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Letter

Historical Redlining Is Associated with Present-Day Air Pollution Disparities in U.S. Cities

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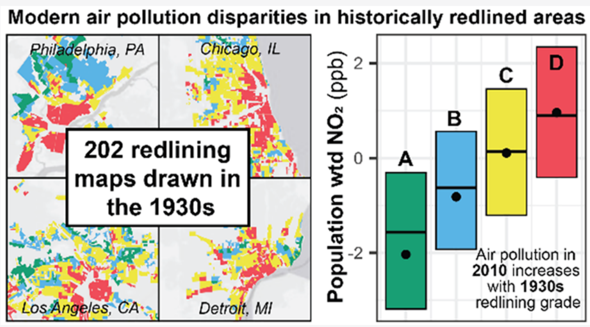
ABSTRACT: Communities of color in the United States are systematically exposed to higher levels of air pollution. We explore here how redlining, a discriminatory mortgage appraisal practice from the 1930s by the federal Home Owners' Loan Corporation (HOLC), relates to present-day intraurban air pollution disparities in 202 U.S. cities. In each city, we integrated three sources of data: (1) detailed HOLC security maps of investment risk grades [A ("best"), B, C, and D ("hazardous", i.e., redlined)], (2) year-2010 estimates of NO_2 and $PM_{2.5}$ air pollution levels, and (3) demographic information from the 2010 U.S. census. We find that pollution levels have a consistent and nearly monotonic association with HOLC grade, with especially pronounced (>50%) increments in NO_2 levels between the most (grade A) and least (grade D) preferentially graded neighborhoods. On a national basis, intraurban disparities for NO_2 and $PM_{2.5}$ are substantially larger by historical HOLC grade than they are by race and ethnicity. However, within each HOLC grade, racial and ethnic air pollution exposure disparities persist, indicating that redlining was only one of the many racially discriminatory policies that impacted communities. Our findings illustrate how redlining, a nearly 80-year-old racially discriminatory policy, continues to shape systemic environmental exposure disparities in the United States.



KEYWORDS: *air pollution, redlining, NO_2, $PM_{2.5}$*

INTRODUCTION

In the United States, communities of color are exposed to higher levels of air pollution at every income level.[1−4] As with other environmental justice (EJ) issues, the causes of systemic racial/ethnic air pollution exposure disparities are complex and rooted in part in historical patterns of exclusion and discrimination. While air quality has improved in the United States over the past several decades,[5−7] people of color (POC), particularly Black and Hispanic Americans, are still exposed to higher-than-average levels of air pollution.[8−11] We examine here how redlining, a historical, racially discriminatory 1930s federal mortgage appraisal policy, is associated with present-day air pollution disparities in 202 U.S. cities.

Racial/ethnic air pollution exposure disparities persist in part because the underlying sociological, economic, and policy drivers typically evolve on generational time scales. Multiple legacies of discrimination, including redlining and land use decision-making, have shaped the current spatial distributions of pollution sources among diverse communities.[12−18] The resulting locations of emissions infrastructure, including roads, rail lines, industrial facilities, ports, and other major sources of pollution, are typically long-lived. Similarly, while housing discrimination was deemed unconstitutional more than 50 years ago, many areas in the United States remain racially segregated.[19−22]

Redlining has emerged as an area of interest because it is well documented and was explicit in its discriminatory implementation, widespread, and carried out by the federal government. Beginning in the 1930s, the federally sponsored Home Owners' Loan Corporation (HOLC) drew maps characterizing neighborhood security for emergency home lending for several hundred U.S. cities in the wake of the Great Depression.[23,24] These maps, which are digitized for 202 U.S. cities,[25] graded neighborhoods on a four-point scale: A (most desirable), B (still desirable), C (definitely declining), and D (hazardous, i.e., redlined). Many neighborhoods received the worst grade due to the presence of Black and immigrant communities and/or known environmental pollution sources.[25,26] For example, racist language provided to HOLC agents describes "infiltration of foreign-born, Negro, or lower-grade population" as cause for a lower neighborhood grade.[25] Homes in D neighborhoods were typically ineligible for federally backed loans or favorable mortgage terms. This

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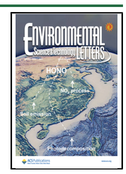

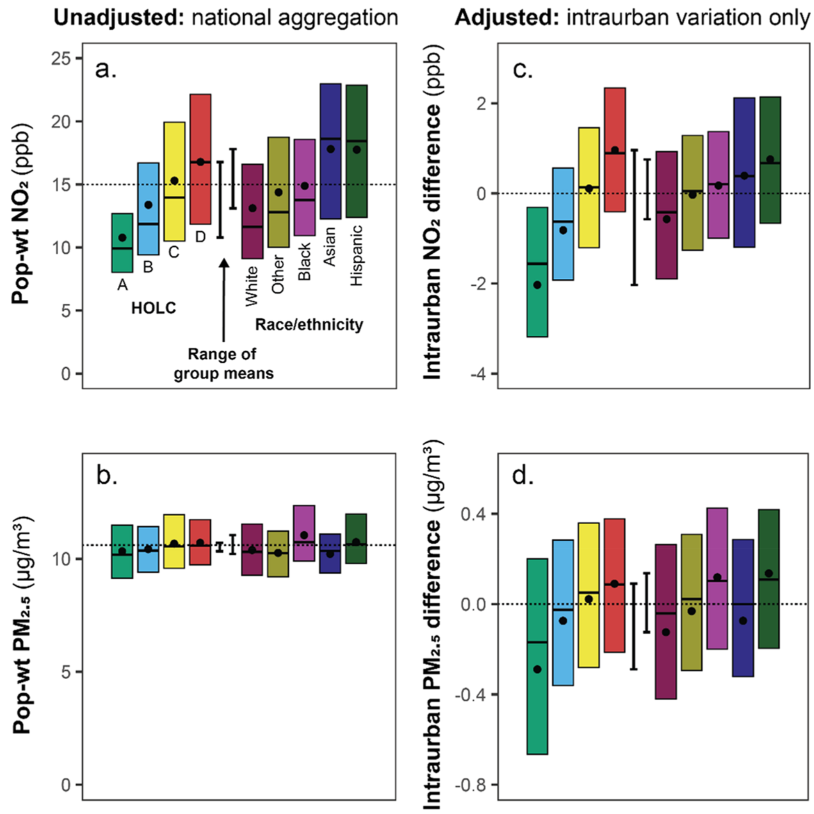

Figure 1. Population-weighted distributions of NO_2 and $PM_{2.5}$ levels within HOLC-mapped areas at the census block level. Bars represent 25th and 75th percentiles. Medians are indicated with horizontal lines, and means by the dot marker; the overall mean is indicated by the dotted line. Unadjusted national distributions are presented for (a) NO_2 and (b) $PM_{2.5}$. Adjusted distributions (c and d) report the national distributions of intraurban differences for census blocks within a given HOLC grade relative to the PWM level within each city. In each panel, pollution level distributions are reported by both HOLC grade (left cluster) and race/ethnicity (right cluster). Vertical lines between these clusters reflect the pollution range of the group means: the difference in the population-weighted mean between groups A and D (left line) and between the highest-exposed and lowest-exposed racial/ethnic group. Panels c and d illustrate how intraurban disparities are consistently higher by historical HOLC grade than by race/ethnicity.

practice isolated communities of color, restricting their ability to build wealth through home ownership, and informed later local government land use decisions that placed hazardous industries in and near D neighborhoods.[24] The discriminatory practices captured by the HOLC maps continued until 1968, when the Fair Housing Act banned racial discrimination in housing, yet the legacy of explicit racial discrimination still shapes patterns of racial residential segregation today.[27]

A growing body of scholarship finds associations between redlining and present-day environmental health disparities in U.S. cities. For example, in 64% of grade D neighborhoods, a majority (>50%) of the population is POC (i.e., not non-Hispanic White); in 74% of grade D neighborhoods, the median income is low to moderate.[27] Redlining designations are associated with a variety of exposures, including greenspace prevalence,[28] tree canopy,[29−31] urban-heat exposure disparities,[29,32,33] and health effects, including asthma,[34] cancer,[35,36] adverse birth outcomes,[37,38] and overall urban health.[39] To date, limited research has investigated air pollution exposure and redlining,[31,34] despite its importance as an environmental risk factor.

We focus here on two key air pollutants that are significant causes of ill health and premature mortality, nitrogen dioxide (NO_2) and fine particulate matter ($PM_{2.5}$), and have distinct sources, atmospheric behavior, and spatial patterns. NO_2 is a relatively short-lived, localized pollutant emitted by traffic, industry, power generation, and other high-temperature combustion processes. Urban areas tend to exhibit spatially sharp NO_2 gradients because primary traffic emissions are a major source of NO_2.[40−43] In contrast, $PM_{2.5}$ varies more on a regional scale because it has an atmospheric lifetime of days to weeks and is influenced strongly by both a broad array of emission sectors and multiple secondary formation processes.[44−47]

This paper explores associations between historical redlining and year-2010 air pollution levels and census demographics for 202 U.S. cities home to 65% of the U.S. urban population. We find monotonic and highly consistent associations between pollution levels and HOLC grades for both pollutants, with larger intraurban disparities associated with NO_2. To the best of our knowledge, this study is the first full-scale examination of air pollution disparities relative to historical redlining and advances our understanding of the origins and persistence of inequities in air pollution exposures in the United States.

MATERIALS AND METHODS

Demographic and HOLC Data. We used georeferenced 1930s era HOLC maps developed by the University of Richmond's Mapping Inequality project to identify HOLC codes in 202 cities (148 U.S. census urbanized areas) across the United States, shown in Figure S1.[25] Mapped neighborhoods were categorized by HOLC into one of four grades: A,

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Environ. Sci. Technol. Lett. 2022, 9, 345−350

best; B, still desirable; C, definitely declining; or D, hazardous for mortgage appraisal. We linked HOLC maps to individual U.S. Census blocks from the most recent available decennial census (2010);[48] census blocks provide a spatial resolution at approximately the scale of a city block in urban areas (geospatial procedures are described in the Supporting Information). The resulting data set incorporates 45 million people in 202 U.S. cities (n = 562,078 census blocks; average population of 80 people per block).

Because of urban expansion post-1930, the HOLC areas represent only a subset of the overall present-day urban footprint in most metropolitan areas: the present-day urban core. To provide context and comparison, we also separately extend our analysis to the full U.S. Census urbanized areas (CUA; n = 148) that contain the HOLC-mapped neighborhoods. These 148 CUAs had a year-2010 population of 161 million people (∼65% of the full U.S. population residing in urbanized areas in 2010).

We combine race/ethnicity data to develop four aggregate groupings for analysis: people who are Hispanic of any race [24% of HOLC population (Table S1)], non-Hispanic White (henceforth White, 43%), non-Hispanic Black (Black, 23%), and non-Hispanic Asian (Asian, 7%). The remaining 3% of the HOLC population (Other) includes Pacific Islander, Native American, and populations self-identifying as belonging to two or more races. The broader CUA population demographics are as follows: 56% White, 15% Black, 7% Asian, and 19% Hispanic.

Air Pollution Data. We characterized NO_2 and $PM_{2.5}$ levels using empirical (i.e., land-use regression) models developed by the Center for Air, Climate and Energy Solutions (CACES; www.caces.us/data).[5] This data set provides annual ambient concentration predictions for census blocks for 1979–2015. We employ year-2010 pollution data here to align with the most recent available (2010) decennial census. This model surface and its predecessors are commonly used for disparity analyses[1,2,49] and predict NO_2 and $PM_{2.5}$ at U.S. EPA monitoring sites with high fidelity (R^2 = 0.81 and 0.84, respectively).[1] Our core results are expressed as population-weighted statistics [i.e., population-weighted mean (PWM) and other percentiles from the population distribution of exposures].

We first aggregate data in terms of unadjusted statistics (e.g., the national PWM concentration for all blocks in the D grade). Next, to isolate associations between redlining and intraurban gradients, we present adjusted statistics that hold constant for city-to-city differences in air pollution and therefore reveal only within-urban disparities. This adjusted statistic is computed as the national PWM of the intraurban concentration difference, i.e., the difference between census block levels and the corresponding urban PWM across all HOLC areas in a CUA (see section S1.2 of the Supporting Information). An example of the input data sets for Atlanta, GA, is included in Figure S2, and population demographics are outlined in Table S1 and Figure S3.

RESULTS AND DISCUSSION

Associations between Concentration and HOLC Category. Because HOLC-mapped areas tend to cover only city centers and exclude suburban areas, air pollution levels in the HOLC-mapped areas tend to be higher than in the corresponding overall CUAs (Figure S4). Year-2010 PWM concentrations were 15.0 ppb (NO_2) and 10.6 $\mu g\ m^{-3}$ ($PM_{2.5}$) for the 45 million people residing in HOLC-mapped areas, versus 10.9 ppb (NO_2) and 9.9 $\mu g\ m^{-3}$ ($PM_{2.5}$) for the corresponding CUAs.

Unadjusted national statistics show that redlining is strongly associated with NO_2 and more weakly but detectably associated with $PM_{2.5}$ (Figure 1a,b). PWM NO_2 pollution levels are 6.0 ppb (56%) higher in the D-grade ("hazardous") than in the A-grade census blocks (16.8 ppb vs 10.8 ppb). PWM concentrations increase monotonically across HOLC grades. For $PM_{2.5}$, this monotonic association also holds, but the PWM difference between A and D groups is smaller, 0.4 $\mu g\ m^{-3}$ (4%; 10.7 $\mu g\ m^{-3}$ vs 10.3 $\mu g\ m^{-3}$). The smaller difference for $PM_{2.5}$ aligns with existing research showing comparatively smaller intraurban pollution variations that are superimposed on a larger regional (mostly secondary) background.[50,51]

Redlining is also associated with intraurban pollution gradients. PWM NO_2 pollution levels for each HOLC zone, relative to that city's average level (Figure 1), are 1.0 and 0.1 ppb higher for D and C areas, respectively, and 0.8 and 2.0 ppb lower for B and A areas, respectively (Figure 1c). Therefore, the PWM intraurban difference between the D and A grades is ∼3 ppb NO_2. Intraurban differences are smaller for $PM_{2.5}$ than for NO_2 (Figure 1d): maximum of 0.1 $\mu g\ m^{-3}$ (D grade) and minimum of −0.3 $\mu g\ m^{-3}$ (A grade), for a net 0.4 $\mu g\ m^{-3}$ difference.

We find a high degree of city-to-city consistency in intraurban disparities. PWM NO_2 levels are higher in D neighborhoods than overall (i.e., considering all HOLC-mapped areas) in 80% of the 202 cities and are lower in A neighborhoods than overall in 84% of cities. Disparities exist not only for the average (PWM) but also throughout the distribution. Indeed, in most (52%) cities, the interquartile ranges (IQRs) for NO_2 exhibited no overlap for the A and D neighborhoods (i.e., the A group 75th percentile was lower than the D group 25th percentile). For $PM_{2.5}$, disparities are again in the same direction though more modest. PWM $PM_{2.5}$ levels were higher than average for D neighborhoods in 55% of cities and lower than average for A neighborhoods in 68% of the cities, and the A and D IQRs exhibit no overlap in 20% of cities. Overall, trends associated with redlining hold across city size (Figure S5), across geographical region (Figure S6), and for the most recent-year (2015) CACES model predictions (Figure S7).

HOLC security maps were drawn on the basis of the demographic makeup of neighborhoods, reflecting preexisting racial residential segregation. However, redlining further solidified and accelerated those patterns that exist today. In addition, areas graded as C or D often hosted industrial facilities, railroads, and other pollution sources. We find that, within HOLC-mapped areas, D-grade neighborhoods are more likely to be near industrial sources and that the average number of sources nearby increases from A to D (Figure S8). Additionally, the portion of people living near railroads and primary roadways increases monotonically by HOLC grade from A to D (Figure S9). While U.S. rail infrastructure was largely constructed before the 1930s, limited-access highways were constructed almost entirely after the 1930s and were preferentially constructed through Black and brown communities in U.S. cities. This comparison using rail lines and highways emphasizes that racial disparities in air pollution exposure reported here reflect infrastructure placement that occurred both before and after HOLC redlining.[52,53]

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Environ. Sci. Technol. Lett. 2022, 9, 345−350

Disparities by Race/Ethnicity. We further stratified our results by comparing each HOLC-grade PWM concentration for individual racial/ethnic groups. Consistent with the substantial literature on racial/ethnic disparities for air pollution, we find that people of color experience higher-than-average NO_2 and $PM_{2.5}$ levels and are overrepresented within C and D neighborhoods, consistent with prior redlining research (Figure 1). For example, on average, PWM intraurban pollution differences for NO_2 (Figure 1c) are greater than average for Hispanic, Asian, and Black populations (0.8, 0.4, and 0.2 ppb higher than the urban average, respectively) and below average for the White population (−0.6 ppb). Differences for $PM_{2.5}$ are proportionally smaller (Figure 1d) but reflect similar racial disparities (PWMs of -0.1 $\mu g\ m^{-3}$ for White and Asian populations and 0.1 $\mu g\ m^{-3}$ for Black and Hispanic populations). Overall, intraurban PWM differences by HOLC grade are larger than by race/ethnicity (Figure 1). We find a substantially larger PWM differences between D and A HOLC grades (3.0 ppb NO_2 and 0.4 $\mu g\ m^{-3}$ $PM_{2.5}$) than between the most- and least-exposed racial/ethnic groups [1.3 ppb NO_2 and 0.26 $\mu g\ m^{-3}$ $PM_{2.5}$ (see Figure 1c,d)].

Next, we examined how racial/ethnic disparities interact with historical HOLC grade. Figure 2 illustrates PWM intraurban disparities that exist by race/ethnicity along the A−D HOLC grade gradient. Smaller, but still substantial, intraurban racial/ethnic disparities exist for $PM_{2.5}$ and NO_2 within each historical HOLC grade. On average, the within-grade white population experiences lower than average levels of NO_2 and $PM_{2.5}$ while the Hispanic population experiences above average levels. The Black population experiences consistently above HOLC-grade-average $PM_{2.5}$ levels while the Asian population experiences above HOLC-grade-average NO_2 levels. These within-grade disparities are nearly as large as the overall racial/ethnic disparity for the HOLC-mapped areas, implying that a substantial portion of the racial/ethnic exposure disparity within the study areas exists independently of historical HOLC status.

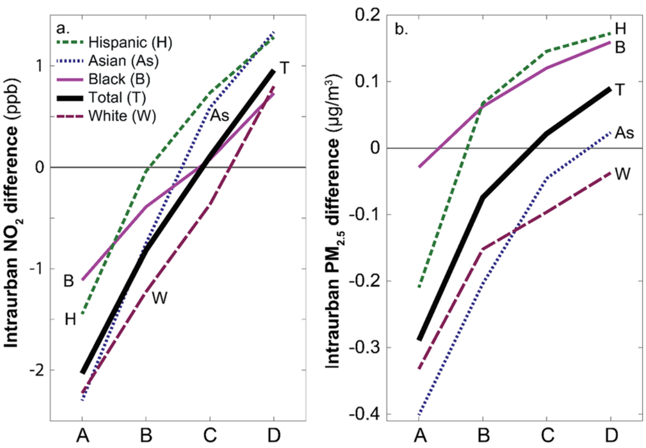

Figure 2. Population-weighted mean annual intraurban PWM levels by HOLC grade and race/ethnicity for (a) NO_2 and (b) $PM_{2.5}$. All race/ethnicity groups demonstrate monotonic increases by HOLC grade. Disparities by HOLC grade were larger than those associated with differences between racial/ethnic groups (100% higher for NO_2 and 50% higher for $PM_{2.5}$).

Racial/ethnic air pollution disparities reported here are subdivided next into two distinct effects: those that are associated with historical HOLC redlining and those that are not. To explore the sensitivity of our overall results to racial/ethnic segregation (i) between and (ii) within each HOLC grade, we used stylized demographic scaling factors to mathematically redistribute the populations in every city to (as a counterfactual approach) eliminate intraurban racial/ethnic segregation first between, and then within, HOLC grades (details in section S1.3). The reduction in racial/ethnic disparity from removing between-grade segregation was larger for NO_2 than for $PM_{2.5}$. However, both results were modest relative to the reductions produced by removing within-grade segregation (Figure S10). These findings may reflect various factors, including changes in demographics since the 1930s (e.g., gentrification), within-grade gradients of proximity to undesirable/polluting land uses (potentially preceding redlining), and later emission source placement (e.g., highways).

Figure S11 offers a complementary insight. Intraurban air pollution disparities show distinct relationships with demographics, but there is also a stratified gradient from HOLC grade A to D for nearly any level of demographic composition. This suggests redlining disparity effects are one of multiple factors that contribute to intraurban racial/ethnic disparities in pollution exposure. Importantly, if one could remove all between-grade disparities, that would only modestly change the overall, because within-grade disparities are the larger contributor to overall racial/ethnic disparities.

Broader Implications. Converging lines of evidence from our analysis suggest the following key points. First, redlining is associated with substantial intraurban air pollution disparities for NO_2 and $PM_{2.5}$. These findings are consistent with a broad body of evidence that adverse historical HOLC designations are associated with worse present-day local environmental quality and health outcomes, including air pollution, green space,[28] tree canopy,[29−31] COVID risk,[54] and urban heat.[29,32,33] Second, for the 45 million Americans who live in HOLC-mapped areas, NO_2 and $PM_{2.5}$ disparities by grade are larger than those by race/ethnicity. Third, despite the substantial association between HOLC redlining and aggregate pollution disparities, we find that intraurban racial/ethnic disparities in NO_2 and $PM_{2.5}$ are only moderately correlated with historical HOLC status; most of the disparities we observe are within grade rather than between grade. This finding likely reflects that historical redlining is only one of many racially discriminatory policies that have contributed to disparate environmental exposures for people of color.

Findings here highlight that present-day disparities in U.S. urban pollution levels reflect a legacy of structural racism in federal policy-making—and resulting investment flows and land use decisions—apparent in maps drawn more than 80 years ago. NO_2 and $PM_{2.5}$ are considered "short-lived" pollutants (atmospheric lifetimes of approximately hours and days, respectively), yet the systems that created these disparities span more than a human lifetime. Results from this work[55] can support decision-makers in their efforts to improve air pollution policy in ways that address exposure inequities. Future work should propose, evaluate, and implement solutions that can benefit disparately impacted communities. Fully addressing exposure inequities will require transformations sustained across generations.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.1c01012.

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Environ. Sci. Technol. Lett. 2022, 9, 345−350

Detailed description of materials and methods, supporting demographic tables, and supporting figures S1−S11 (PDF)

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Notes

The authors declare no competing financial interest.

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REFERENCES

(1) 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.

(2) 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), e94431.

(3) 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.

(4) Tessum, C. W.; Paolella, D. A.; Chambliss, S. E.; Apte, J. S.; Hill, J. D.; Marshall, J. D. $PM_{2.5}$ Polluters Disproportionately and Systemically Affect People of Color in the United States. *Sci. Adv.* **2021**, *7* (18), eabf4491.

(5) Kim, S.-Y.; Bechle, M.; Hankey, S.; Sheppard, L.; Szpiro, A. A.; Marshall, J. D. Concentrations of Criteria Pollutants in the Contiguous U.S., 1979 − 2015: Role of Prediction Model Parsimony in Integrated Empirical Geographic Regression. *PLoS One* **2020**, *15* (2), e0228535.

(6) Fann, N.; Kim, S.-Y.; Olives, C.; Sheppard, L. Estimated Changes in Life Expectancy and Adult Mortality Resulting from Declining $PM_{2.5}$ Exposures in the Contiguous United States: 1980−2010. *Environ. Health Perspect* **2017**, *125* (9), No. 097003.

(7) McDonald, B. C.; Dallmann, T. R.; Martin, E. W.; Harley, R. A. Long-Term Trends in Nitrogen Oxide Emissions from Motor Vehicles at National, State, and Air Basin Scales. *J. Geophys. Res.: Atmos.* **2012**, *117* (D21), D00V18.

(8) 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. *Soc. Sci. Res.* **2015**, *53*, 375−390.

(9) Kravitz-Wirtz, N.; Crowder, K.; Hajat, A.; Sass, V. The Long-Term Dynamics of Racial/Ethnic Inequality in Neighborhood Air Pollution Exposure, 1990−2009. *Bois Rev. Soc. Sci. Res. Race* **2016**, *13* (2), 237−259.

(10) Post, E. S.; Belova, A.; Huang, J. Distributional Benefit Analysis of a National Air Quality Rule. *Int. J. Environ. Res. Public. Health* **2011**, *8* (6), 1872−1892.

(11) Demetillo, M. A. G.; Harkins, C.; McDonald, B. C.; Chodrow, P. S.; Sun, K.; Pusede, S. E. Space-Based Observational Constraints on NO_2 Air Pollution Inequality From Diesel Traffic in Major US Cities. *Geophys. Res. Lett.* **2021**, *48* (17), e2021GL094333.

(12) Schell, C. J.; Dyson, K.; Fuentes, T. L.; Des Roches, S.; Harris, N. C.; Miller, D. S.; Woelfle-Erskine, C. A.; Lambert, M. R. The Ecological and Evolutionary Consequences of Systemic Racism in Urban Environments. *Science* **2020**, *369*, aay4497.

(13) Morello-Frosch, R. A. Discrimination and the Political Economy of Environmental Inequality. *Environ. Plan. C Gov. Policy* **2002**, *20* (4), 477−496.

(14) Morello-Frosch, R.; Lopez, R. The Riskscape and the Color Line: Examining the Role of Segregation in Environmental Health Disparities. *Environ. Res.* **2006**, *102* (2), 181−196.

(15) Heblich, S.; Trew, A.; Zylberberg, Y. East-Side Story: Historical Pollution and Persistent Neighborhood Sorting. *J. Polit. Econ.* **2021**, *129* (5), 1508−1552.

(16) Pastor, M.; Sadd, J.; Hipp, J. Which Came First? Toxic Facilities, Minority Move-In, and Environmental Justice. *J. Urban Aff.* **2001**, *23* (1), 1−21.

(17) Mohai, P.; Lantz, P. M.; Morenoff, J.; House, J. S.; Mero, R. P. Racial and Socioeconomic Disparities in Residential Proximity to Polluting Industrial Facilities: Evidence From the Americans' Changing Lives Study. *Am. J. Public Health* **2009**, *99* (S3), S649−S656.

(18) Houston, D.; Wu, J.; Ong, P.; Winer, A. Structural Disparities of Urban Traffic in Southern California: Implications for Vehicle-Related Air Pollution Exposure in Minority and High-Poverty Neighborhoods. *J. Urban Aff.* **2004**, *26* (5), 565−592.

(19) Massey, D. S. Still the Linchpin: Segregation and Stratification in the USA. *Race Soc. Probl.* **2020**, *12* (1), 1−12.

(20) Hall, M.; Iceland, J.; Yi, Y. Racial Separation at Home and Work: Segregation in Residential and Workplace Settings. *Popul. Res. Policy Rev.* **2019**, *38* (5), 671−694.

(21) Morello-Frosch, R.; Jesdale, B. M. Separate and Unequal: Residential Segregation and Estimated Cancer Risks Associated with Ambient Air Toxics in U.S. Metropolitan Areas. *Environ. Health Perspect.* **2006**, *114* (3), 386−393.

(22) Bravo, M. A.; Anthopolos, R.; Bell, M. L.; Miranda, M. L. Racial Isolation and Exposure to Airborne Particulate Matter and Ozone in Understudied US Populations: Environmental Justice Applications of Downscaled Numerical Model Output. *Environ. Int.* **2016**, *92−93*, 247−255.

(23) Hillier, A. Who Received Loans? Home Owners' Loan Corporation Lending and Discrimination in Philadelphia in the 1930s. *J. Plan. Hist.* **2003**, *2* (1), 3−24.

(24) Rothstein, R. *The Color of Law*; Liveright Publishing Corp.: New York, 2017.

(25) Nelson, R. K.; Winling, L.; Marciano, R.; Connolly, N., et al. Mapping Inequality. *American Panorama*, ed. Robert K. Nelson and

Edward L. Ayers; https://dsl.richmond.edu/panorama/redlining (accessed 28 Feb 2022).

(26) Nelson, R.; Winling, L. Mapping Inequality. U.S. EPA Environmental Justice and Systemic Racism Session #1; 2021.

(27) Mitchell, B.; Franco, J. HOLC "Redlining" Maps: The Persistent Structure of Segregation and Economic Inequality. National Community Reinvestment Coalition, 2018.

(28) Nardone, A.; Rudolph, K. E.; Morello-Frosch, R.; Casey, J. A. Redlines and Greenspace: The Relationship between Historical Redlining and 2010 Greenspace across the United States. *Environ. Health Perspect.* **2021**, *129* (1), No. 017006.

(29) Hoffman, J. S.; Shandas, V.; Pendleton, N. The Effects of Historical Housing Policies on Resident Exposure to Intra-Urban Heat: A Study of 108 US Urban Areas. *Climate* **2020**, *8* (1), 12.

(30) Locke, D. H.; Hall, B.; Grove, J. M.; Pickett, S. T. A.; Ogden, L. A.; Aoki, C.; Boone, C. G.; O'Neil-Dunne, J. P. M. Residential Housing Segregation and Urban Tree Canopy in 37 US Cities. *Npj Urban Sustain.* **2021**, *1* (1), 1−9.

(31) Namin, S.; Xu, W.; Zhou, Y.; Beyer, K. The Legacy of the Home Owners' Loan Corporation and the Political Ecology of Urban Trees and Air Pollution in the United States. *Soc. Sci. Med.* **2020**, *246*, 112758.

(32) Wilson, B. Urban Heat Management and the Legacy of Redlining. *J. Am. Plann. Assoc.* **2020**, *86* (4), 443−457.

(33) Saverino, K. C.; Routman, E.; Lookingbill, T. R.; Eanes, A. M.; Hoffman, J. S.; Bao, R. Thermal Inequity in Richmond, VA: The Effect of an Unjust Evolution of the Urban Landscape on Urban Heat Islands. *Sustainability* **2021**, *13* (3), 1511.

(34) Nardone, A.; Casey, J. A.; Morello-Frosch, R.; Mujahid, M.; Balmes, J. R.; Thakur, N. Associations between Historical Residential Redlining and Current Age-Adjusted Rates of Emergency Department Visits Due to Asthma across Eight Cities in California: An Ecological Study. *Lancet Planet. Health* **2020**, *4* (1), e24−e31.

(35) Collin, L. J.; Gaglioti, A. H.; Beyer, K. M.; Zhou, Y.; Moore, M. A.; Nash, R.; Switchenko, J. M.; Miller-Kleinhenz, J. M.; Ward, K. C.; McCullough, L. E. Neighborhood-Level Redlining and Lending Bias Are Associated with Breast Cancer Mortality in a Large and Diverse Metropolitan Area. *Cancer Epidemiol. Prev. Biomark.* **2021**, *30* (1), 53−60.

(36) Krieger, N.; Wright, E.; Chen, J. T.; Waterman, P. D.; Huntley, E. R.; Arcaya, M. Cancer Stage at Diagnosis, Historical Redlining, and Current Neighborhood Characteristics: Breast, Cervical, Lung, and Colorectal Cancers, Massachusetts, 2001−2015. *Am. J. Epidemiol.* **2020**, *189* (10), 1065−1075.

(37) Nardone, A. L.; Casey, J. A.; Rudolph, K. E.; Karasek, D.; Mujahid, M.; Morello-Frosch, R. Associations between Historical Redlining and Birth Outcomes from 2006 through 2015 in California. *PLoS One* **2020**, *15* (8), No. e0237241.

(38) Krieger, N.; Van Wye, G.; Huynh, M.; Waterman, P. D.; Maduro, G.; Li, W.; Gwynn, R. C.; Barbot, O.; Bassett, M. T. Structural Racism, Historical Redlining, and Risk of Preterm Birth in New York City, 2013−2017. *Am. J. Public Health* **2020**, *110* (7), 1046−1053.

(39) Nardone, A.; Chiang, J.; Corburn, J. Historic Redlining and Urban Health Today in U.S. Cities. *Environ. Justice* **2020**, *13* (4), 109−119.

(40) Nicholas Hewitt, C. Spatial Variations in Nitrogen Dioxide Concentrations in an Urban Area. *Atmospheric Environ. Part B Urban Atmosphere* **1991**, *25* (3), 429−434.

(41) Mead, M. I.; Popoola, O. A. M.; Stewart, G. B.; Landshoff, P.; Calleja, M.; Hayes, M.; Baldovi, J. J.; McLeod, M. W.; Hodgson, T. F.; Dicks, J.; Lewis, A.; Cohen, J.; Baron, R.; Saffell, J. R.; Jones, R. L. The Use of Electrochemical Sensors for Monitoring Urban Air Quality in Low-Cost, High-Density Networks. *Atmos. Environ.* **2013**, *70*, 186−203.

(42) Apte, J. S.; Messier, K. P.; Gani, S.; Brauer, M.; Kirchstetter, T. W.; Lunden, M. M.; Marshall, J. D.; Portier, C. J.; Vermeulen, R. C. H.; Hamburg, S. P. High-Resolution Air Pollution Mapping with Google Street View Cars: Exploiting Big Data. *Environ. Sci. Technol.* **2017**, *51* (12), 6999−7008.

(43) Karner, A. A.; Eisinger, D. S.; Niemeier, D. A. Near-Roadway Air Quality: Synthesizing the Findings from Real-World Data. *Environ. Sci. Technol.* **2010**, *44* (14), 5334−5344.

(44) Eeftens, M.; Tsai, M.-Y.; Ampe, C.; Anwander, B.; Beelen, R.; Bellander, T.; Cesaroni, G.; Cirach, M.; Cyrys, J.; de Hoogh, K.; De Nazelle, A.; de Vocht, F.; Declercq, C.; Dėdelė, A.; Eriksen, K.; Galassi, C.; Gražulevičienė, R.; Grivas, G.; Heinrich, J.; Hoffmann, B.; Iakovides, M.; Ineichen, A.; Katsouyanni, K.; Korek, M.; Krämer, U.; Kuhlbusch, T.; Lanki, T.; Madsen, C.; Meliefste, K.; Mölter, A.; Mosler, G.; Nieuwenhuijsen, M.; Oldenwening, M.; Pennanen, A.; Probst-Hensch, N.; Quass, U.; Raaschou-Nielsen, O.; Ranzi, A.; Stephanou, E.; Sugiri, D.; Udvardy, O.; Vaskövi, É.; Weinmayr, G.; Brunekreef, B.; Hoek, G. Spatial Variation of $PM_{2.5}$, PM_{10}, $PM_{2.5}$ Absorbance and PM_{coarse} Concentrations between and within 20 European Study Areas and the Relationship with NO_2 − Results of the ESCAPE Project. *Atmos. Environ.* **2012**, *62*, 303−317.

(45) Thakrar, S. K.; Balasubramanian, S.; Adams, P. J.; Azevedo, I. M. L.; Muller, N. Z.; Pandis, S. N.; Polasky, S.; Pope, C. A.; Robinson, A. L.; Apte, J. S.; Tessum, C. W.; Marshall, J. D.; Hill, J. D. Reducing Mortality from Air Pollution in the United States by Targeting Specific Emission Sources. *Environ. Sci. Technol. Lett.* **2020**, *7* (9), 639−645.

(46) Kroll, J. H.; Seinfeld, J. H. Chemistry of Secondary Organic Aerosol: Formation and Evolution of Low-Volatility Organics in the Atmosphere. *Atmos. Environ.* **2008**, *42* (16), 3593−3624.

(47) Gentner, D. R.; Jathar, S. H.; Gordon, T. D.; Bahreini, R.; Day, D. A.; El Haddad, I.; Hayes, P. L.; Pieber, S. M.; Platt, S. M.; de Gouw, J.; Goldstein, A. H.; Harley, R. A.; Jimenez, J. L.; Prévôt, A. S. H.; Robinson, A. L. Review of Urban Secondary Organic Aerosol Formation from Gasoline and Diesel Motor Vehicle Emissions. *Environ. Sci. Technol.* **2017**, *51* (3), 1074−1093.

(48) U.S. Census Bureau. 2010 Census Summary File 2 - United States; 2011.

(49) Chambliss, S. E.; Pinon, C. P. R.; Messier, K. P.; LaFranchi, B.; Upperman, C. R.; Lunden, M. M.; Robinson, A. L.; Marshall, J. D.; Apte, J. S. Local- and Regional-Scale Racial and Ethnic Disparities in Air Pollution Determined by Long-Term Mobile Monitoring. *Proc. Natl. Acad. Sci. U. S. A.* **2021**, *118* (37), e2109249118.

(50) Lal, R. M.; Ramaswami, A.; Russell, A. G. Assessment of the Near-Road (Monitoring) Network Including Comparison with Nearby Monitors within U.S. Cities. *Environ. Res. Lett.* **2020**, *15* (11), 114026.

(51) Gu, P.; Li, H. Z.; Ye, Q.; Robinson, E. S.; Apte, J. S.; Robinson, A. L.; Presto, A. A. Intracity Variability of Particulate Matter Exposure Is Driven by Carbonaceous Sources and Correlated with Land-Use Variables. *Environ. Sci. Technol.* **2018**, *52* (20), 11545−11554.

(52) Ananat, E. O. The Wrong Side(s) of the Tracks: The Causal Effects of Racial Segregation on Urban Poverty and Inequality. *Am. Econ. J. Appl. Econ.* **2011**, 3 (2), 34−66.

(53) Archer, D. N. Transportation Policy and the Underdevelopment of Black Communities. *Iowa Law Review* **2021**, *106* (2125), 21-12.

(54) Li, M.; Yuan, F. Historical Redlining and Resident Exposure to COVID-19: A Study of New York City. *Race and Social Problems* **2021**, 1−16, DOI: 10.1007/s12552-021-09338-z.

(55) 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 − Extended Data Files, 2022. DOI: 10.6084/m9.figshare.19193243