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Letter

Spatial Decomposition of Air Pollution Concentrations Highlights Historical Causes for Current Exposure Disparities in the United States

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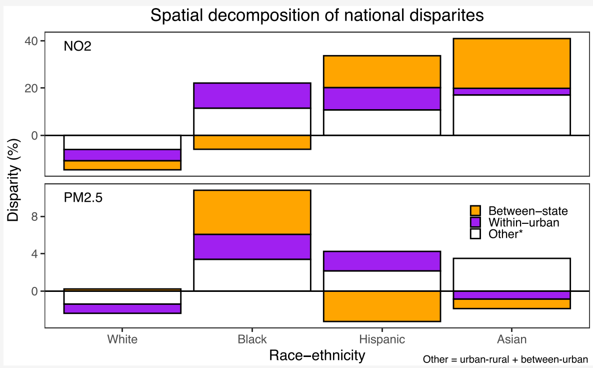
ABSTRACT: Racial−ethnic disparities in exposure to air pollution in the United States (US) are well documented. Studies on the causes of these disparities highlight unequal systems of power and longstanding systemic racism—for example, redlining, white flight, and racial covenants—which reinforced racial segregation and wealth gaps and which concentrated polluting land uses in communities of color. Our analysis is based on empirical estimates of ambient concentrations for two important pollutants (NO_2 and $PM_{2.5}$). We show that spatially decomposed concentrations can be used to infer and quantify types of root causes for local- to national-scale disparities. Urban-scale segregation is important yet reflects less than half of the overall national disparities. Other historical causes of national exposure disparities include those that led current populations of Black, Asian, and Hispanic Americans to live in larger cities; those outcomes are consistent with, for example, greater economic opportunity in large cities, land-takings from non-White farmers, and racism in homesteading and between-state migration. Our results suggest that contemporary national exposure disparities in the US reflect a broad set of historical local- to national-scale mechanisms—including racist laws and actions that include, but also extend beyond, urban-scale aspects—and offer a first attempt to quantify their relative importance.



KEYWORDS: *Spatial decomposition, Air pollution, Environmental justice, Environmental inequality, Health risk*

INTRODUCTION

Findings from environmental justice (EJ) research documents higher-than-average exposures and attributable health risks for communities of color in the United States (US).[1−3] Studies on the underlying causes of environmental disparities[4−7] point to longstanding systems of racism, oppression, and unequal power, reflecting actions by individuals, companies, and government (more detailed literature review in the SI[8−33]). Current explanations generally focus on neighborhood- and urban-scale inequalities, rather than the nature and causes of national-scale disparities.

Nitrogen dioxide (NO_2) and fine particulate matter ($PM_{2.5}$) are important criteria pollutants, associated with substantial health risks such as cardiovascular disease, respiratory disease, and cognitive decline.[1,34−40] $PM_{2.5}$ caused an estimated 47,000−460,000 premature deaths in the US in 2019;[41,42] NO_2 caused an estimated ∼794,000 asthma cases among children in 2010.[43] Pollution levels and attributable health risks for NO_2 and $PM_{2.5}$ in the US are disproportionately higher for communities of color.[1,2,9,44−47]

To advance our understanding of overall disparities, from local to national scale, and to explore spatial heterogeneity in the causes of disparities, here we use spatial decomposition of the ambient concentrations of two criteria pollutants (NO_2 and $PM_{2.5}$) to reveal and quantify contemporary disparities at multiple spatial levels and to shed light on potential causes of decomposed disparities. In our study, we find that urban-scale segregation reflects less than half of the national disparities; that is, within-urban segregation (an outcome consistent with redlining and racial covenants) is important, yet, surprisingly, it does not dominate national disparities. Instead, other social dynamics—e.g., reflecting national migration patterns—are even more important in explaining current national exposure disparities on different scales. These findings are informed by spatial decomposition using two distinct approaches: by administrative boundaries and by length scales.

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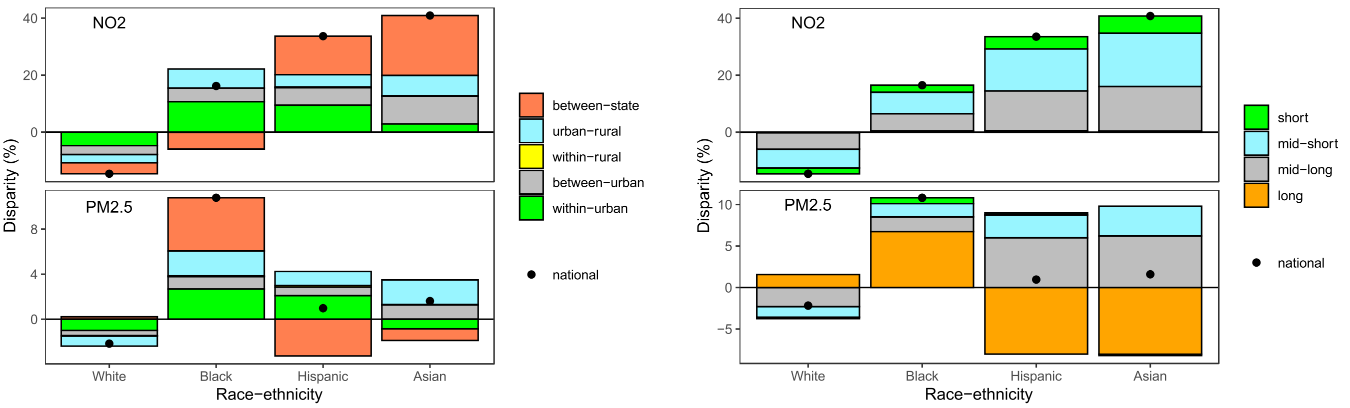

Figure 1. Normalized decomposed disparities for administrative boundaries (left) and length scales (right) for the four main racial−ethnic groups. Within-urban disparities account for less than half (here, between 7% and 39%) of total national exposure disparities.

■ MATERIALS AND METHODS

Air Pollution Data and Spatial Decomposition. National annual-average ambient air pollution estimates are publicly available for the continuous US[48] (www.caces.us/data), derived from government ambient monitoring data, spatial interpolation (kriging) of those data, and an empirical modeling technique that employs variables such as the road network, land uses, and satellite-derived information on land cover and pollution concentrations. Spatial decomposition of the empirical model predictions has been published for two pollutants: NO_2 and $PM_{2.5}$.[49] For those two pollutants, the empirical models have mean errors of −0.09 ppb [NO_2] and −0.02 μg/m^3 [$PM_{2.5}$] and mean biases of 8% [NO_2] and 2% [$PM_{2.5}$].[48]

The air pollution exposure disparity between a racial−ethnic group and the whole population is calculated using eq 1

$$\text{Disparity} = \frac{\sum_{b=1}^{n} C_b P_{r,b}}{\sum_{b=1}^{n} P_{r,b}} - \frac{\sum_{b=1}^{n} C_b P_{t,b}}{\sum_{b=1}^{n} P_{t,b}} \tag{1}$$

Here, n is the number of census blocks in the spatial unit; C_b is the pollution level for census block b; $P_{r,b}$ is population for each racial−ethnic group r for census block b; $P_{t,b}$ is the total population for census block b.

We employ here two types of spatial decompositions: one based on administrative boundaries (main analysis) and one based on length scales (sensitivity analysis). Both approaches employ geographic boundaries (e.g., census block centroid locations) for the most recent publicly available US Census (2010) at the time of the study. The methods are summarized here and described in further detail in the SI. Spatial decomposition indirectly sheds light on likely sources contributing to predicted concentrations: if concentrations at a location are highly variable in space (greater heterogeneity), that suggests that the location may be close to one or more emission sources; conversely, if concentrations exhibit little variability (spatially homogeneous), that suggests the location may be not close to emission sources.

Spatial decomposition based on administrative boundaries involves four successive spatial-smoothing steps to disaggregate each concentration estimate into five components. Step 1: first, we spatially smooth concentrations within each individual state, i.e., we replace each concentration estimate with the population-weighted average concentration for that state. Doing so removes all within-state disparities; the resulting calculated national exposure disparity reflects only the *between-state* disparities. Step 2: next, within each state, spatially smooth all urban and (separately) all rural locations, i.e., replace each concentration estimate with the population-average urban concentration in that state (for urban locations) and with the population-average rural concentration in that state (for rural locations). The increase in the calculated national exposure disparity, relative to the disparity calculated in step 1, is attributable to within-state *urban/rural* concentration differences. Step 3: assign rural locations their true predicted concentration; the increase in the calculated national exposure disparity, relative to that in step 2, is attributable to *within-rural* disparities. Step 4: for each urban location, assign the population-weighted average concentration for that urban area; the increase in the calculated national exposure disparity, relative to that in step 3, is attributable to *between-urban* disparities in each state. Step 5: last, assign urban locations their true estimated concentration; the increase in the calculated national exposure disparity, relative to that in step 4, is attributable to *within-urban* disparities. Concentrations for each of the five components add up to the overall population-average concentration.

To further investigate spatial patterns based on administrative boundaries, we conducted two sensitivity analyses. First, we separately studied four regions of the US (Northeast, Midwest, South, and West), repeating the analyses above separately for each region. Second, we investigated areas based on their degree of segregation. Specifically, we used the G* statistic as a marker of racial segregation[51−54] and then separated all census blocks into three categories: <10th percentile, 10 −90th percentile, >90th percentile of G* statistic. We repeated the analyses above separately for each of the three G* categories.

Spatial decompositions based on length scales were developed for NO_2 and $PM_{2.5}$.[50] Their approach involved disaggregating each concentration estimate into four categories: long, mid-long, mid-short, and short, corresponding to length scales of, respectively, >100 km, 10−100 km, 1−10 km, and <1 km. Additional details are in the SI and in Wang et al.[49]

Demographic Data. We obtained population estimates by race−ethnicity and map boundaries (states, urban areas, urban/rural blocks) for the lower 48 contiguous US states (i.e., excluding Alaska, Hawaii, and Washington, DC), from the 2010 decennial census from the IPUMS National Historic Geographic Information System (NHGIS).[54]

NHGIS provides easy access to US census data. Here, we use population estimates for seven census racial groups and two ethnic groups for each census block, for a total of 14 racial−ethnic groups (details in the SI). Because of space constraints,

Table 1. Spatial Decomposition Disparity Results and Potential Related Causes for These Disparities

Spatial level	Interpretation	Example causes	Example emission sources
Within-urban	People live in more polluted places within their urban area in that state	Redlining; racial covenants; exclusionary zoning; land-use policy; highway development; minority move-in	Transportation; commercial cooking
Between-urban	Within their state, urbanites live in cities that are more polluted (potentially, larger cities) rather than in less polluted (potentially, smaller) cities	Historic migration: job opportunities; social connections	Industrial; road dust; construction; transportation
Within-rural	Within their state, people in rural areas live in more polluted rural areas. (This aspect contributes ~0%, so is not explored further.)	N/A	N/A
Urban-rural	People live in urban environments (which are more polluted than rural environments)	Historic migration: job opportunities; social connections; disparities in access to historical homesteading, farming subsidies and other rural empowerment; land grabs; discriminatory agricultural loan practices	Agriculture; transportation; road dust; wood combustion
Between state	People live in more polluted states	Migration patterns; state laws for pollution; historical race-based state laws regarding in-migration	Agriculture; wildfire; electricity

our main analyses here focus on the four largest racial−ethnic groups, which in total cover 297 million people (97.1% of the population) in the continuous US in 2010: (i) non-Hispanic White alone (64.0% of the population; hereafter, "White"), (ii) Hispanic of any race(s) (16.4%; hereafter, "Hispanic"), (iii) non-Hispanic Black or African Americans alone (12.2%; hereafter, "Black"), and (iv) non-Hispanic Asian and Pacific Islander alone (4.5%; hereafter, "Asian"). We use the term "People of Color" ("POC") to refer to the latter three groups (i.e., Hispanic, Black, and Asian) combined. Results for the 10 other racial−ethnic groups are in the SI.

RESULTS

Spatial Decomposition Based on Administrative Boundaries. The results are decomposed national exposure disparities based on administrative units by race−ethnicity, for both pollutants and for each spatial component (Figure 1). (As described in Table 1, each spatial component then sheds light on types of potential causes for those disparities.) The results reveal, first, that within-urban disparities are important, but less so than expected. Among POC, the largest contributor to disparities is between-state in four cases (NO_2−Hispanic, NO_2−Asian, $PM_{2.5}$−Black, $PM_{2.5}$−Hispanic), within-urban in one case (NO_2−Black), and urban-rural in one case ($PM_{2.5}$−Asian) (Figure 1, left). For White people, within-urban is the largest contributor for both pollutants. Thus, as a second finding, spatial patterns leading to exposures being higher than average for POC are somewhat different than those leading to lower than average exposures for White people.

All four spatial levels (with only one exception: between-state for $PM_{2.5}$) result in lower exposures for White people. Most spatial levels result in higher exposures for POC. All three POC groups live in more polluted parts of their state, more polluted urban areas within their state, and more polluted parts of their urban area. The only exception is $PM_{2.5}$ for Asian people in urban areas: this group lives, on average, in less polluted parts within the urban area.

The relative contribution from the within-urban component ranges from 7% (NO_2−Asian) to 39% (NO_2−Black). Thus, consistent with the first result above, in no case does within-urban dominate the overall disparities. Surprisingly, between-state disparity, which typically is not a major focus for EJ studies, contributes 8% ($PM_{2.5}$−White) to 51% (NO_2−Asian).

Between-state disparities, which are large contributors for overall disparities, have various potential causes. For example, historical causes include those that led current populations of non-White people to live in larger cities; such outcomes are consistent with, e.g., land-takings from non-White farmers, racism in homesteading and between-state migration, and greater economic opportunity in large cities. Historically, the first European settlers arrived on the East Coast; over time, the population of European settlers, immigrants, and descendants remained higher in the eastern half of the US than in the western half. Contemporary location patterns for non-Europeans reflect their history of immigration and migration. These patterns are complex, multifaceted, and have changed over time. Contemporary aspects include that, for example, population density for Asian Americans is greatest on the West Coast (closest to Asia) and for Hispanic Americans is greatest in Florida and the Southwest (closest to Latin America) (Figure S3). The history of Black Americans includes forcibly being brought to slave states in the southeast of the United States, and multiple waves of migration, during and after slavery, to the West, large urban areas in the Midwest and Northeast, and return migration to cities of the southeast.[55−58]

Reflecting the greater overall population density, as well as additional factors (e.g., coal reserves located in the Appalachia region), the overall density of emissions from power plants (an important source of $PM_{2.5}$) is greater in the East than in the West. Another factor is meteorology: in the US, wind commonly travels from west to east, bringing air pollution (e.g., from the Midwest and the Mid-Atlantic regions) to the east.

$PM_{2.5}$−Hispanic reveals a third, and unexpected, finding: the overall national $PM_{2.5}$ disparity for Hispanic people is minor, not because of a lack of disparities in the decomposed components, but instead because two competing factors nearly balance: (i) a lower than average between-state component, i.e., living in less polluted than average states in the US and (ii) higher than average values for the three other components (within-urban, between-urban, urban-rural), i.e., living in more polluted than average parts of a city, more polluted cities within a state, and in cities rather than rural areas. People's living experiences typically reflect local conditions; if that holds here, then Hispanic people may observe and experience more $PM_{2.5}$ inequality than the national results would suggest. Importantly, that result would be unlikely to be noticed by researchers, except via a spatial decomposition approach.

Of the five spatial levels (Figure 1, left), within-rural contributes ~0%. That result indicates that, within each state, concentration differences among rural areas are, on average, small. This finding has also been reported elsewhere for empirical[9] and mechanistic models.[59]

We conducted two sensitivity analyses to further explore spatial patterns based on administrative boundaries: by region

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and by segregation level. The results by region (Figure S4) are broadly consistent with the main results above, with some differences by region. For example, NO_2 disparities are larger for all four racial−ethnic groups in the Northeast than in the South. For the Black populations' $PM_{2.5}$ exposure, within-urban disparities are more important in the Midwest than in the West (∼2 times larger), whereas between-state disparities are the reverse (i.e., ∼2 times larger in the West than in the Midwest).

Results by segregation level (Figure S5) are also generally consistent with the national results. However, for the least-segregated census blocks, all racial−ethnic groups experience smaller disparities (disparities were less positive or more negative) than the other two categories (Table S5). This finding suggests that in more integrated (less segregated) areas, all groups (including whites) experience smaller values for disparities (less positive or more negative).

Spatial Decomposition Based on Length Scales. The following investigation based on length scales represents a sensitivity analysis against the main (i.e., by administrative boundary) investigation above. Here, we quantify the degree to which ambient concentrations vary *within* versus *between* four length scales: short (within 1 km), mid-short (1−10 km), mid-long (10−100 km), and long (more than 100 km). Methodological details are in the SI.

Results (Figure 1, right) are broadly consistent with results by administrative boundary (Figure 1, left). As expected, exposure disparities are more local for NO_2 than for $PM_{2.5}$: the short-mid disparity contributed the most for all racial−ethnic groups for NO_2 (45% on average), while the long disparity contributed the most (46% on average) for all POC groups for $PM_{2.5}$. White people experienced lower than average exposure for both pollutants at all length scales (exception: long, $PM_{2.5}$). For NO_2, POC experienced higher than average exposure at all length scales. For $PM_{2.5}$, Asian and Hispanic populations both experience lower than average exposure at the long scale. The large advantage from the long scale cancels out disadvantages from the other scales, leading to an overall small national disparity for the two groups (i.e., Asian and Hispanic); that finding is consistent with the result above, that Hispanic people live in less polluted states but more polluted parts of those states. The finding here that Asian people experience a slightly lower than average exposure at short scale for $PM_{2.5}$ is consistent with the result above that Asian people on average live in the less polluted parts of a city.[12]

■ DISCUSSION

Our national investigation using spatially decomposed air pollution concentrations reveals multiple patterns of spatial scales of exposure disparities; as discussed below, those results uncover a new set of possible explanations for national disparities and quantify their relative importance. For nearly all scales, POC experience higher than average exposures and White people experience lower than average exposures. Within-urban disparities, which are a common explanation for national exposure disparities, contribute a surprisingly modest amount (7%−39% for cases considered here) to overall disparities. Equally surprisingly, in certain cases, the spatial scales of disparity counteract—for example, higher than average exposures across local scales and lower than average exposures for between-state scales, resulting in an overall nearly zero net national disparity. These results emphasize the need to study disparities separately at different spatial levels. Results here are broadly consistent with patterns that are well documented in prior studies, for example, that $PM_{2.5}$ is dominated by regional sources (e.g., power plants), whereas NO_2 comes more from local sources (e.g., traffic). Yet, they go beyond existing knowledge, by using spatial decomposition to highlight and quantify possible causes of current inequalities.

We hypothesize that policy responses to existing national disparities can be most effective if they come from a level of government that best matches the disparities themselves or at broader scale (e.g., national, regional) and if they include local interventions to eliminate disparities. We further hypothesize that ethical arguments, and public concern, about inequality may vary by spatial scale and may be greatest for local disparities and lowest for between-state disparities. Steps to address disparities risk missing large portions of, perhaps even the majority of, those disparities, if they tackle only one spatial scale (e.g., only within-urban disparities). National-level policy is required to address national-scale disparities; indeed, it would be challenging or impossible for state and local government, acting individually, to address disparities at larger spatial scales (i.e., between-state).

Limitations on our study include the following. We only study two pollutants; results for other pollutants may differ. Concentration estimates employed here have known levels of error and bias (see above; reported bias < 10%) and may underestimate within-urban variability.[29] We employ racial−ethnic categories used in the US Census; findings here and elsewhere hint at important heterogeneities within racial−ethnic groups, which merit further investigation.[29] We aim to propose and explore how possible explanatory factors would be consistent with observed spatial patterns (Table 1) but do not aim to test the underlying root causes. Future research can explore and test root causes, especially possible causes that have not previously been explored in detail in terms of air pollution. We used a "snapshot" in time (spatial patterns in present-day disparities to inform possible historical causes) instead of longitudinal data. Previous studies using longitudinal data found evidence that disproportionate siting is the major cause for disparities (i.e., in general, pollution sources have located near black and brown communities, not that those communities have moved near to the pollution).[18,60−63]

The lower than average $PM_{2.5}$ exposure for Asian people in urban areas, mentioned above, may be explained in part by diverse experiences of Asian Americans. Recent evidence for the Bay Area, California, indicated that Asian Americans are over-represented in neighborhoods with higher *and* lower than average concentrations (and are under-represented in locations with ∼average concentrations).[29] Those findings, and findings here, highlight that the census terms "Asian" or "Asian American" reflect a broad category of people, with diverse experiences.

Many previous EJ studies specifically investigated only one urban area, thereby focusing mostly on within-urban disparities; results here suggest that those studies are important but, even if repeated across a large number of urban areas, would miss most of the total national disparities. Urban-scale phenomena such as racial segregation and redlining are major causes for within-urban disparities[61,64] but are only part of the total disparities. Within-urban disparities only dominated disparities for the White population (for NO_2 and $PM_{2.5}$) and Black population (for NO_2). In contrast, between-state disparities dominated in more cases (Hispanic population for NO_2, $PM_{2.5}$; Asian, NO_2; Black, $PM_{2.5}$). Between-state disparities reflect national patterns in where groups live. Lastly, urban-rural differences also contributed to disparities for all POC, most notably for $PM_{2.5}$ for Black people. Consideration of length scales contributing to disparities highlights many examples of racist policies and other causes for those disparities, in addition to more common explanations such as redlining and racial covenants; some examples are in Table 1.

Previous studies on length scales and environmental inequalities have often focused on one city or state[31] and/or air toxics.[27] As prior articles point out, using a different spatial unit may shift the conclusion of a study, and coarser spatial scales (e.g., county-level data) may mask out results at finer scales.[27−31] Ash and Fetter suggested the need to control for regional variation in studying inequalities; they reported, "African Americans tend to live both in more polluted cities in the United States and in more polluted neighborhoods within cities. Hispanics live in less polluted cities on average, but they live in more polluted areas within cities."[27] Those findings are broadly consistent with the findings here. We found that in less segregated locations, all groups experience smaller values for disparities (less positive or more negative). That finding is consistent with an article by Ash et al., titled "Is Environmental Justice Good for White Folks?", which reported that "improvement in environmental justice could benefit not only minorities but also whites."[12]

In summary, spatial decomposition of NO_2 and $PM_{2.5}$ pollution in the US provides novel insights into historical causes for contemporary exposure disparities and quantifies their potential importance. Within-urban disparities, which reflect systemic racism operating on urban-scale outcomes, contribute less than half of the total disparities. Multiple other disparities and their root causes, reflecting systemic racism operating at other spatial scales (Table 1), also contribute to national disparities; those historical aspects must be reflected in environmental policy and discourse if we aim to understand and eliminate existing disparities.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.2c00826.

Scatterplot for within-state disparity and between-state disparity (Figure S1), scatterplot for within-urban/rural disparity and between-urban/rural disparity (Figure S2), population density map for US (Figure S3), decomposed disparities for administrative boundaries for four regions in the US (Figure S4), decomposed disparities for administrative boundaries for three different ranges of G* values in the US (Figure S5), normalized decomposed disparities for administrative boundaries for 7 racial-ethnic groups in the US for Hispanic, non-Hispanic, and any ethnicity (Figure S6), decomposed disparities for administrative boundaries (Table S1), absolute contribution for decomposed disparities for administrative boundaries (Table S2), decomposed disparities for length scales (Table S3), absolute contribution for decomposed disparities for length scales (Table S4), total disparity percentage for three categories of G* statistics (Table S5), and a literature review, demographic data, and methods of spatial decomposition on administration boundaries and on length scales (PDF)

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Notes

The authors declare no competing financial interest.

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