppb (5.4 ppb vs. 7.3 ppb)] mean NO₂ concentrations 2000] and 0.8 times lower [–0.9 (3.8 ppb vs. 4.6 ppb)] mean NO₂ concentration in 2010).

In urban areas, disparities in block group estimated mean NO₂ concentrations by race-ethnicity (for nonwhites vs. whites) persisted over time, regardless of average block group per capita income or the size of the urban area (large, medium, or small), and were generally larger than disparities by income (see Figure S6). For example, in large urban areas in 2010, estimated mean NO₂ concentrations were 3.0 ppb higher (16.8 ppb vs. 13.8 ppb) for block groups with the highest versus lowest quintile percent nonwhite residents at the 25th percentile income (\$18,000) and

Table 1. Estimated NO₂ population-weighted mean concentration (ppb) for year 2000, year 2010, and estimated change over time (year 2010–year 2000), by race-ethnicity, household income quintile, educational attainment, and age.

Demographic characteristic	Population (%)		Mean NO ₂ concentration (ppb)		Change in mean NO ₂ concentration:	
	2000	2010	2000	2010	Absolute (ppb) 2010–2000	Relative (%) 2010–2000
Total	100	100	14.1	8.9	–5.2	–37
Race-ethnicity						
Non-Hispanic	87	84	13.4	8.4	–5.0	–37
White alone	69	64	12.6	7.8	–4.7	–38
Black or African American alone	12	12	16.2	10.0	–6.1	–38
American Indian or Native American alone	0.7	0.7	10.1	6.6	–3.5	–35
Asian alone	3.4	4.5	20.2	12.1	–8.1	–40
Native Hawaiian or other Pacific Islander alone	0.1	0.1	17.7	10.6	–7.1	–40
Other race alone	0.2	0.2	17.9	10.8	–7.1	–40
Two or more races	1.6	1.8	16.1	9.3	–6.8	–42
Hispanic	13	16	18.9	11.2	–7.7	–41
White alone	6.0	8.7	17.6	10.6	–7.0	–40
Black or African American alone	0.3	0.4	20.8	12.2	–8.6	–41
American Indian or Native American alone	0.1	0.2	18.8	11.2	–7.6	–41
Asian alone	0.04	0.1	19.3	11.8	–7.5	–39
Native Hawaiian or other Pacific Islander alone	0.01	0.02	18.4	10.8	–7.6	–41
Other race alone	5.3	6.0	20.2	12.0	–8.2	–41
Two or more races	0.8	1.0	19.3	11.3	–8.0	–41
Household income quintile ^a						
<\$20,000	8.3	6.7	14.2	9.0	–5.2	–36
\$20,000–\$35,000	7.3	5.9	13.7	8.7	–5.0	–37
\$35,000–\$50,000	6.2	5.1	13.7	8.6	–5.0	–37
\$50,000–\$75,000	7.3	6.8	13.8	8.6	–5.2	–38
>\$75,000	8.4	13	14.6	9.0	–5.7	–39
Educational attainment ^b						
<High school degree	13	19	14.9	9.3	–5.6	–37
High school degree	19	10	13.2	8.8	–4.4	–33
Some college	18	12	13.7	8.9	–4.9	–35
College degree	10	5.5	14.6	9.3	–5.3	–36
Graduate degree	5.7	6.2	14.9	9.3	–5.6	–38
Age (y)						
<5	6.8	6.5	14.4	9.0	–5.4	–38
5–17	19	17	14.0	8.8	–5.2	–37
18–65	62	63	14.2	9.0	–5.2	–37
>65	12	13	13.7	8.4	–5.3	–38

^aHousehold income quintiles are based on year-2000 population and income data. Income is reported for householders (38% of the total population in year 2000).

^bEducational attainment data is reported for population >25 y (65% of the total population in year 2000).

4.2 ppb higher (16.4 ppb vs. 12.2 ppb) for block groups with the highest versus lowest quintile nonwhite residents at the 75th percentile income (\$33,000). Estimated mean NO₂ concentrations were 1.6 ppb higher (13.8 ppb vs. 12.2 ppb) for the block groups at the 25th percentile income than at the 75th percentile income among lowest quintile percent nonwhite block groups, and 0.4 ppb (16.8 ppb vs. 16.4 ppb) higher among the highest quintile percent nonwhite block groups. In large urban areas, in 2000, the estimated mean NO₂ concentration was 2.9 ppb higher for highest income category block groups with the highest quintile nonwhite residents (mean per capita income: \$74,000; mean percent nonwhite residents: 88%; mean NO₂: 25.4 ppb; population: 56,000) than the lowest income block groups with the lowest quintile nonwhite residents (mean per capita income: \$6,400; mean percent nonwhite residents: 2.9%; mean NO₂: 22.4 ppb; population: 14,000), and in 2010, 1.2 ppb higher (16.7 ppb vs. 15.5 ppb).

Estimated Changes in NO₂ Environmental Injustice Metrics

Nationally, on an absolute basis, environmental injustice declined from 2000 to 2010. The nonwhite–white NO₂ disparity decreased from 5.0 ppb in 2000 to 2.9 ppb in 2010 (–2.1 ppb [–42%]; Table 2). However, nationally, on a relative basis, environmental injustice persisted. Nonwhites remained more exposed to outdoor NO₂ air pollution than whites on average in 2010, and there was

little change in the relative NO₂ difference between nonwhites and whites between 2000 and 2010: The nonwhite–white NO₂ difference was 33% in 2000 (nonwhites were 40% more exposed than whites) and 31% in 2010 (nonwhites were 37% more exposed than whites).

Environmental injustice declined in most, but not all, locations. In all regions and in most (>75%) states, counties, and urban areas, the nonwhite–white NO₂ disparity decreased over time (Figure 3). The nonwhite–white NO₂ disparity decreased by >1 ppb in 16 urban areas (accounting for 32% of the urban area population; 49 million in year 2000), including Detroit (Michigan), Los Angeles (California), New Orleans (Louisiana), and Chicago (Illinois). The nonwhite–white NO₂ disparity increased by >1 ppb in two urban areas (accounting for <1% of the urban population): Watertown (New York) and Delano (California): both are urban areas for which mean NO₂ concentrations were higher for whites than nonwhites in 2000, and for which concentrations decreased to a greater extent for whites than for nonwhites during 2000 to 2010. Similar patterns hold among counties: the nonwhite–white NO₂ disparity decreased by >1 ppb in 75 counties (accounting for 16% of the population in 2000), and increased by >1 ppb in 6 counties (accounting for <0.1% of the population in 2000), for all of which NO₂ concentrations were higher for whites than for nonwhites in 2000.

The alternate environmental injustice metrics considered (see Figures S7–S10) were moderately correlated (see Tables

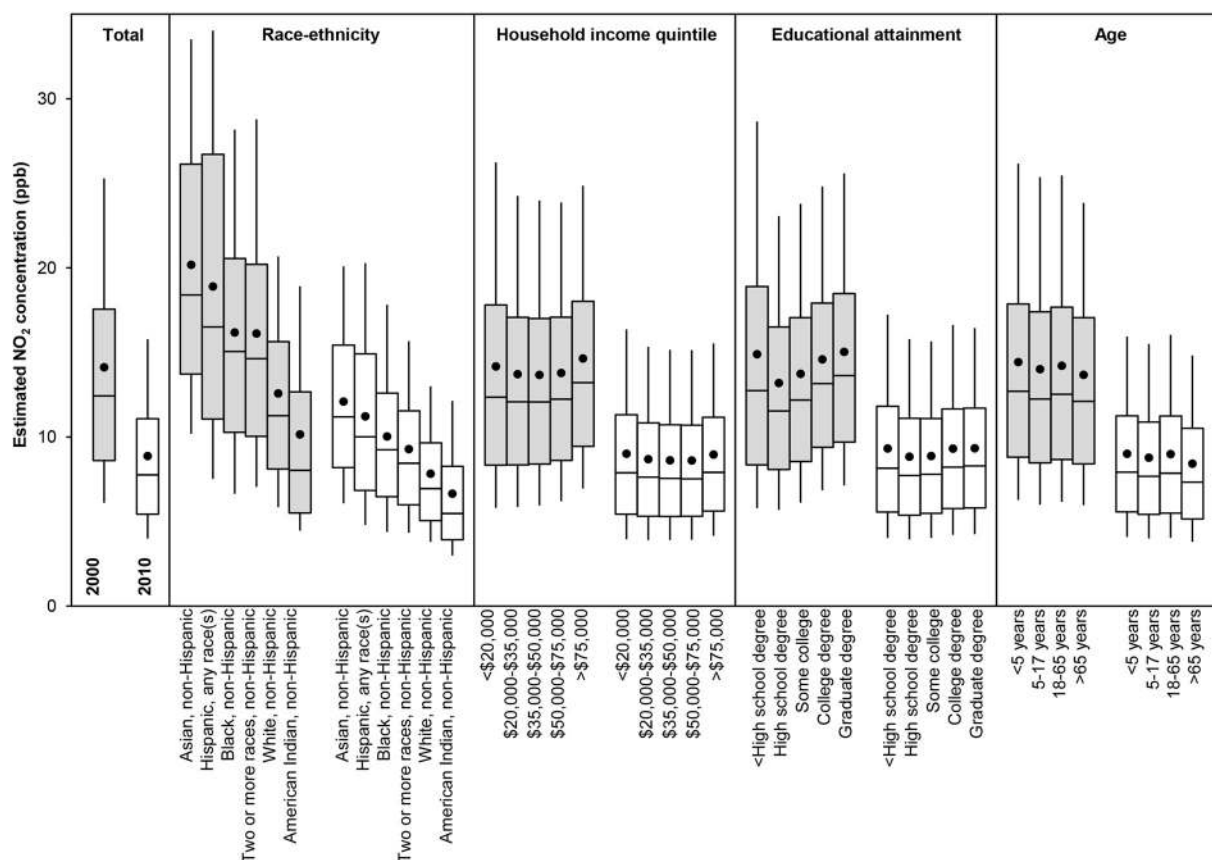


Figure 1. Estimated NO₂ concentration (ppb) by race-ethnicity, household income quintile, educational attainment, and age group, for year 2000 and year 2010. Box-and-whiskers indicate the 90th, 75th, 50th, 25th, and 10th percentile concentrations, and circles indicate population-weighted mean concentration. Race-ethnicity groups shown above are the six largest groups (Table 1 includes remaining race-ethnicity groups). Income groups are quintiles on a national basis for year-2000 households (38% of total population in year 2000). Educational attainment is reported for population over 25 y (65% of total population in year 2000).

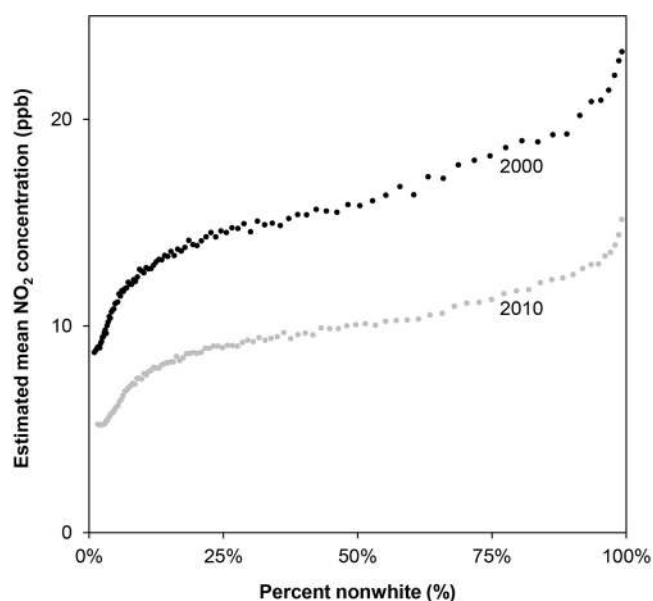


Figure 2. Estimated mean NO₂ concentration versus percent nonwhite population for block groups in year 2000 and year 2010. Each point represents the mean NO₂ concentration for 1% of the 210,000 block groups in the United States, binned by percent nonwhite residents. (The first point represents the 1% of block groups with the lowest percent nonwhite population, and the last point represents the 1% of block groups with the highest percent nonwhite population.)

S3–S5). For example, for urban areas, changes in alternate environmental injustice metrics were moderately correlated (Pearson’s correlation coefficient, r , range: 0.3–0.8; Spearman’s rank coefficient, s , range: 0.2–0.9). New York and California had large reductions (high decile reductions) in all five environmental injustice metrics, and North Dakota had increases (low decile reductions) in all five environmental injustice metrics. Similar to the patterns for the nonwhite–white NO₂ disparity, the black–white, Hispanic–white, and Asian–white NO₂ disparity decreased in most (>75%) regions, states, counties, and urban areas from 2000 to 2010. In contrast, the poverty-based NO₂ disparity increased in nearly half of states and counties, although in general, the poverty-based NO₂ disparities were smaller than the race-based NO₂ disparity metrics (e.g., among states the mean change in the poverty-based NO₂ disparity was –0.2 ppb vs. –1.0 ppb for the Asian–white NO₂ disparity). Estimated population-weighted mean NO₂ concentrations and environmental injustice metrics for each region, state, county, and urban area included in our analyses are available in Supplemental Material (Excel Tables A–D).

Potential Influence of Changes in NO₂ Emissions and Changes in Demographic Patterns to Changes in Environmental Injustice over Time

When we estimated what population-weighted mean NO₂ concentrations in 2010 would have been if residential demographic patterns changed as observed but NO₂ concentrations were fixed as in 2000, we predicted a decrease in mean NO₂ exposure for

Table 2. Estimated population-weighted mean NO₂ concentrations (ppb) for nonwhites and whites: year 2000, year 2010, and change over time (year 2010–year 2000).

Race-ethnicity	2000	2010	Change: 2010–2000
Nonwhites ^a	17.6	10.7	-6.9 (-39%)
Whites ^b	12.6	7.8	-4.7 (-38%)
Difference: nonwhites–whites	5.0 (33%)	2.9 (31%)	-2.1 (-42%)

^aNonwhites includes all race-ethnicity minority groups (i.e., people who reported any race-ethnicity other than white alone, non-Hispanic).

^bWhites includes people who reported white alone, non-Hispanic race-ethnicity.

nonwhites from 17.6 ppb to 16.6 ppb (-1.0 ppb) and for whites from 12.6 ppb to 12.1 ppb in whites (-0.5 ppb), for a change of -0.6 ppb in the nonwhite–white NO₂ disparity over time (5.0 ppb in 2000, 4.5 ppb in 2010), in contrast with the estimated change of -2.1 ppb in the nonwhite–white NO₂ disparity (Table 2). When we estimated what population-weighted mean NO₂ concentrations in 2010 would have been if residential demographic patterns were fixed as in 2000 but NO₂ concentrations

decreased as observed, we predicted a decrease in mean NO₂ exposure for nonwhites to 11.4 ppb (-6.3 ppb) and for whites to 8.1 ppb (-4.5 ppb), for a change of -1.8 ppb in the nonwhite–white NO₂ disparity over time (5.0 ppb in 2000, 3.3 ppb in 2010). This analysis of counterfactual scenarios suggests that both changes in NO₂ and changes in residential demographic patterns contributed to the observed reductions in the national nonwhite–white NO₂ disparity, with changes in NO₂ contributing to a larger extent (83%, i.e., -1.8 ppb of the -2.1 ppb observed change in environmental injustice metric) than changes in residential demographic patterns (26%, i.e., -0.6 ppb of the -2.1 ppb observed change in environmental injustice metric). [The individual contributions of these two factors sum to greater than 100%, indicating interaction effects (9%) due to air pollution and population changing together.]

Potential Relevance of Changes in Environmental Injustice for Public Health

In 2000 and in 2010, nonwhites were more likely than whites to live in block groups with NO₂ concentrations above international

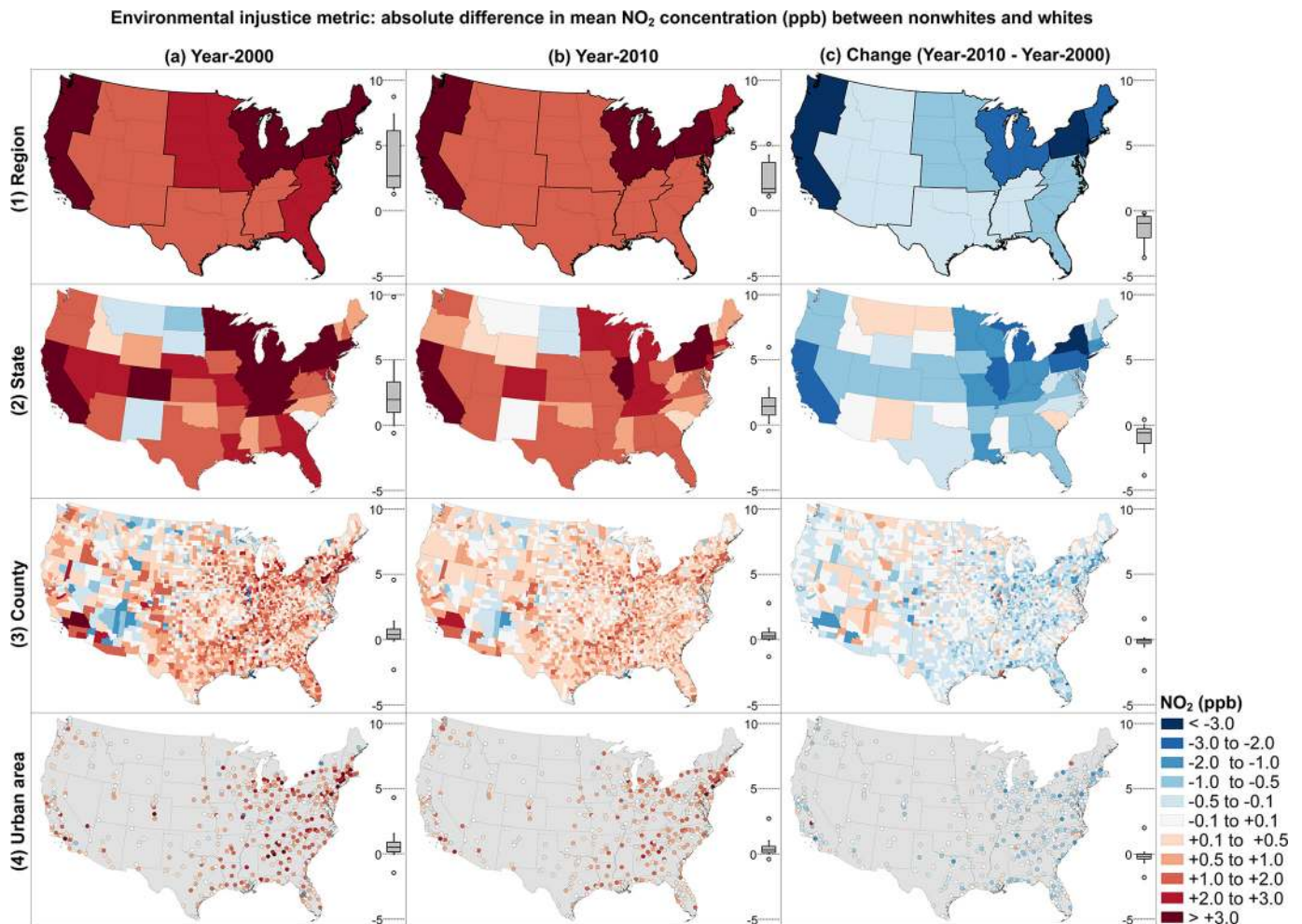


Figure 3. Estimated environmental injustice metric (absolute difference in population-weighted mean NO₂ concentration (ppb) between nonwhites and whites) (a) in year 2000, (b) in year 2010, and, (c) change over time (year 2010–year 2000) for United States (1) regions ($n=9$), (2) states ($n=49$ [including District of Columbia]), (3) counties ($n=3,109$), and (4) urban areas ($n=481$). For maps in columns (a) and (b), red indicates that annual mean NO₂ concentrations are higher for nonwhites than whites, blue indicates that annual mean NO₂ concentrations are higher for whites than nonwhites, and white indicates that annual mean NO₂ concentrations are equal for nonwhites and whites. For maps in column (c), red indicates that the absolute difference in annual mean NO₂ concentration between nonwhites and whites increased over time, blue indicates that the absolute difference decreased over time, and white indicates no change in the absolute difference over time. For maps in row (4), circle icons are located at the centroid of the urban area. For all plots, the box-and-whiskers indicate 90th, 75th, 50th, 25th, and 10th percentiles, and circles indicate maximum and minimum. Map boundary data are from the National Historical Geographic Information System (MPC 2011).

health-based guidelines. In 2000, 30% of nonwhites and 10% of whites lived in block groups with NO₂ concentrations above the WHO annual guideline (>21 ppb), compared with 5% of nonwhites and 2% of whites in 2010 (see Figures S11–S12, Table S6). Thus, nonwhites were three times as likely as whites to live in a block group above the WHO guideline in 2000, and 2.5 times as likely in 2010. Conversely, 23% of nonwhites and 44% of whites lived in block groups with NO₂ concentrations below 50% of the WHO guideline (<11 ppb) in 2000, compared with 56% of nonwhites and 80% of whites in 2010. Thus, nonwhites were 0.5 and 0.7 times as likely as whites to live in a block group with population-weighted mean NO₂ concentrations <50% of the WHO guideline in 2000 and 2010, respectively. For the urban population in 2000 and 2010, nonwhites were 2.1 times and 3.5 times as likely, respectively, to live in a block group with mean NO₂ concentrations above the WHO guideline. Most of the rural population (95% of whites and 97% of nonwhites in 2000; 99% of whites and nonwhites in 2010) lived in blocks groups with NO₂ concentrations below 50% of the WHO guidelines.

Based on the simplified health impact calculation, the estimated mean NO₂ concentration burden for nonwhites relative to whites (5.0 ppb in 2000, 2.9 ppb in 2010) was associated with an estimated ~7,000 (95% CI: 2,000, 10,000) additional premature IHD deaths for nonwhites in the United States in 2000 and an estimated ~5,000 (95% CI: 1,000, 9,000) in 2010 (calculations presented in Table S7). Thus, the reduction in the mean nonwhite–white NO₂ disparity (–2.1 ppb between 2000 and 2010) was associated with preventing an estimated ~2,000 (95% CI: 400, 3,000) premature IHD deaths per year among nonwhites. The purpose of this simplified (back-of-the-envelope) calculation was to provide background and context for concentration disparities reported here. This health impact calculation was limited by several important simplifying assumptions and considerations [i.e., this calculation assumed that the U.S. population breathed the national mean NO₂ concentration, considered only one health impact (IHD mortality), assumed that the IHD mortality rate is constant over time and by race-ethnicity and U.S. location, and did not adjust for differences in age by race-ethnicity or over time]. This simplified health impact calculation suggests that the estimated nonwhite–white NO₂ disparity may have been associated with potentially large health impacts (i.e., thousands of IHD deaths per year in the United States); more detailed analyses are needed to fully investigate the implications of NO₂ disparities for public health.

Sensitivity Analyses on Uncertainty in NO₂ LUR Model Estimates

When we compared LUR model-based NO₂ estimates for the 366 block groups with U.S. EPA monitors to the monitor-based NO₂ observations, median model-based NO₂ concentrations were lower for block groups in the middle and highest tertiles of percent nonwhite residents, and higher for block groups in the lowest tertile of percent nonwhite residents (see Figure S13). Median model-based estimates were also higher than monitor-based estimates for block groups in the highest tertile of average per capita income. When we estimated the nonwhite–white NO₂ disparity for these block groups in 2006 (the year for which monitor data were available; 670,000 people, 48% nonwhite) the disparity was larger when based on monitor data (3.3 ppb; 13.4 ppb vs. 10.1 ppb for nonwhites and whites, respectively) than LUR model predictions (2.3 ppb; 12.2 ppb vs. 9.8 ppb for nonwhites and whites, respectively). These findings suggest that our model-based results may under-estimate disparities in exposures.

Discussion

Estimated average NO₂ concentrations decreased for almost all U.S. populations and locations from 2000 to 2010. Disparities in average NO₂ concentrations by race-ethnicity decreased on an absolute basis (e.g., the nonwhite–white difference decreased from 5.0 ppb in 2000 to 2.9 ppb in 2010). However, despite these improvements, estimated average annual concentrations continued to be higher for nonwhite populations than for white populations in 2010 (nonwhite–white difference: 31% in 2010, 33% in 2000). In 2010, the estimated average concentration in the 5% of block groups with the highest proportion of nonwhite residents was 2.7 times higher than in the 5% of block groups with the lowest proportion of nonwhite residents (2.5 times higher in 2000). Therefore, our findings suggest that over time, NO₂ concentrations decreased; disparities by race-ethnicity decreased on an absolute basis but on a relative basis have persisted.

Our finding that, on a relative basis, NO₂ air pollution disparities by race-ethnicity persisted in the United States over time is consistent with a recent U.S. cohort study that reported that estimated NO₂ concentrations during 1990 to 2009 were ~10% higher for blacks and Hispanics than whites, even after controlling for individual socioeconomic characteristics (income, employment, home ownership) and metropolitan area characteristics (residential segregation, industry) (Kravitz-Wirtz et al. 2016). Our findings are also consistent with a national study of industry-related air pollution that reported that, although estimated exposures to industrial hazardous air pollutants (HAPs) decreased in the United States during 1994–2005, HAPs exposures remained ~1.5 times higher for African Americans than whites (Ard 2015); in our study, NO₂ exposures remained ~1.3 times higher for African Americans than whites.

Our findings suggested that most of the reduction in nonwhite–white NO₂ disparities between 2000 and 2010 was attributable to overall reductions in outdoor NO₂ concentrations. Emissions-reductions were achieved in part via emission-control technology in motor vehicles (particularly in gasoline vehicles during this time period; McDonald et al. 2012) and stationary sources (e.g., power plants) (U.S. EPA 2016). In addition, U.S. metropolitan regions became more suburban, and suburban areas became more racially diverse during 2000 to 2010 (Howell and Timberlake 2014). Shifts in demographic residential patterns leading to larger proportions of race-ethnicity minorities in suburban locations (where TRAP concentrations are typically lower compared with central cities or downtown locations) also may have contributed to reductions in NO₂ disparities by race-ethnicity during this time period.

Our evidence of larger NO₂ disparities by race-ethnicity than by income is consistent with previous studies of environmental injustice in TRAP (e.g., Clark et al. 2014) and with persistent patterns of residential segregation in U.S. metropolitan regions, which remain more segregated by race than by income (Reardon et al. 2015). Additional work is needed to further investigate potential underlying causes (e.g., changes in patterns of residential segregation) of changes in environmental injustice in exposure to TRAP over time.

Although absolute NO₂ exposure disparities reduced substantially during this period, there remain potentially large public health benefits from eliminating these disparities: nonwhites remained 2.5 times more likely than whites to live in block groups above WHO guidelines for NO₂ in 2010, and based on the back-of-the-envelope calculation described above, the estimated nonwhite–white NO₂ disparity may have been associated with thousands of premature IHD deaths among nonwhites in 2010.

Our analyses have several important limitations. Due to limitations in the spatial resolution of the Census data, we were

unable to explore spatial patterns in air pollution and demographics at spatial scales finer than Census block groups. We focused on outdoor air pollution exposures, and we were unable to explore the potential influence of time-activity patterns for which air pollution exposure gradients by race-ethnicity and socioeconomic status may exist, including exposures during commuting, at work, or indoors (O'Neill et al. 2003). In addition, we evaluated only one pollutant at only two time points. Spatial patterns may differ for other TRAPs or for cumulative exposures to multiple pollutants. We also did not account for joint effects (interactions) of race-ethnicity and socioeconomic characteristics. Finally, our estimates were limited by uncertainties in the NO₂ LUR model estimates and Census data. The impact of uncertainties in the Census data, particularly for national race-ethnicity data that represent an almost complete sample of ~300 million people, is likely to be small relative to the potential impact of uncertainties in NO₂ LUR model estimates. Findings from a sensitivity analysis comparing results when NO₂ exposure estimates were based on U.S. EPA monitor data instead of our LUR model suggested that exposure misclassification may have varied in a way that would have caused us to underestimate true disparities by race-ethnicity in outdoor NO₂ concentrations in the United States. However, we were unable to directly test the potential consequences of exposure misclassification on our national-scale estimates of environmental injustice.

Conclusion

During 2000 to 2010, estimated annual average exposures to outdoor NO₂ air pollution declined across all race-ethnicity and socioeconomic groups [range of mean change: -33% to -42% (-3.5 ppb to -8.6 ppb)]. The most exposed groups in 2000 experienced, on average, the largest reductions in NO₂ during 2000 to 2010. Disparities in NO₂ exposure were larger by race-ethnicity than by other demographic characteristics (income, education, age) in 2000 and 2010, with higher exposures for race-ethnicity minorities. The estimated national mean nonwhite-white NO₂ disparity decreased from 5.0 ppb in 2000 to 2.9 ppb in 2010. Most of this reduction in the national mean nonwhite-white NO₂ disparity over time is attributable to reductions in outdoor NO₂ concentrations, suggesting that existing efforts to reduce TRAP are also reducing TRAP exposure disparities by race-ethnicity over time. Despite these improvements in absolute exposures, relative exposure disparities persisted, with nonwhites remaining exposed to 37% more NO₂ than whites on average in 2010, and 2.5 times more likely than whites to live in a block group with NO₂ concentration above WHO guidelines in 2010. Overall, these findings suggest that continued improvements to air quality may further reduce TRAP exposure disparities by race-ethnicity. However, eliminating disparities may require additional policies and interventions that target the underlying causes of environmental injustice.

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