Environmental Science & Technology LETTERS

Editors' Choice

pubs.acs.org/journal/estlcu

Letter

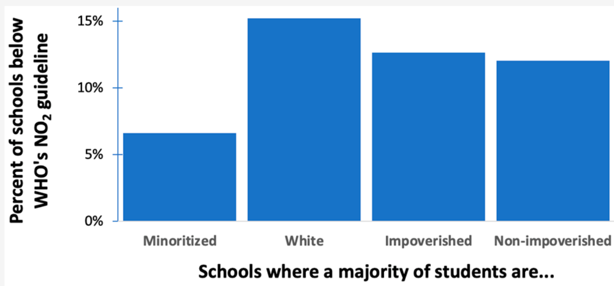
Ambient NO_2 Air Pollution and Public Schools in the United States: Relationships with Urbanicity, Race−Ethnicity, and Income

Matthew J. Bechle, Dylan B. Millet, and Julian D. Marshall*

Cite This: *Environ. Sci. Technol. Lett.* 2023, 10, 844−850

Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information



ABSTRACT: Schools may have important impacts on children's exposure to ambient air pollution, yet ambient air quality at schools is not consistently tracked. We characterize ambient air quality at home and school locations in the United States using satellite-based empirical model (i.e., land use regression) estimates of outdoor annual nitrogen dioxide (NO_2). We report disparities by race−ethnicity and impoverishment status, and investigate differences by level of urbanicity. Average NO_2 levels at home and school for racial−ethnic minoritized students are 18−22% higher than average (and 37−39% higher than for non-Hispanic, white students). Minoritized students are less likely than their white peers to live (0.55 times) and attend school (0.58 times) in areas below the World Health Organization's NO_2 guideline. Predominantly minoritized schools (i.e., >50% minoritized students) are less likely than predominantly white schools (0.43 times) to be in locations below the guideline. Income and race−ethnicity impacts are intertwined, yet in large cities, racial disparities persist after controlling for income.

KEYWORDS: *air pollution, disparities, environmental justice, equity, schools, empirical model*

1. INTRODUCTION

We aim to assess ambient nitrogen dioxide (NO_2) exposures and exposure disparities for school-aged children at home and at public schools throughout the contiguous United States. We study NO_2 in part because it is a criteria pollutant, has well-documented health effects, and is a key marker for a toxic mix of pollutants associated with automobile and other combustion-related emissions.[1] For example, a literature review of traffic-related air pollution (TRAP) and childhood asthma found NO_2 exhibited the most significant and consistent association with childhood asthma onset and prevalence.[2] Another reason to study NO_2 is the public availability of national empirical-model predictions at excellent spatial resolution (e.g., by Census Block).

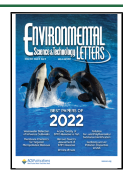
In general, children may be more susceptible than adults to health effects from air pollution, owing to their developing biological systems, higher intake of air relative to body mass, and greater time spent outdoors.[3] Children's exposure to TRAP is associated with the onset and exacerbation of asthma,[4] decreased cognitive and neurological function,[5,6] and exhaled nitric oxide[7] and may be associated with poorer academic performance.[8] Because children spend significant time at school, pollutant levels at schools may play an important role in their total exposure.

Schools are lasting infrastructure. A 2012−2013 survey found that U.S. public school buildings have an average age of 44 years.[9] The U.S. Environmental Protection Agency (EPA) provides voluntary guidance on school siting and for reducing near-roadway exposure at schools, and only 10 U.S. states have laws that prohibit siting new schools near environmental hazards;[10,11] to the best of our knowledge, no other legislation exists to assess or mitigate ambient air pollution hazards at existing schools. In this context, quantifying outdoor air pollution levels at school locations throughout the United States offers insights into an important risk factor for children, potentially informing future legislation or other action.

Research on improving indoor air quality in schools through better ventilation and air cleaning recently received renewed interest because of COVID-19, to reduce transmission of the airborne virus.[12−14] Such shifts can (in addition to reducing COVID-19 risks) increase or decrease indoor concentrations of outdoor pollution.[15−17]

Environmental injustice in residential air pollution exposure is well documented in North America.[18−22] Relative disparities have persisted despite decreasing concentrations.[22−24] Air pollution in schools may play an important role in children's exposure disparities. Studies in multiple U.S. locations have

Received: July 16, 2023
Revised: August 18, 2023
Accepted: August 21, 2023
Published: September 24, 2023



found that students of color are more likely to attend schools near major roadways and with higher levels of hazardous air pollutants and TRAP, including NO_2.[25−30]

To the best of our knowledge, only four studies in the peer-reviewed and gray literature have attempted to assess air pollution levels at schools, with a national-level scope (i.e., throughout the contiguous United States). (1) A *USA Today* article, using emissions from the U.S. EPA Toxic Release Inventory, estimated industrial air pollution levels outside public and private schools, finding hundreds of U.S. schools with potentially toxic air.[31] That article did not explore TRAP or exposure disparities. (2) Kingsley et al. reported that schools with a majority of black students were more likely to be near a major roadway than were majority-white schools.[32] They also reported that schools with a majority of students eligible for free or reduced-price lunch (hereafter "impoverished") were more likely to be near a major roadway than were non-impoverished students and schools. That study highlights racial and economic disparities based on a proxy for TRAP; it did not investigate pollution levels or sources other than major roadways. (3) Grineski and Collins, investigating neurotoxicant concentrations from the U.S. EPA's National Air Toxic Assessment (NATA) at public schools throughout the contiguous United States, found that students attending schools in the highest 10% of risk were more likely to be Hispanic, black, Asian/Pacific Islander, and impoverished.[33] NATA may underestimate concentrations, particularly high concentrations.[34] None of the three studies mentioned above considered criteria air pollutants explicitly. All three focus exclusively on children's exposure to ambient air pollution at school; an important policy consideration is whether exposures and exposure disparities differ between home and school locations. (4) Cheeseman et al. reported NO_2 and $PM_{2.5}$ exposure disparities for public schools across the United States.[35] They found higher concentrations for schools with a larger proportion of People of Color and low-income students. That study has the strongest overlap with the study presented here; advances in the study presented here include greater spatial precision [concentrations at the school location (study presented here) vs from a 1 km gridded prediction (prior study)] and direct comparisons between children's concentrations at school versus at home. The prior study considered demographics only in terms of school composition (the unit of analysis is a school; for example, concentrations for schools with 0−10% Hispanic students, 10−20% Hispanic students, etc.); here, we employ the same approach (school composition) and another approach using demographic groups themselves (i.e., the unit of analysis is a subpopulation; for example, concentrations for all Hispanic students, all Asian students, etc.).

Our approach combines satellite-based empirical-model NO_2 estimates with administrative data for public school and student residence locations. We compare average NO_2 levels and the proportion of public schools below the World Health Organization (WHO) guideline. We then apply this information to understand the impact of schools on childhood NO_2 disparities throughout the contiguous United States.

2. METHODS

2.1. Input Data. *2.1.1. School-Location Data.* Public-school location data are from the National Center for Education Statistics (NCES) School Universe Survey (SUS) for 2005−2006.[36] NCES SUS provides, for ∼100 000 public schools, the name, location (address and geographic coordinates), grade levels, enrollment by race−ethnicity (i.e., American Indian/Alaska Native; Asian/Pacific Islander; Hispanic; black, non-Hispanic; or white, non-Hispanic), enrollment by eligibility for free or reduced price lunch (at or below 185% of the federal poverty level), and the number of full-time-equivalent classroom teachers.[37] NCES SUS includes all public schools providing education services to prekindergarten, kindergarten, grade 1−12, and ungraded students. Data are collected via surveys of each U.S. state education agency (SEA) and a few other entities (e.g., Bureau of Indian Education and Department of Defense dependent schools). Herein, "minoritized students" refers to all students except non-Hispanic white students; "white students" refers to non-Hispanic white students.

We exclude schools that are inactive, report zero student enrollment or zero full-time-equivalent classroom teachers, and are missing location information. The database contains online schools; to the extent possible, we exclude these schools via relevant keyword searches (keywords: virtual, electronic, online, e-school). The resulting list of schools represent the "universe" of relevant schools. We then removed schools missing pertinent demographic information (number of minoritized students and number of impoverished students). The data are pre-COVID-19; therefore, COVID-related online schooling and hybrid schooling are excluded. Other data sets described next aim to temporally match the school data set.

2.1.2. Home-Location Data. We use the U.S. Census 5-year (2005−2009) American Community Survey at the block group level for student home-location data.[38] The survey provides population counts for people 3+ years of age by school-type enrollment status (nursery school, preschool, kindergarten, grades 1−8, grades 9−12, college or graduate school, or not enrolled), race (white alone, black or African American alone, American Indian and Alaska Native alone, Asian alone, Native Hawaiian and other Pacific Islander alone, some other race alone, and two or more races), and ethnicity (white alone, not Hispanic or Latino; Hispanic or Latino). Corresponding with the school-location data set, we consider only students enrolled in nursery school through grade 12. These data do not state school type (e.g., private, public, online, home school, etc.). As mentioned above, "white" refers to non-Hispanic white students and "minoritized" indicates groups other than non-Hispanic white.

2.1.3. Urbanization Data. We use year 2000 Decennial U.S. Census boundaries and population counts[39] for urbanized areas (UAs; cities with ≥50 000 people) and urban clusters (UCs; cities with 2500−49 999 people) to classify schools and residential block groups as within a UA or UC; we classify all remaining schools as rural. We further classify UAs by population tertile: large (nine cities; 3.9 million−18 million residents), medium (41 cities; 720 000−3.8 million residents), and small (397 cities; 50 000−720 000 residents). To avoid issues with locations near urban/rural borders, a 1 km buffer is applied to all UAs and UCs; within-buffer locations are assigned to the corresponding UA or UC. Some results are subdivided into UA and non-UA (i.e., UC plus rural).

2.1.4. Air Pollution Predictions. We employ estimated annual average, year 2006, outdoor NO_2 mixing ratios from a published satellite-based land use regression model for the contiguous United States.[40] Model predictions are calculated (1) for each public school location and (2) as the population-weighted average of block centroid predictions within each block group for home locations. We employ NO_2 in part because of its importance as a criterion pollutant and because of the

https://doi.org/10.1021/acs.estlett.3c00507
Environ. Sci. Technol. Lett. 2023, 10, 844−850

epidemiological evidence of its health effects. The NO_2 empirical model we employ has a mean absolute error of 2.55 ppb (normalized to the mean, 21%) and an R^2 of 0.74 in 10-fold holdout cross-validation.

2.2. Analysis. For all public schools in the contiguous United States, we assess student population-weighted NO_2 distributions at school by the following attributes: school type (elementary or secondary), level of urbanization (rural, UCs, small UAs, medium UAs, or large UAs), race−ethnicity (white, non-Hispanic vs racial−ethnic minoritized students), and income (impoverished vs non-impoverished students). We also assess student population-weighted NO_2 distributions at home by level of urbanization and by race−ethnicity for all block groups in the contiguous United States.

We estimate prevalence ratios, nationally and by level of urbanization, to assess the likelihood of minoritized and impoverished students experiencing low outdoor NO_2 levels relative to their non-Hispanic, white, and non-impoverished peers. Specifically, the prevalence ratio is calculated as the ratio of the percentage in one population (e.g., that is exposed to low NO_2 levels) to the percentage in another population. We also estimate prevalence ratios with schools as the unit of analysis, to compare schools serving predominantly minoritized or impoverished students (>50% of enrolled students) with those serving predominantly non-Hispanic, white, and non-impoverished students. Our comparison metrics include population-average pollution levels and proportions of people or schools with "clean" air (pollution levels below a cutoff value); in a sensitivity analysis, we also consider proportions with "elevated" pollution levels (above a cutoff value, but using a different cutoff, as described next).

As our cutoff for "clean" pollution levels, we use the World Health Organization (WHO) annual-average outdoor NO_2 guideline, established in 2021, of 10 $\mu g/m^3$ (∼5.3 ppb).[41] Analyses below investigate schools with concentrations below this standard. We do not use the U.S. EPA annual average standard of 53 ppb for several reasons. (1) No location has NO_2 levels above this standard. (2) No area has been in nonattainment with this standard since 1998. (3) The standard has not changed since its introduction in 1971.[42,43] In a sensitivity analysis, we employ the prior (i.e., pre-2021) WHO NO_2 guideline of 40 $\mu g/m^3$ (∼21.3 ppb) as the "elevated" cutoff, investigating schools and residences above this earlier, higher guideline.

We also assess population-weighted NO_2 levels by school-wide percentages of racial−ethnic minoritized students and impoverished students. We perform two school-based analyses: (1) line plots of student population-weighted NO_2 levels by student percentile bins (bin size of 5%), reflecting the school-level percentages of minoritized and impoverished students (i.e., each bin corresponds to 5% of the students, centered on the median student percentile of that bin), and (2) in a sensitivity analysis, line plots of population-weighted NO_2 levels for 10 equally spaced bins reflecting the percentages of minoritized and impoverished students (i.e., ten 10% bins corresponding to 0−100%). We summarize each level of urbanization separately.

We use two approaches to explore the interactions between race and ethnicity and income. First, we consider population-weighted NO_2 levels for impoverished and non-impoverished students separately within each race−ethnicity bin. Second, we consider the converse: population-weighted NO_2 levels for minoritized and white students separately within each income category.

3. RESULTS AND DISCUSSION

Of the starting "universe" of 117 311 public schools, 27 892 schools (24% of schools, 9% of students) were excluded because of missing information (almost exclusively, regarding free/reduced lunch enrollment). The schools and students excluded were less minoritized than schools and students not excluded, and the average student enrollment per school was smaller for excluded schools than for non-excluded schools (see Table S6). Within the contiguous United States, 47.9 million students attending 89 419 public schools remain in our analysis after data screening (Tables S1 and S6). For comparison, the Census American Community Survey database of residential block group locations (n = 207 225) reports a higher number of enrolled students, 51.7 million, owing largely to their inclusion of students not in public schools (e.g., private schools and home schooling) and students in schools that have missing data in the NCES SUS database (Table S1). Most students live (67%) and attend school (71%) in UAs (Table S1), but for students who attend a school that meets the WHO guideline, 19% are in UAs (Table S2; for schools exceeding the prior WHO standard, 100% are in UAs). The student population-weighted average NO_2 level is 11.4 ppb [UA, 12.9 ppb; non-UA, 6.7 ppb (Table S3)]. NO_2 levels are similar for elementary and secondary schools, when considered nationally [11.4 and 11.3 ppb, respectively (Table S5)] and by urbanization level (Figure S1); remaining analyses therefore aggregate elementary and secondary schools.

Population-weighted annual average at-school outdoor NO_2 levels are higher for minoritized students (13.4 ppb) than for white students (9.8 ppb) (Figure 1 and Table S2). A similar disparity is observed at home locations (13.5 and 9.7 ppb, respectively). As described below, impoverished students, on average, attend schools with a level of NO_2 (12.2 ppb) higher than that of non-impoverished students (10.8 ppb). The mean at-school NO_2 disparity by income (1.4 ppb) is 24 to 3 times smaller than the disparity by race−ethnicity (3.6 ppb).

Disparities at the lower end of the distribution, i.e., when comparing the schools experiencing clean air (below the WHO guideline), are as follows. Minoritized students and impoverished students are less likely both to attend schools and to live in areas below the WHO guideline than are, respectively, white students and non-impoverished students (Figure 1). Locations below the WHO guideline occur at all levels of urbanization but are more common in non-urban locations. Overall, 4.6% of minoritized students versus 8.0% of white students attend schools with NO_2 levels below the WHO guideline (Figure 1 and Table S2); for residential locations, values are 7.5% (minoritized) versus 13.6% (white). That is, minoritized students are 0.55 times as likely as their white peers to live in neighborhoods below the WHO guideline and 0.58 times as likely to attend school at locations below the guideline (Table S2). Results for UAs are similar (relative likelihood of NO_2 levels being below WHO standards for minoritized students, relative to that for white students: 0.53 times for home and 0.64 times for school). Predominantly minoritized schools (i.e., >50% minoritized students) are less likely (0.90 times) than predominantly white schools to be in locations below the WHO guideline.

Impoverished students are more likely than non-impoverished students to attend schools below the WHO guideline overall (1.2 times) and in non-UAs (1.3 times), but in UAs, the reverse holds (0.75 times). Results for predominantly impoverished schools (>50% impoverished students) are

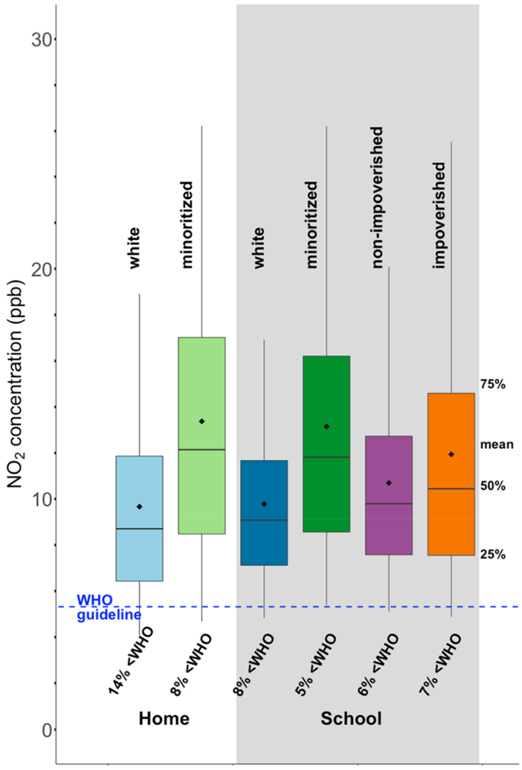


Figure 1. Summary of home-location (left, without shading) and school-location (right, shaded gray) NO_2 mixing ratios for non-Hispanic white, minoritized, non-impoverished, and impoverished students. Horizontal bars and boxes show the median and interquartile range; vertical lines show the 5th and 95th percentiles, and diamonds show mean values. The dashed blue horizontal line shows the World Health Organization (WHO) annual NO_2 guideline (~5 ppb). Numeric values at the bottom (e.g., 14% for white and Home) indicate the percentage of students attending schools with clean air (i.e., predicted NO_2 levels below the WHO guideline).

somewhat different. Those schools are less likely than predominantly non-impoverished schools to be below the WHO guidelines overall (0.85 times) and in UAs (0.75 times), but in non-UAs, the reverse holds (1.09 times).

As a sensitivity analysis and to investigate disparities at the upper end of the distribution, we compared schools experiencing dirtier air, defined herein as NO_2 levels above the earlier (i.e., pre-2021) WHO guideline, ~21 ppb. We find that minoritized students and impoverished students are more likely to attend schools and to live in areas above the earlier WHO guideline than are white students and non-impoverished students, respectively (Figure 1). School locations exceeding the earlier WHO guideline are exclusively in UAs. In UAs, 17% of minoritized students, versus 3% of white students, attend school above the earlier WHO guideline (Table S2b). Overall, minoritized students are 5.2 times as likely as their white peers to live in neighborhoods above the earlier WHO guideline, compared to 8.0 times as likely to attend school at locations above the earlier guideline (Table S2b); considering UAs only, the values are 3.9 times (home) and 5.9 times (school). Of predominantly minoritized schools, 14% experience "dirtier" air (exceeding the earlier WHO standard), versus 0.7% for predominantly white schools, a difference of 20 times (Table S3b). For UAs only, the same statistics are 17% (predominantly minoritized schools) versus 1.4%, a difference of 12 times (Table S3b). Predominantly impoverished schools are 4.0 times as likely as predominantly non-impoverished schools to have NO_2 levels be above the earlier WHO guideline (9% vs 2%); analogous values for UAs are 3.8 times (15% vs 4%).

The statistics given above indicate that the likelihood of experiencing NO_2 levels below the WHO guideline is lower for minoritized students and predominantly minoritized schools than for impoverished students and predominantly impoverished schools, respectively. Thus, race−ethnicity plays a larger role than income in understanding correlations with access to "clean" (i.e., below-guideline) pollution levels and the associated disparities.

Figure 2 shows student population-weighted average NO_2 levels as a function of the school proportion of racial−ethnic minoritized (Figure 2A) and impoverished (Figure 2B) students by urbanization level. Three aspects stand out.

(1) For UAs [but not for urban clusters (UCs) or rural areas], slopes are positive in both plots. That is, for UAs, NO_2 levels are higher for schools with a greater proportion of impoverished students and, independently, for schools with a greater proportion of minoritized students. For large UAs, the line slopes increase from left to right (are "superlinear"), especially in Figure 2A and especially above 60% minoritized students, indicating that in large UAs, schools that have the highest racial−ethnic percentages (and highest percent impoverished) have sharply higher exposures and disparities.

(2) Figure 2 emphasizes the intertwined nature of race and income. A large proportion of students of different demographic groups attend fundamentally different schools. That is, for UAs in Figure 2, especially for large UAs, the bold lines (i.e., interquartile range) for impoverished and non-impoverished students (panel A) and for white and minoritized students (panel B) have little to modest overlap in *x*-axis values. For large UAs, this lack of substantial overlap for the bold lines occurs for *y*-axis values, too.

(3) For large UAs (25% of all public school students), race−ethnicity is separately and distinctly related to at-school NO_2 levels. For a given level of impoverishment at a school, minoritized students on average attend schools with higher NO_2 levels than do white students (Figure 2B). When controlling for school-level income at other levels of urbanization, differences in NO_2 level by race are generally small to negligible (Figure 2B), and when controlling for school-level race−ethnicity, differences by poverty are generally small to negligible for all levels of urbanization (Figure 2A). That is, Figure 2 indicates that race and income are intertwined, and minoritized and impoverished students experience higher average NO_2 levels; it further indicates that one can disentangle those two factors in large UAs but not in medium and small UAs. As a sensitivity analysis, we plotted the same data as in Figure 2 but using 10 equally spaced bins; the results show similar patterns (Figure S3).

This work advances our understanding of school-aged children's air pollution exposure by comparing NO_2 air pollution levels at school and home locations. Minoritized students are less likely than their white peers to (1) live in neighborhoods with NO_2 levels below the WHO guideline and (2) attend schools with NO_2 levels below the WHO guideline. When instead considering average values, NO_2 levels and disparities between minoritized and white students are similar in school

https://doi.org/10.1021/acs.estlett.3c00507
Environ. Sci. Technol. Lett. 2023, 10, 844−850

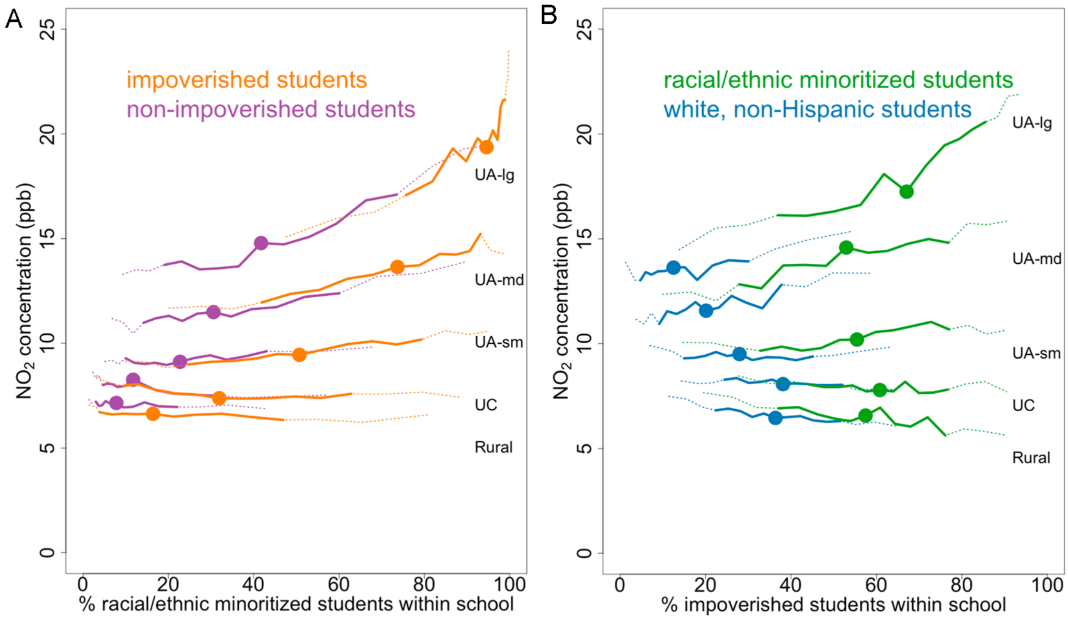


Figure 2. At-school population-weighted NO_2 levels by proportion of (A) minoritized students and (B) impoverished students. Data are separated by level of urbanization (large UA, medium UA, small UA, UC, and rural) and student subpopulation [impoverished vs non-impoverished students (A) and racial−ethnic minoritized students vs non-Hispanic, white students (B)]. Circles indicate the student population-weighted mean NO_2 mixing ratios for the 5% of students centered at the median (47.5−52.5 percentiles) for the corresponding school-level demographics. The bold lines indicate student population-weighted mean NO_2 values for the five-percentile bins approximating the interquartile range (22.5−77.5 percentiles). The thin dotted lines indicate student population-weighted mean NO_2 values for the five-percentile bins approximating the portion of the 10−90th percentile range (7.5−92.5 percentiles) that is outside the interquartile range. UA = urban area. UC = urban cluster.

and home locations. This finding that public schools exacerbate disparities for minoritized students with access to cleaner (below-guideline) NO_2 levels suggests that identifying and mitigating air pollution at public schools could reduce overall air pollution disparities in children. Another important goal of this work is to explore the intersection of race−ethnicity and income. Recent work on outdoor air pollution disparities has found that disparities by race−ethnicity are typically larger than other factors such as income and education.[23] Here we find evidence that this phenomenon exists for at-school NO_2 levels in large UAs, accounting for one-quarter of all students enrolled in public schools.

Disparities in air pollution exposure by race−ethnicity have many underlying causes,[44] including racist urban planning that results in pollution sources being more likely to be located in black and brown communities.[45] Some causes, such as redlining,[46,47] reflect decisions made many decades ago. Our results indicate correlations, not necessarily causations.

Limitations of this article include the following. All inputs (e.g., pollution levels, school locations and demographics, and census data) have errors and uncertainties and likely differ for present-day conditions compared to the prior-year values employed here. Schools may have opened, closed, or moved locations in the years between the survey and the present. We have not investigated variability in time or space (other than comparisons by the urbanization level). We are unable to investigate conditions for schools with missing information. Another limitation is that pollution estimates employed here reflect ambient concentrations, not exposures; issues such as commuting exposures, indoor sources, indoor air cleaning, and indoor−outdoor relationships are omitted.

Perhaps the most important limitation of this work is it documents a problem without proposing or testing solutions.[48] For example, Mohai and Kweon suggest best practices for school-siting policies, based on a review of policies in seven states.[49] Our results emphasize the importance of action, including reducing pollution in overburdened communities.[50,51]

■ ASSOCIATED CONTENT

Data Availability Statement

All data are available in the main text or the Supporting Information.

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.3c00507.

Graphical displays (Figures S1−S3), including the number of students and schools by level of urbanization, prevalence ratios, sensitivity analyses, average NO_2 concentrations, and excluded data (PDF)

Additional data sets (Tables S1−S6), including the number of students and schools by level of urbanization, prevalence ratios, sensitivity analyses, average NO_2 concentrations, and excluded data (XLSX)

■ AUTHOR INFORMATION

Corresponding Author

Julian D. Marshall − *Department of Civil & Environmental Engineering, University of Washington, Seattle, Washington 98195, United States*; orcid.org/0000-0003-4087-1209; Email: jdmarsh@uw.edu

Authors

Matthew J. Bechle − *Department of Civil & Environmental Engineering, University of Washington, Seattle, Washington 98195, United States*; orcid.org/0000-0001-8076-5457

https://doi.org/10.1021/acs.estlett.3c00507
Environ. Sci. Technol. Lett. 2023, 10, 844−850

Dylan B. Millet − *Department of Soil, Water, and Climate, University of Minnesota, St. Paul, Minnesota 55108, United States;* orcid.org/0000-0003-3076-125X

Complete contact information is available at:
https://pubs.acs.org/10.1021/acs.estlett.3c00507

Author Contributions

Conceptualization: M.J.B., D.B.M., and J.D.M. Methodology: M.J.B., D.B.M., and J.D.M. Investigation: M.J.B. Visualization: M.J.B. Funding acquisition: J.D.M. Project administration: J.D.M. Supervision: J.D.M. Writing of the original draft: M.J.B. and J.D.M. Review and editing: M.J.B., D.B.M., and J.D.M.

Funding

This work was supported by Assistance Agreement RD83587301 awarded by the U.S. Environmental Protection Agency (EPA) to the Center for Air, Climate, and Energy Solutions (CACES). This article has not been formally reviewed by EPA or other funders. The views expressed in this document are solely those of the authors and do not necessarily reflect those of the Agency. EPA does not endorse any products or commercial services mentioned in this publication.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The authors thank John Michael for assistance with calculations and plotting.

■ REFERENCES

(1) Brook, J. R.; Burnett, R. T.; Dann, T. F.; Cakmak, S.; Goldberg, M. S.; Fan, X.; Wheeler, A. J. Further Interpretation of the Acute Effect of Nitrogen Dioxide Observed in Canadian Time-Series Studies. *J. Exposure Sci. Environ. Epidemiol.* **2007**, *17* (S2), S36−S44.

(2) Jadaan, K.; Khreis, H.; Török, Á. Exposure to Traffic-Related Air Pollution and the Onset of Childhood Asthma: A Review of the Literature and the Assessment Methods Used. *Periodica Polytechnica Transportation Engineering* **2017**, *46*, 21.

(3) Brumberg, H. L.; Karr, C. J. Ambient Air Pollution: Health Hazards to Children. *Pediatrics* **2021**, No. e2021051484.

(4) Jadaan, K.; Khreis, H.; Török, Á. Exposure to Traffic-Related Air Pollution and the Onset of Childhood Asthma: A Review of the Literature and the Assessment Methods Used. *Periodica Polytechnica Transportation Engineering* **2017**, *46*, 21.

(5) Sunyer, J.; Esnaola, M.; Alvarez-Pedrerol, M.; Forns, J.; Rivas, I.; López-Vicente, M.; Suades-González, E.; Foraster, M.; Garcia-Esteban, R.; Basagaña, X.; Viana, M.; Cirach, M.; Moreno, T.; Alastuey, A.; Sebastian-Galles, N.; Nieuwenhuijsen, M.; Querol, X. Association between Traffic-Related Air Pollution in Schools and Cognitive Development in Primary School Children: A Prospective Cohort Study. *PLoS Med.* **2015**, *12* (3), e1001792.

(6) Annavarapu, R. N.; Kathi, S. Cognitive Disorders in Children Associated with Urban Vehicular Emissions. *Environ. Pollut.* **2016**, *208*, 74−78.

(7) Jung, K. H.; Goodwin, K. E.; Perzanowski, M. S.; Chillrud, S. N.; Perera, F. P.; Miller, R. L.; Lovinsky-Desir, S. Personal Exposure to Black Carbon at School and Levels of Fractional Exhaled Nitric Oxide in New York City. *Environ. Health Perspect.* **2021**, *129* (9), No. 097005.

(8) Stenson, C.; Wheeler, A. J.; Carver, A.; Donaire-Gonzalez, D.; Alvarado-Molina, M.; Nieuwenhuijsen, M.; Tham, R. The Impact of Traffic-Related Air Pollution on Child and Adolescent Academic Performance: A Systematic Review. *Environ. Int.* **2021**, *155*, 106696.

(9) Alexander, D.; Lewis, L. Condition of America's Public School Facilities: 2012−13 First Look.

(10) U.S. Environmental Protection Agency. School Siting Guidelines. 2011.

(11) U.S. Environmental Protection Agency. Best Practices for Reducing Near-Road Pollution Exposure at Schools. 2015.

(12) Corsi, R.; Miller, S. L.; VanRy, M. G.; Marr, L. C.; Cadet, L. R.; Pollock, N. R.; Michaels, D.; Jones, E. R.; Levinson, M.; Li, Y.; Morawska, L.; Macomber, J.; Allen, J. G.; ben Amor, Y. Designing Infectious Resilience into School Buildings Through Improvements to Ventilation and Air. 2021.

(13) Dowell, D.; Lindsley, W. G.; Brooks, J. T. Reducing SARS-CoV-2 in Shared Indoor Air. *Journal of the American Medical Association* **2022**, *328* (2), 141−142.

(14) Austin, E.; Carmona, N.; Gould, T.; Shirai, J. H.; Cummings, B. J.; Hayward, L.; Larson, T.; Seto, E. Healthy Air, Healthy Schools Study: Phase 1 Report to the Washington State Legislature. 2021.

(15) Laguerre, A.; George, L. A.; Gall, E. T. High-Efficiency Air Cleaning Reduces Indoor Traffic-Related Air Pollution and Alters Indoor Air Chemistry in a Near-Roadway School. *Environ. Sci. Technol.* **2020**, *54* (19), 11798−11808.

(16) Martenies, S. E.; Batterman, S. A. Effectiveness of Using Enhanced Filters in Schools and Homes to Reduce Indoor Exposures to PM2.5 from Outdoor Sources and Subsequent Health Benefits for Children with Asthma. *Environ. Sci. Technol.* **2018**, *52* (18), 10767−10776.

(17) Matthaios, V. N.; Kang, C.-M.; Wolfson, J. M.; Greco, K. F.; Gaffin, J. M.; Hauptman, M.; Cunningham, A.; Petty, C. R.; Lawrence, J.; Phipatanakul, W.; Gold, D. R.; Koutrakis, P. Factors Influencing Classroom Exposures to Fine Particles, Black Carbon, and Nitrogen Dioxide in Inner-City Schools and Their Implications for Indoor Air Quality. *Environ. Health Perspect.* **2022**, *130* (4), 47005 DOI: 10.1289/EHP10007.

(18) Hajat, A.; Hsia, C.; O'Neill, M. S. Socioeconomic Disparities and Air Pollution Exposure: A Global Review. *Current Environmental Health Reports* **2015**, *2* (4), 440−450.

(19) Zwickl, K.; Ash, M.; Boyce, J. K. Regional Variation in Environmental Inequality: Industrial Air Toxics Exposure in U.S. Cities. *Ecological Economics* **2014**, *107*, 494−509.

(20) Marshall, J. D.; Swor, K. R.; Nguyen, N. P. Prioritizing Environmental Justice and Equality: Diesel Emissions in Southern California. *Environ. Sci. Technol.* **2014**, *48* (7), 4063−4068. See Table S2.

(21) Clark, L. P.; Millet, D. B.; Marshall, J. D. National Patterns in Environmental Injustice and Inequality: Outdoor NO_2 Air Pollution in the United States. *PLoS One* **2014**, *9* (4), No. e94431.

(22) Clark, L. P.; Millet, D. B.; Marshall, J. D. Changes in Transportation-Related Air Pollution Exposures by Race-Ethnicity and Socioeconomic Status: Outdoor Nitrogen Dioxide in the United States in 2000 and 2010. *Environ. Health Perspect.* **2017**, *125* (9), 097012 DOI: 10.1289/EHP959.

(23) Liu, J.; Clark, L. P.; Bechle, M. J.; Hajat, A.; Kim, S.-Y.; Robinson, A. L.; Sheppard, L.; Szpiro, A. A.; Marshall, J. D. Disparities in Air Pollution Exposure in the United States by Race/ethnicity and Income, 1990−2010. *Environ. Health Perspect.* **2021**, *129* (12), 127005 DOI: 10.1289/EHP8584.

(24) Ard, K. Trends in Exposure to Industrial Air Toxins for Different Racial and Socioeconomic Groups: A Spatial and Temporal Examination of Environmental Inequality in the U.S. from 1995 to 2004. *Social Science Research* **2015**, *53*, 375−390.

(25) Gaffron, P.; Niemeier, D. School Locations and Traffic Emissions—Environmental (in)Justice Findings Using a New Screening Method. *International Journal of Environmental Research and Public Health* **2015**, *12* (2), 2009−2025.

(26) Pastor, M.; Sadd, J. L.; Morello-Frosch, R. Reading, Writing, and Toxics: Children's Health, Academic Performance, and Environmental Justice in Los Angeles. *Environment and Planning C: Government and Policy* **2004**, *22* (2), 271−290.

(27) Stuart, A. L.; Zeager, M. An Inequality Study of Ambient Nitrogen Dioxide and Traffic Levels near Elementary Schools in the Tampa Area. *Journal of Environmental Management* **2011**, *92* (8), 1923−1930.

(28) Grineski, S. E.; Clark-Reyna, S. E.; Collins, T. W. School-Based Exposure to Hazardous Air Pollutants and Grade Point Average: A Multi-Level Study. *Environmental Research* **2016**, *147*, 164−171.
(29) Batisse, E.; Goudreau, S.; Baumgartner, J.; Smargiassi, A. Socio-economic Inequalities in Exposure to Industrial Air Pollution Emissions in Quebec Public Schools. *Canadian Journal of Public Health* **2017**, *108*, e503−e509.
(30) Gunier, R. B.; Hertz, A.; von Behren, J.; Reynolds, P. Traffic Density in California: Socioeconomic and Ethnic Differences Among Potentially Exposed Children. *Journal of Exposure Science & Environmental Epidemiology* **2003**, *13*, 240−246.
(31) Morrison, B.; Heath, B. The Smokestack Effect: Toxic Air and America's Schools. *USA Today*, December 8, 2008. http://content.usatoday.com/news/nation/environment/smokestack/index (accessed 2015-02-11). Archived version, published September 15, 2022. https://eu.usatoday.com/story/news/nation/2022/09/03/schools-surrounded-toxic-air-pollution-puts-children-health-risk/10337072002/ (accessed 2022-10-28).
(32) Kingsley, S. L.; Eliot, M.; Carlson, L.; Finn, J.; MacIntosh, D. L.; Suh, H. H.; Wellenius, G. A. Proximity of US Schools to Major Roadways: A Nationwide Assessment. *J. Exposure Sci. Environ. Epidemiol.* **2014**, *24* (3), 253−259.
(33) Grineski, S. E.; Collins, T. W. Geographic and Social Disparities in Exposure to Air Neurotoxicants at U.S. Public Schools. *Environmental Research* **2018**, *161*, 580−587.
(34) Xue, Z.; Jia, C. A Model-to-Monitor Evaluation of 2011 National-Scale Air Toxics Assessment (NATA). *Toxics* **2019**, *7* (1), 13.
(35) Cheeseman, M. J.; Ford, B.; Anenberg, S. C.; Cooper, M. J.; Fischer, E. V.; Hammer, M. S.; Magzamen, S.; Martin, R. V.; van Donkelaar, A.; Volckens, J.; Pierce, J. R. Disparities in Air Pollutants Across Racial, Ethnic, and Poverty Groups at US Public Schools. *GeoHealth* **2022**, *6*, No. e2022GH000672.
(36) Common Core of Data. Public Elementary/Secondary School Universe Survey Data. https://nces.ed.gov/ccd/pubschuniv.asp (accessed 2021-10-21).
(37) Sable, J.; Gaviola, N.; Garofano, A. Documentation to the NCES Common Core of Data Public Elementary/Secondary School Universe Survey: School Year 2005−06. NCES 2007-365; Washington, DC, 2007.
(38) U.S. Census Bureau. American Community Survey Data. https://www.census.gov/programs-surveys/acs/data.html.
(39) U.S. Census Bureau. Decennial Census by Decade. https://www.census.gov/programs-surveys/decennial-census/decade.html.
(40) Bechle, M. J.; Millet, D. B.; Marshall, J. D. National Spatiotemporal Exposure Surface for NO2: Monthly Scaling of a Satellite-Derived Land-Use Regression, 2000−2010. *Environ. Sci. Technol.* **2015**, *49* (20), 12297.
(41) World Health Organization. *Air Quality Guidelines: Global Update 2005*; 2006.
(42) U.S. Environmental Protection Agency. Green Book Nitrogen Dioxide (1971) Area Information. https://www.epa.gov/green-book/green-book-nitrogen-dioxide-1971-area-information (accessed 2020-05-04).
(43) U.S. Environmental Protection Agency. Table of Historical NO_2 NAAQS. https://www3.epa.gov/ttn/naaqs/standards/nox/s_nox_history.html (accessed 2020-05-01).
(44) Liu, J.; Marshall, J. D. Spatial Decomposition of Air Pollution Concentrations Highlights Historical Causes for Current Exposure Disparities in the United States. *Environmental Science & Technology Letters* **2023**, *10* (3), 280−286.
(45) Tessum, C. W.; Paolella, D. A.; Chambliss, S. E.; Apte, J. S.; Hill, J. D.; Marshall, J. D. PM2.5 Polluters Disproportionately and Systemically Affect People of Color in the United States. *Sci. Adv.* **2021**, *7* (18), abf4491 DOI: 10.1126/sciadv.abf4491.
(46) Lane, H. M.; Morello-Frosch, R.; Marshall, J. D.; Apte, J. S. Historical Redlining Is Associated with Present-Day Air Pollution Disparities in U.S. Cities. *Environ. Sci. Technol. Lett.* **2022**, *9* (4), 345.
(47) Bramble, K.; Blanco, M. N.; Doubleday, A.; Gassett, A. J.; Hajat, A.; Marshall, J. D.; Sheppard, L. Exposure Disparities by Income, Race and Ethnicity, and Historic Redlining Grade in the Greater Seattle Area for Ultrafine Particles and Other Air Pollutants. *Environ. Health Perspect.* **2023**, *131* (7), 077004 DOI: 10.1289/EHP11662.
(48) Levy, J. I. Invited Perspective: Moving from Characterizing to Addressing Racial/Ethnic Disparities in Air Pollution Exposure. *Environ. Health Perspect.* **2021**, *129*, 12.
(49) Mohai, P.; Kweon, B.-S. Michigan School Siting Guidelines: Taking the Environment into Account. Ann Arbor, MI, 2020. https://deepblue.lib.umich.edu/handle/2027.42/156009.
(50) Wang, Y.; Apte, J. S.; Hill, J. D.; Ivey, C. E.; Patterson, R. F.; Robinson, A. L.; Tessum, C. T.; Marshall, J. D. Location-specific Strategies for Eliminating US National Racial-ethnic $PM_{2.5}$ Exposure Inequality. *Proc. Natl. Acad. Sci. U. S. A.* **2022**, *119* (44), e2205548119.
(51) Wang, Y.; Apte, J. S.; Hill, J. D.; Ivey, C. E.; Johnson, D.; Min, E.; Morello-Frosch, R.; Patterson, R. F.; Robinson, A. L.; Tessum, C. T.; Marshall, J. D. Air Quality Policy Should Quantify Effects on Disparities. *Science* **2023**, *381* (6655), 272−274.