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The effects of the historical practice of residential redlining in the United States on recent temporal trends of air pollution near New York City schools

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Abstract

Background: In the 1930's the United States (US) sponsored Home Owners' Loan Corporation (HOLC) created maps that determined risk for mortgage lending based on the racial and

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Declaration of Competing Interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envint.2022.107551>.

ethnic composition of neighborhoods leading to disinvestment in “redlined” or highest risk neighborhoods. This historical practice has perpetuated racial and economic segregation, and health disparities, that persist today. Interventions near schools where children spend large portions of the day, could impact large groups of children but schools are an often-overlooked environment for exposure. Despite a declining trend of ambient pollution in New York City (NYC) between 1998 and 2012, little is known about differences in air quality improvement near schools by historical redlining neighborhood status. Our objective was to examine if recent temporal trends of air pollution near NYC public schools differed in historically redlined neighborhoods.

Methods: We examined annual average street-level concentrations of combustion-related air pollutants (black carbon (BC), particulate matter (PM_{2.5}), nitrogen dioxide (NO₂), and nitric oxide (NO)), within a 250-m radius around schools using NYC Community Air Survey land-use regression models (n = 1,462). Year of monitoring, historical redlining (binary), and summer ozone were included in multivariable linear regression using generalized estimating equation models. Average annual percent change (APC) in pollutant concentration was calculated. Models were further stratified by historical redlining and a multiplicative interaction term (year of monitoring × historical redlining) was used to assess effect modification.

Results: Overall, there was a decreasing trend of BC (APC = −4.40%), PM_{2.5} (−3.92%), NO₂ (−2.76%), and NO (−6.20%) during the 10-year period. A smaller reduction of BC, PM_{2.5} and NO was observed in redlined neighborhoods (n = 722), compared to others (n = 740): BC (APC: −4.11% vs −4.69%; P_{interaction} < 0.01), PM_{2.5} (−3.82% vs −4.11%; P_{interaction} < 0.01), and NO (−5.73% vs −6.67%; P_{interaction} < 0.01). Temporal trends of NO₂ did not differ by historical redlining (P_{interaction} = 0.60).

Conclusions: Despite significant reductions in annual average pollution concentrations across NYC, schools in historically redlined neighborhoods, compared to others, experienced smaller decrease in pollution, highlighting a potential ongoing ramification of the discriminatory practice.

Keywords

School environment; Temporal variations; Air pollutants; Redlining; Social vulnerability

1. Introduction

In the 1930’s, the Home Owners’ Loan Corporation (HOLC), sponsored by the United States (US) government during the Great Depression, began categorizing neighborhoods based on racial demographics and perceived risk for mortgage investment to ameliorate the financial crisis (Hillier 2003). Neighborhoods were assigned one of four HOLC grades (A, B, C, and D), with higher grades (A) denoting lower risk and therefore increased accessibility of mortgage lending (Hillier 2003). The neighborhoods assigned the lowest grade (D) were shaded red on the HOLC maps, hence why the practice is known as “redlining” (Nelson et al. Accessed on June 2021). Neighborhoods primarily populated by Black, Asian, Hispanic, and non-Western-European White households systematically received a D grade (Hillier 2003). Although the HOLC housing practices were outlawed under the Fair Housing Act of 1968, the historical place-based discriminatory housing practices from the 1930’s has had extended effects in many areas through the 21st

century. Several studies have demonstrated that historical redlining has perpetuated racial (e.g., persons of color and immigrant residents) (Hillier 2003) and economic segregation (Mitchell and Franco 2018), social and environmental inequalities (Grove et al. 2018), health disparities (Krieger et al. 2020; Nardone et al. 2020b; Nardone et al. 2020c), and Coronavirus Disease 2019 (COVID-19) risks (Li and Yuan 2021) on current residents living in these neighborhoods. Segregated communities of color have limited access to health care, healthy food, and green space and increased proximity to industrial pollution and highways (Gaskin et al. 2012; Grove et al. 2018; Lane et al. 2022; Nardone et al. 2021), therefore, potentially impacting resident's health. For example, living in areas with lower historical HOLC grades is associated with present day higher rates of preterm birth (Nardone et al. 2020c), emergency department visits for asthma (Nardone et al. 2020a), and higher risk of late-stage breast and lung cancer diagnosis (Krieger et al. 2020). Gentrification is a process by which urban neighborhoods that have undergone disinvestment undergo reinvestment and in-migration of upper and upper-middle class people (Smith 1998). Gentrification has the potential to interplay with the lasting impacts of redlining but has not been shown to have clear negative or positive impacts on population health (Schnake-Mahl et al. 2020). Given the observed health disparities associated with historical redlining, it is important that future research investigates the impact of gentrification to better understand current environmental risk factors that may be a contributor to health disparities.

Exposure to combustion-related air pollutants, is one of the most critical environmental risk factors with direct ties to a multitude of health outcomes including cardiovascular disease, respiratory disease, and cardiovascular mortality (HEI 2010). Pollutants include fine particulate matter (PM)_{2.5}, black carbon (BC) or soot, a major component of PM_{2.5} and gaseous pollutants including nitrogen oxide (NO) and nitrogen dioxide (NO₂). Throughout the United States, significant disparities exist in exposure to air pollutants. For example, Black, Hispanic, and Asian people are exposed to higher levels of PM_{2.5}, on average, compared to White people (Tessum et al. 2021). Black and Hispanic communities also have higher exposure to BC, even after adjustment for socioeconomic position (Krieger et al. 2014). Additional evidence highlights similar disparities in trends of NO₂ and PM₁₀ exposure (Kravitz-Wirtz et al. 2016). Furthermore, a recent study found that disparities in air pollution levels have been linked to historical redlining across U.S. Cities, showing higher levels of PM_{2.5} and NO₂ in redlined neighborhoods, compared to non-redlined neighborhoods (Lane et al. 2022) .

Studies have shown that school environments (both indoors and outdoors) may be an important source of BC and PM_{2.5} exposure because 1) schools in urban communities like NYC are often located near roadways and heavy truck routes (Kingsley et al. 2014), 2) BC and PM_{2.5} can penetrate into indoor environments (Gaffin et al. 2017), and 3) children spend 7 to 12 hours per day in school (Permaul and Phipatanakul 2018). Associations between exposure to combustion-related air pollutants in school settings and adverse health outcomes have been also reported among school-age children (Annesi-Maesano et al. 2012; Baloch et al. 2020; Jung et al. 2021). For example, our previous study found that personal BC levels measured specifically while children were in school were associated with greater airway inflammation among NYC school children (Jung et al. 2021). A European study demonstrated that school children exposed to higher levels of PM_{2.5} in school were at

significantly higher odds of suffering from upper and lower airway disorders (Baloch et al. 2020). Similarly, a French study with primary school children found that those in classrooms with high PM_{2.5} and NO₂ exposure were associated with higher odds of allergic asthma (Annesi-Maesano et al. 2012). This research highlights the importance of school-based exposures in overall child health.

Our previous studies reported that temporal trends in both indoor and outdoor air pollution (i.e., BC and PM_{2.5}) in New York City (NYC) decreased from 1998 to 2012 (Jung et al. 2014; Narvaez et al. 2008). However, little is known about neighborhood-specific differences in air quality improvement near schools in NYC. Our objectives were to 1) compare neighborhood characteristics including race/ethnicity, deprivation index (DI) (Brokamp et al. 2019), social vulnerability index (SVI) (CDC Accessed on July 30, 2021) and child opportunity index (COI) (Noelke et al. 2020) by historical redlining, 2) determine recent temporal trends of air pollution levels from 2009 to 2018 near NYC schools, and 3) examine if trends in pollution levels differ in historically redlined compared to non-redlined neighborhoods. We hypothesized that disparities in air pollution exposure, socioeconomic status, and opportunities for children would persist in redlined neighborhoods. An additional hypothesis was that levels of combustion-related air pollutants (e.g., BC, PM_{2.5}, NO₂, and NO) near NYC schools have declined between 2009 and 2018; yet recent declines in air pollutants would be less apparent in historically redlined neighborhoods compared to others based on previous studies that observed disparities in air pollution exposure by race and neighborhood-level segregation (Krieger et al. 2014; Tessum et al. 2021).

2. Methods

2.1. Study design

NYC public school information (2018–2019) were obtained from NYC Open Data (OpenData Accessed July 2021). Redlining data were retrieved from the publicly available 1935 Home Owners' Loan Corporation (HOLC) security maps from the Mapping Inequality project developed by the University of Richmond (Nelson et al. Accessed on June 2021). Each current NYC school was assigned a letter grade representing the HOLC risk level based on the location of the school relative to the 1935 HOLC maps: A (best; n = 9), B (still desirable; n = 175), C (definitely declining; n = 556), or D (hazardous; n = 722) (Fig. S1). Redlined areas were considered those assigned a HOLC risk grade of D (hazardous). NYC schools were dichotomized based on redlined (D or hazardous; n = 722) vs others (A, B, or C; n = 740) for the analysis (Fig. 1). There were n = 1,814 schools with air pollution data (Fig. S2). Among them, n = 1,482 (81.7 %) schools were located in regions that had an HOLC classification on the 1935 map and n = 332 (18.3 %) schools were located in regions that did not have an HOLC designation in 1935 and thus were excluded from this analysis.

Socioeconomic variables from the American Community Survey (ACS) (5-year averages within the same 10-year census period: 2010–2019) were analyzed to characterize historically redlined neighborhoods. The following census tract-level variables were included in the descriptive analysis: race and ethnicity (5-year averages 2015–2019); multi-dimensional deprivation index (DI; 0–1 scale with a higher index indicating more deprived; 5-year averages 2014–2018) (Brokamp et al. 2019); social vulnerability index (SVI; 0–1

rank; 5-year averages 2014–2018) (CDC Accessed on July 30, 2021); and child opportunity index (COI; 1–100 scale with higher index indicating more opportunity; 5-year averages 2013–2017) (Noelke et al. 2020). DI, as a measure to capture ‘community deprivation’, has 6 indicators including median household income, percent of households receiving public assistance income, education attainment of at least high school degree, no health insurance coverage, income below poverty level and house vacancy. This differs from the SVI that seeks to assess the resilience (i.e., the ability to survive and thrive) of communities confronted by external stress from environmental hazards, by synthesizing 19 variables from 4 domains (i.e., socioeconomic status, household composition and disability, people of color and English nonproficiency, housing type and transportation). Lastly, COI measures the quality of neighborhood resources and conditions that children need to grow and thrive capturing 29 variables from three domains of opportunity (i.e., Education, Health and Environment, and Social and Economic) at the neighborhood level. To assess sources of pollution we compared between redlined and other neighborhoods we analyzed publicly available diesel emission data from the US Environmental Justice Screen (EJScreen) (EPA, U.S., 2020) and density of local truck routes from NYC Department of transportation (DOT, NYC, 2019). See Table 1 for the details.

In this study, NYC school neighborhoods were categorized as gentrifying ($n = 620$), non-gentrifying ($n = 192$), and higher socioeconomic status (SES; $n = 650$) based on NYU Furman Center classification (NYU Furman Center). Gentrifying neighborhoods were defined as low income in 1990 (below 40 % of average household income) and experienced high rental growth between 1990 and 2010–2014 (higher than the median sub-borough areas). Non-gentrifying neighborhoods are those with low income in 1990 and low rental growth. Higher SES neighborhoods were in the top 60% of the 1990 average household income, therefore, ineligible for gentrification.

2.2. Estimated air pollution levels based on land use regression modeling

Location-specific outdoor air pollution measures were collected from the New York City Community Air Survey (NYCCAS) air quality-monitoring program between 2009 and 2018. $N = 150$ monitoring sites were selected in order to capture the range of variation in key local emission sources such as traffic and building density and to be spatially representative of NYC (Matte et al. 2013). Six 2-week samplings were conducted at street level in each season (i.e., winter, spring, summer and fall), comprising a total of 48 weeks of distributed site monitoring each year (Matte et al. 2013). Land use regression models were used by others to create estimates of annual average concentrations of combustion-related air pollutants (BC, $PM_{2.5}$, NO_2 and NO) and summer ozone (O_3) in 300-meter grid units across NYC (Clougherty et al. 2013; Kheirbek et al. 2014; Matte et al. 2013). Models are updated and published annually (NYCCAS). For this current analysis we used the publicly available citywide 300-meter Esri grid raster files of annual average predicted combustion-related air pollutants and O_3 downloaded from NYC OpenData (OpenData). Air pollution grids were then converted to point locations. Point-in polygon geoprocessing was performed in Esri ArcGIS Pro (version 2.8x) to associate the predicted surface grid points with a buffer, and finally the values behind the points were averaged by a 250-meter buffer.

2.3. Data analyses

Analyses were restricted to NYC public schools with unique District Borough Number (DBN) that had complete estimated air pollutant levels, HOLC spatial data, and socioeconomic variables from ACS data, resulting in a final sample of 1,462 (Fig. S2). Estimated outdoor air pollutant levels were averaged over 10 years (2009–2018) for descriptive statistics. Mann-Whitney and Kruskal-Wallis tests were performed as appropriate. Due to non-normal distribution of air pollutants, log-transformed air pollutant levels were used for subsequent analyses.

The effect of year of monitoring on repeated air pollutant concentrations over 10 years was analyzed in a model using generalized estimating equation (GEE) with robust standard errors where year of monitoring, historical redlining (binary variable: redlining vs others), and averaged summer O₃ levels were included (adjusted model). Models were further stratified by historical redlining (stratified model). To test whether temporal trends of air pollution differ by historical redlining, a multiplicative interaction term (year of monitoring × redlining) was included in the adjusted model. The five NYC boroughs have different neighborhood characteristics such as traffic density, building density, commuting patterns, and tree coverage (Khan et al. 2021; King et al. 2014), that may further affect annual trends of air pollutants. Exploratory analysis was conducted to examine if annual trends in redlined neighborhoods differ by five NYC boroughs (i.e., Total N_{redlined} = 722; Manhattan [n = 182 schools], the Bronx [n = 178], Brooklyn [n = 286], Queens [n = 53], and Staten Island [n = 23]).

Average annual percent change (APC) in air pollutant concentration was calculated by $100[\exp(\beta_{\text{adj}})-1]$ where β_{adj} is a coefficient of year of monitoring in log-transformed air pollutants in adjusted models. Sensitivity analyses were conducted by reanalysis after 1) removing gentrifying neighborhoods (n = 620) due to rapid changes in neighborhood demographics, resources, and economic opportunities in these neighborhoods (Mitchell and Franco 2018; Schnake-Mahl et al. 2020) and 2) removing co-located schools in the same building (same building code; n = 412). All analyses were performed using SPSS version 25 (Chicago, IL, USA) where $p < 0.05$ was considered statistically significant.

3. Results

3.1. Neighborhood characteristics by historically redlined neighborhoods

Overall NYC school characteristics are presented in Table S1. The largest proportion (43%) were elementary schools. When compared to other neighborhoods, historically redlined neighborhoods typically had a higher prevalence of Black residents (Table 1 and Fig. 2. Median: 34.6 % vs 16.9 % for historically redlined vs other neighborhoods, respectively; $p < 0.01$), higher DI (median: 0.48 vs 0.41; $p < 0.01$), higher SVI (0.85 vs 0.77; $p < 0.01$) and lower COI (19.0 vs 28.0; $p < 0.01$). Similarly, historically redlined neighborhoods had higher diesel emissions and density of local truck routes, compared to other neighborhoods (Table 1. 2.00 vs 1.79 $\mu\text{g}/\text{m}^3$ for diesel emissions and 2.28 vs 1.41 (length of local truck routes-[km]/area-[km²]) for density of local truck routes in redlined vs other neighborhoods; $p < 0.01$ for all). Furthermore, a greater percentage of historically redlined neighborhoods

were classified as gentrifying as compared to other neighborhoods (Table 1. [64.3 %] vs [21.1 %] for redlined vs other neighborhoods, respectively; $p < 0.01$).

3.2. Comparisons of estimated air pollution levels by historical redlining

The average concentrations (\pm standard deviation) of air pollutants over 10 years were $1.05 \text{ m}^{-1} \cdot 10^{-5} \pm 0.24$, $9.16 \pm 0.86 \text{ } \mu\text{g}/\text{m}^3$, $22.5 \pm 3.30 \text{ ppb}$ and $21.8 \pm 6.23 \text{ ppb}$ for BC, $\text{PM}_{2.5}$, NO_2 , and NO, respectively (Table S2). When stratified by historical redlining, the median levels of air pollutants were significantly higher in redlined compared to other neighborhoods (Fig. 3 and Table S2. Redlined vs other neighborhoods: $1.13 \text{ vs } 0.97 \text{ m}^{-1} \cdot 10^{-5}$, $9.42 \text{ vs } 8.86 \text{ } \mu\text{g}/\text{m}^3$, $23.2 \text{ vs } 21.6 \text{ ppb}$, and $20.8 \text{ vs } 19.9 \text{ ppb}$ for BC, $\text{PM}_{2.5}$, NO_2 , and NO, respectively; $p < 0.01$ for all). When comparing 2009 vs 2018, the estimated annual average levels of air pollutants decreased from $1.30 \text{ to } 0.83 \text{ m}^{-1} \cdot 10^{-5}$ (-44.1%) for BC, $11.3 \text{ to } 7.6 \text{ } \mu\text{g}/\text{m}^3$ (-39.2%) for $\text{PM}_{2.5}$, $28.1 \text{ to } 20.4 \text{ ppb}$ (-31.8%) for NO_2 , and $29.8 \text{ to } 15.3 \text{ ppb}$ (-64.3%) for NO in redlined neighborhoods. In comparison, similar but slightly greater reductions were observed for BC (-45.8%), $\text{PM}_{2.5}$ (-40.0%), and NO (-68.9%) in other neighborhoods (Fig. 4).

3.3. Year of monitoring as a predictor of air pollutant levels: Effect of historical redlining

Overall annual trends of air pollution over 10 years are shown in Fig. S3. There was a decreasing trend of BC (APC = -4.40%), $\text{PM}_{2.5}$ (-3.92%), NO_2 (-2.76%) and NO (-6.20%) from 2009 and 2018, with the highest annual reduction in NO, followed by BC (Table 2 and Fig. S3). When stratified by historical redlining, a smaller reduction in BC, $\text{PM}_{2.5}$, and NO was observed in redlined neighborhoods, compared to others (Table 2 and Fig. 4. APC: -4.11% vs -4.69% [$P_{\text{interaction}} < 0.01$], -3.82% vs -4.11% [$P_{\text{interaction}} < 0.01$], and -5.73% vs -6.67% [$P_{\text{interaction}} < 0.01$] in redlined vs other neighborhoods for BC, $\text{PM}_{2.5}$, and NO, respectively). Temporal trends of NO_2 did not differ by historical redlining (Table 2. APC: -2.66% vs -2.76% in redlined vs others; $P_{\text{interaction}} = 0.60$).

In exploratory analysis, the levels and annual trends of air pollutants in redlined neighborhoods were compared across the five NYC boroughs. Among redlined neighborhoods, the estimated air pollutant levels significantly differed across the five NYC boroughs (Fig. S4, $p < 0.01$). Manhattan showed the highest levels of estimated air pollutant concentrations, followed by the Bronx and Brooklyn. The greatest reductions in BC (APC -5.45%), $\text{PM}_{2.5}$ (APC -4.40%), NO_2 (APC -3.05%), and NO (APC -7.69%) were observed in the Bronx (Fig. 5). In contrast, Brooklyn showed the smallest reductions in BC (APC -3.73%), $\text{PM}_{2.5}$ (APC -3.54%), and NO (APC -4.50%).

3.4. Sensitivity analysis

After removing gentrifying neighborhoods from the analysis ($n = 620$), the differences in annual percent change of pollutants in redlined versus non-redlined neighborhoods remained statistically significant, with a greater magnitude of difference (Table S3. APC -3.63% vs -4.69% for BC, -3.54% vs -4.11% for $\text{PM}_{2.5}$, -2.37% vs -2.66% for NO_2 and -5.07% vs -6.76% for NO in redlined vs other neighborhoods). When co-located schools ($N = 412$) were removed, the main results shown in Fig. 4 were replicated (Table S3. APC -4.11% vs

–4.59% for BC, –3.82% vs –4.11% for PM_{2.5}, –2.76% vs –2.66% for NO₂ and –5.82% vs –6.57% for NO in redlined vs other neighborhoods).

4. Discussion

Historical redlining in the 1930's, one of many discriminatory and racist policies, may influence the socioeconomic vulnerability of neighborhoods today. This discriminatory policy, based on racial demographics and perceived risk for mortgage investment, led to decreased investment and perpetuated racial and economic segregation in redlined neighborhoods (Hillier 2003; Mitchell and Franco 2018). Further, there is evidence that air pollution levels across the United States are higher in redlined neighborhoods than non-redlined (other) neighborhoods (Lane et al. 2022; Nardone et al. 2020a). In the current study, historically redlined neighborhoods in NYC were more likely to have a higher prevalence of Black residents, higher deprivation, social vulnerability, and lower childhood opportunity as well as higher diesel emissions and density of local truck routes, compared to other neighborhoods. We sought to assess if differences exist in air quality improvement near NYC schools by historical redlining. We observed overall decreasing trends of estimated mean levels of BC, PM_{2.5}, NO₂, and NO near NYC public schools between 2009 and 2018. This pattern was less apparent in historically redlined neighborhoods when compared to other neighborhoods for BC, PM_{2.5} and NO, suggesting a residual impact of discrimination in NYC. We also observed that historically redlined neighborhoods exhibited different degrees of air quality improvements across the five NYC boroughs, with greater reductions of air pollutant levels in the Bronx where the air quality was among the poorest.

To our knowledge, this is the first study to examine the role of historical redlining on present annual trends of air pollutant levels near schools. In our previous studies we reported declining trends in BC and PM_{2.5}, directly measured in indoor and outdoor environments in NYC between 1998 and 2012, that may have been attributed to multiple NYC legislative regulations targeting traffic-related air pollution, which include the conversion and replacement of city-owned or operated diesel fuel powered vehicles such as garbage trucks, school busses and fleet trucks to low emission diesel and alternative fuel vehicles (Jung et al. 2014; Narvaez et al. 2008). The Clean Heat Rule to phase out the use of dirty fuel oils (low grade, types #4 and #6) for heating by 2012 could have further contributed to improvement of recent air quality. The current study provides an update of the previous findings with more recent ambient air pollutant data (2009–2018), based on the estimated concentrations near NYC schools. Despite the positive news of significant reductions in estimated annual mean concentrations of air pollutants throughout NYC over the past decade, historically redlined neighborhoods experienced poorer air quality and smaller decreases in BC, PM_{2.5} and NO compared to other neighborhoods. Unlike other pollutants, the effect modification of the association between year of monitoring and NO₂ by historical redlining was not significant despite higher 10-year average levels of NO₂ in redlined neighborhoods.

Gentrification, a process of displacement of long-term residents occurring in many redlined neighborhoods could have an influence on present day air pollutant concentrations, particularly if point sources of pollution that were located in marginalized communities

have changed over time. Also, a study has shown that gentrification was associated with the changes in redlined neighborhoods, economic inequality, and segregation (Mitchell and Franco 2018). One of the strengths of our study is that we were able to perform a sensitivity analysis excluding gentrifying neighborhoods. The results showed larger differences in pollution changes over time between historically redlined and other neighborhoods, suggesting the potential role of gentrification in air quality.

Understanding racial and ethnic inequities, socioeconomic factors, neighborhood characteristics, environmental pollution, and built environments may be potential pathways to delineate the links between historical redlining and current health disparities. In line with other studies (Aaronson et al. 2021; Mitchell and Franco 2018), we also observed that schools in historically redlined neighborhoods, compared to other neighborhoods, had a higher percentage of Black residents, greater community deprivation, lower levels of resilience and lower childhood opportunity. Literature also illustrates that there is a robust relationship between racial and ethnic segregation and poverty levels, demonstrating that African American residents are more likely to live in neighborhoods with spatially concentrated poverty (Lichter et al. 2012). Also, we found that redlined neighborhoods exhibited significantly higher levels of combustion-related air pollutants than other neighborhoods, potentially placing individuals from these communities at greater risk of pollution-related health outcomes including cardiovascular disease, pulmonary disease and cardiovascular mortality (HEI 2010). Despite increasing attention to historical redlining and present-day environmental health disparities, research on air pollution disparities relative to historical redlining are limited. Lane et al. reported monotonic associations between pollution levels (i.e., $PM_{2.5}$ and NO_2) measured in year 2010 and HOLC grades in 202 U.S. cities (Lane et al. 2022). Furthermore, they found that the average number of industrial emission sources and primary road and rail line prevalence also increased with worsening HOLC grades (Lane et al. 2022). Similarly, Nardone et al. found that diesel exhaust particles (DEP) emission estimates in historically redlined neighborhoods were nearly twice as high as the best grade areas in California (Nardone et al. 2020a). They explained that highways, a major source of diesel emissions, were often constructed in communities which had less/least resistance to land acquisition, probably overlapped with redlined areas. Additional research in NYC has demonstrated that on-road air pollutant emissions disproportionately impact high poverty neighborhoods, likely due to traffic patterns of diesel trucks and buses in high poverty neighborhoods, that make up the largest share of on-road air pollution (Kheirbek et al. 2016). Indeed, in our study we observed higher diesel emissions ($\mu g/m^3$) and density of local truck routes (i.e., length of local truck routes-[km]/area-[km^2]) in historically redlined neighborhoods compared to others. Neighborhood dis-amenities such as proximity to truck routes and traffic emissions in redlined neighborhoods are likely to increase air pollution levels, as shown in our study, further negatively impacting current residents' health.

Other studies have examined associations between historical redlining and other health outcomes (Krieger et al. 2020; Nardone et al. 2020a; Nardone et al. 2020c). For example, studies in California found worsening HOLC grade was associated with increased asthma-related emergency department visits and odds of preterm birth (Nardone et al. 2020a; Nardone et al. 2020b). In a study in Massachusetts, Krieger et al. reported that risk of

late-stage breast and lung cancer diagnosis was associated with historical redlining (Krieger et al. 2020). One potential mechanism to understand these health disparities is allostatic load, which refers to the cumulative wear and tear of physiological responses to stressors such as major life events, social and environmental burden (Guidi et al. 2021). For example, African American adults experienced higher pervasive discrimination scores and allostatic load, compared to White adults when adjusting for socioeconomic status (Van Dyke et al. 2020). Furthermore, allostatic load was associated with chronic diseases such as abdominal obesity, hypertension, diabetes, and self-reported cardiovascular disease and arthritis (Mattei et al. 2010). Taken together, impaired immune responses through a mechanism of increased allostatic load, induced by chronic stress from racial discrimination, could be a potential pathway to understand some of the health disparities in redlined neighborhoods.

Policy implications from this research point to the importance of considering historical injustice in the discussion of equitable urban planning. Research from Nardone et al. illustrates that worse HOLC grades are associated with less present-day greenspace across the United States (Nardone et al. 2021). Reduced NO₂ levels associated with urban tree canopy could further result in lower incidences of respiratory disorders (Rao et al. 2014). Furthermore, redlined areas have been shown to have 2.6 °C higher land surface temperature, compared to other areas in urban cities in the United States (Hoffman et al. 2020), particularly amplifying urban heat stress risks to residents in redlined neighborhoods. To combat such disparities, urban planners need to be proactive in building greenspaces in historically redlined communities to reduce air pollutant levels and heat stress in these neighborhoods. Since children spend a significant portion of their days at school, including outdoor time, schools, especially those in urban communities like NYC that are often located near roadways and heavy truck routes (Kingsley et al. 2014), are an important level of spatial analysis for air pollution studies. In this study, we observed almost half of NYC public schools (722/1462, 49 %) are located in historically redlined neighborhoods. Given the knowledge of the associations between chronic exposure to combustion-related air pollutants and increased mortality, cardiovascular morbidity, and respiratory disease (HEI 2010) interventions to reduce children's exposure to air pollutants, particularly in school settings, could lead to lasting benefits in later life (Milanzi et al. 2018). Also, in our study, schools in historically redlined neighborhoods had inequity of opportunities and limited resources such as access to green space and healthy food options for children. Multi-faceted, community-level interventions that aim to change places and social environments can improve child health, development, and well-being (Sandel et al. 2016).

We acknowledge several limitations to our study. For one, this analysis includes only a 10 year period, which could miss historical time periods in which pollution and redlining status had a different relationship. Another is that this study does not consider changes in traffic patterns/counts over time that are likely an important driver of the observed trends. Also, it is possible that the differences in time trends seen in 5 boroughs could be due to regression to the mean (RTM), which is a statistical phenomenon that occurs in repeated measurements when unusually high or low measurements are followed by measurements closer to the mean (Barnett et al. 2005). While direct measures of air pollutants at school sites would provide better precision on the levels of air pollution, those data are not available; therefore, we used publicly available LUR model estimates for air pollutants

within a 250 m buffer near schools. Nevertheless, the use of NYCCAS monitoring data allowed for wider inclusion of school sites and multiple pollutants throughout NYC. Lastly, we acknowledge that despite the significant differences observed in annual trends between redlined and other neighborhoods in this study, those differences were very small, and the baseline geographical differences in air pollution levels in redlined vs other neighborhoods may be more relevant.

Our study highlights the important relationship between historical discriminatory practices and current environmental inequity in NYC. Disparities in air pollutant levels by historical redlining persist near NYC schools. Despite the good news of reporting overall improvement of air quality over the 10-year study period, historically redlined neighborhoods have experienced smaller decreases in BC, PM_{2.5} and NO. These findings, combined with analysis demonstrating that redlined neighborhoods are more likely to have a higher deprivation index and social vulnerability, and lower childhood opportunity, compared to other neighborhoods, highlight the importance of considering historical inequities in discussions of current disparities. Given the observed environmental injustice in air pollution exposure levels over time near NYC schools that were associated with historical redlining, it is crucial that current pollution reduction policies or interventions target historically marginalized neighborhoods or neighborhoods that experienced discrimination in an effort to reduce health inequities among children.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Data availability

All data analyzed in this publication are publicly available.

Abbreviations:

ACS	American Community Survey
APC	Annual percent change
BC	black carbon
COI	child opportunity index
DBN	District borough number
DI	deprivation index
DEP	diesel exhaust particle

GEE	generalized estimating equations
HOLC	Home Owners' Loan Corporation
LUR	land use regression
NYC	New York City
NYCCAS	New York City Community Air Survey
NO₂	nitrogen dioxide
NO	nitric oxide
O₃	ozone
PM	particular matter
SES	socioeconomic status
SVI	social vulnerability index

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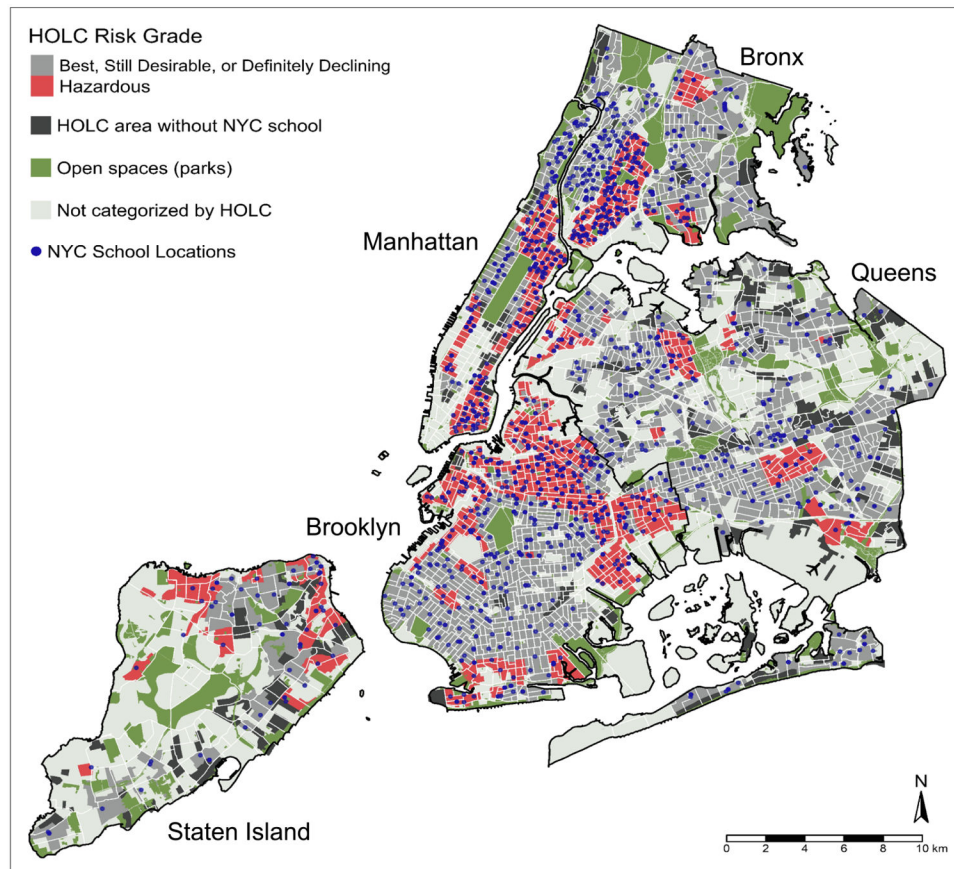
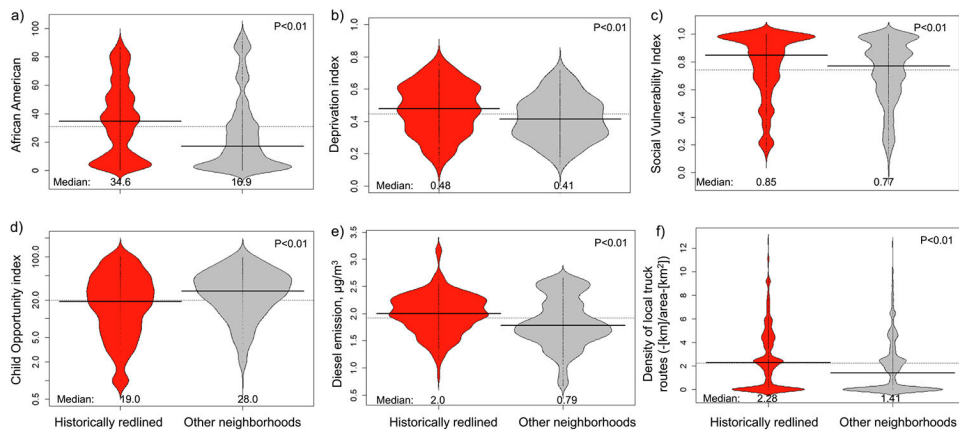


Fig. 1. NYC public schools located in historically redlined ($n = 722$) vs other neighborhoods ($n = 740$). Historically redlined neighborhoods were defined as HOLC grade D (Hazardous); Other neighborhoods includes HOLC grade A (Best), B (Still Desirable), and C (Definitely Declining); NYC school information in 2018–2019 was used ($N = 1,462$).

**Fig. 2.**

Comparisons of neighborhood characteristics between historically redlined neighborhoods vs other neighborhoods. Mann-Whitney test performed. Bean plots with median values presented; The colored areas (red and gray) show the distribution of neighborhood characteristics of historically redlined ($n = 722$) vs other neighborhoods ($n = 740$), respectively; The dotted line indicates the overall mean and the thicker solid line shows the median concentration of air pollutants; Deprivation Index (DI; 0–1 scale; 5-year estimates 2014–2018) derived based on a principal components analysis of six different ACS measures; Social vulnerability index (SVI; 0–1; 5-year estimates 2014–2018), comprising of 4 domains (i.e., socioeconomic status, household composition and disability, people of color and English nonproficiency, and housing and transportation), was calculated based on the percentile rank on the sum of all 4 domain's percentile ranking sums; Child opportunity index (COI; 0–100; 5-year estimates 2013–2017), comprising of 3 domains (i.e., Education, Health and Environment, and Social and Economic), was defined as the percentile score of overall child opportunity index.

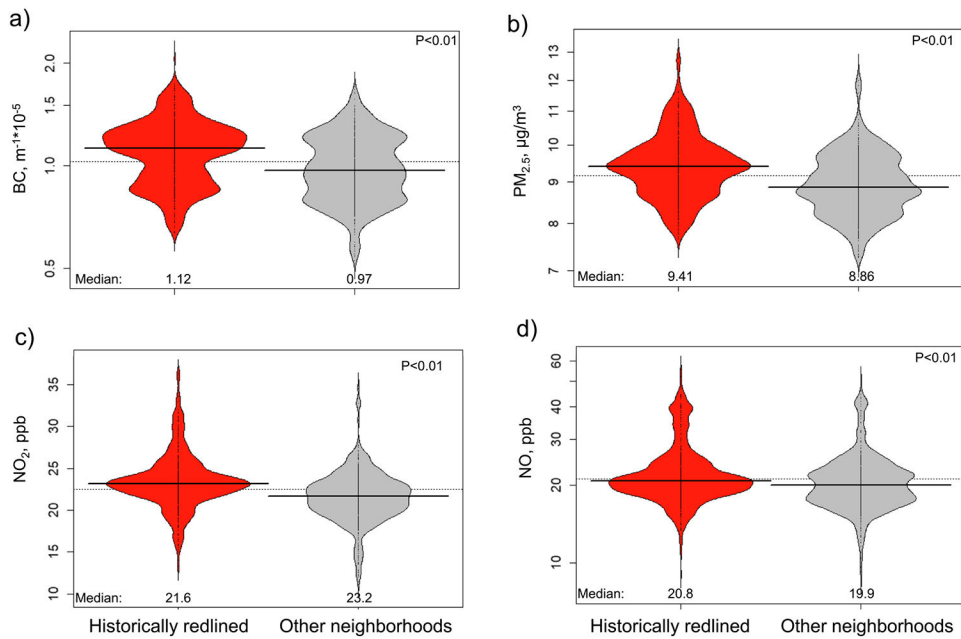


Fig. 3. Comparisons of estimated 10-year averaged air pollutant levels between historically redlined vs other neighborhoods. Mann-Whitney test performed. Bean plots with median values presented; The colored areas (red and gray) show the distribution of air pollutant concentrations of historically redlined ($n = 722$) vs other neighborhoods ($n = 740$), respectively. The dotted line indicates the overall mean and the thicker solid line shows the median concentration of air pollutants.

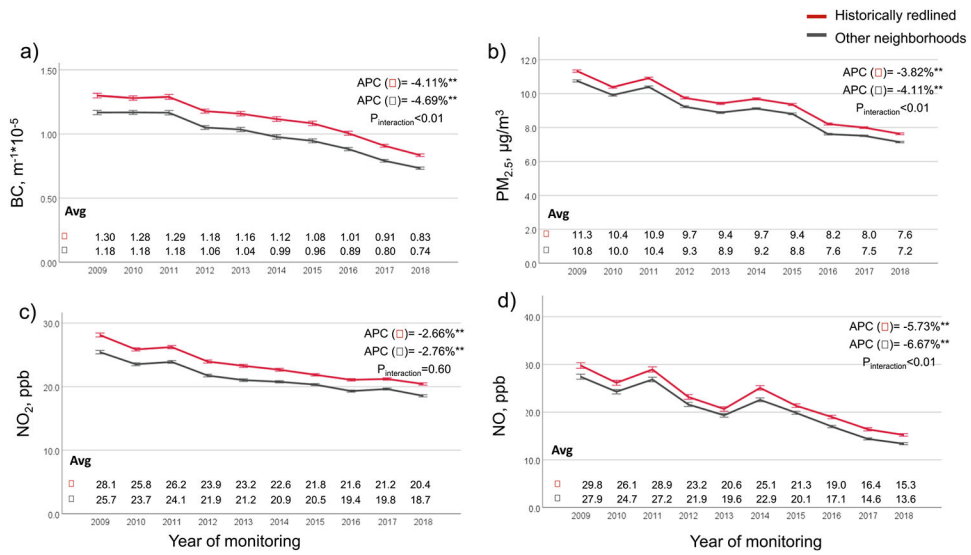


Fig. 4. Average annual trends of estimated air pollutant levels near NYC schools between 2009 and 2018: Historically redlined (n = 722) vs other neighborhoods (n = 740). Annual arithmetic mean concentrations of estimated air pollutant levels with 95% confidence interval are presented by historically redlined neighborhoods; Multivariable linear regression in generalized estimating equation (GEE) models was used to test trends over time; Annual percent change (APC) was calculated by $100 * [\exp(\log_{\beta_{adj}}) - 1]$ where $\log_{\beta_{adj}}$ expressed in log-adjusted conc unit/year for air pollutants; **p value < 0.01; p-value for multiplicative interaction term (year of monitoring × historical redlining) are presented.

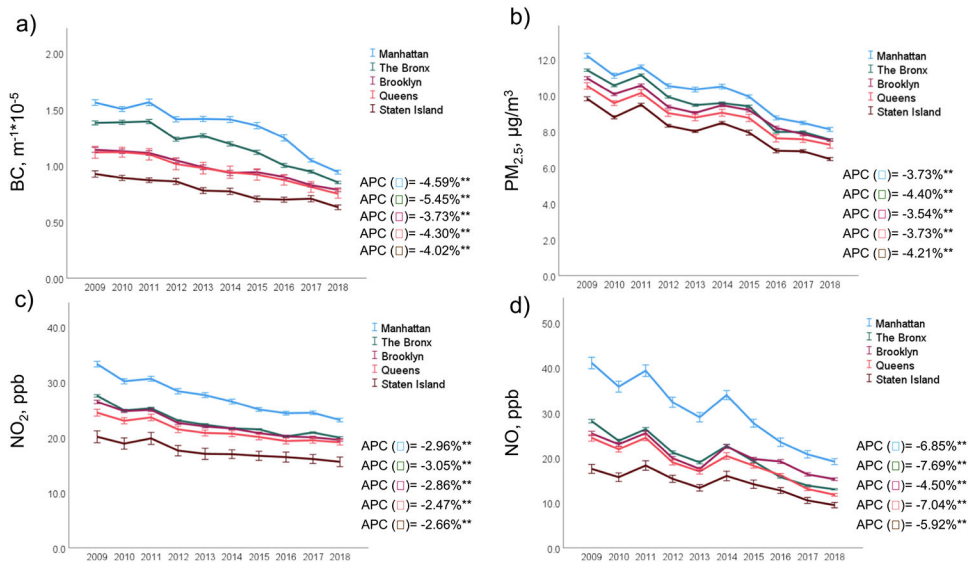


Fig. 5. Average annual trends of estimated air pollutant levels near NYC schools in historically redlined neighborhoods between 2009 and 2018: by 5 boroughs. Manhattan (n = 182), The Bronx (n = 178), Brooklyn (n = 286), Queens (n = 53) and Staten Island (n = 23). Annual arithmetic mean concentrations of estimated air pollutant levels in redlined neighborhoods with 95% confidence interval are presented by NYC 5 boroughs; Multivariable linear regression in generalized estimating equation (GEE) models were used to test trends over time; Annual present change (APC) was calculated by $100 * [\exp(\log_{\beta_{adj}}) - 1]$ where $\log_{\beta_{adj}}$ expressed in log-adjusted conc unit/year for air pollutants; **p value < 0.01.

Table 1

Neighborhoods characteristics near NYC public schools and comparisons by historical redlining.

	Overall (%, N _{schools} = 1,462)	Historically redlined neighborhoods (%, N _{schools} = 722)	Other neighborhoods ^a (%, N _{schools} = 740)	P- value ^b
Black or African American	25.9	34.6	16.9	<0.01
Hispanic or Latino	26.8	26.8	26.8	0.44
People of color ^c	87.8	89.4	86.1	<0.01
English non-proficiency	10.3	9.1	11.3	<0.01
Median household income	\$50,556	\$45,182	\$54,877	<0.01
Income below poverty level	21.3	24.7	17.8	<0.01
Public assistance	24.6	28.5	20.9	<0.01
No health insurance coverage	8.2	7.7	8.6	0.11
Aged 65 years or older	11.9	10.7	13.5	<0.01
Unemployed 16 years and older	7.3	7.9	6.9	<0.01
No high school diploma	20.8	22.8	20.2	<0.01
Housing vacancy	7.4	8.3	6.5	<0.01
House crowding ^d	8.7	8.3	9.5	<0.01
Higher diesel emissions ^e (µg/m ³)	1.92	2.00	1.79	<0.01
Density of local truck routes ^f (length of local truck routes-[km]/area-[km ²])	1.92	2.28	1.41	<0.01
Deprivation index ^g	0.45	0.48	0.41	<0.01
Social vulnerability index ^h	0.81	0.85	0.77	<0.01
Child Opportunity index ⁱ	24.0	19	28.0	<0.01
Gentrification ^j	42.4	64.3	21.1	<0.01

Median values presented

^aInclude best (A), still desirable (B), and definitely declining (C) neighborhoods based on the Home Owners' Loan Corporation (HOLC)^bMann-Whitney test performed^cPeople of color include Black, African American, American Indian, Alaska Native, Asian, Native Hawaiian, other Pacific Islander, Hispanic, and Latino^dTotal occupied housing units with greater than 1 person per room^eDiesel particulate matter level in air in micrograms per cubic meter (µg/m³); 2020 data obtained from Environmental Justice Screen (EJS), U.S. Environmental Protection Agency (EPA)^f2019 data obtained from NYC Department of Transportation (DOT)^gDeprivation index (DI; 0–1 scale; 5-year estimates; 2014–2018) derived based on a principal components analysis of six different ACS measures that include median household income, percent of households receiving public assistance income, education attainment of at least high school degree, no health insurance coverage, income below poverty level and house vacancy^hSocial vulnerability index (SVI; 0–1; 5-year estimates; 2014–2018), comprising of 4 domains (i.e., socioeconomic status, household composition and disability, people of color and English nonproficiency, and housing and transportation), was calculated based on the percentile rank on the

sum of all 4 domain's percentile ranking sums. *Socioeconomic status* includes below poverty, unemployed, income, and no high school diploma; *Household composition and disability* includes aged 65 or older, aged 17 or younger, older than age 5 with a disability, and single-parent households; *Minority status & language* includes people of color and English less than well (nonproficiency); *Housing type and transportation* includes multi-unit structures, mobile home, crowding, no vehicle, and group quarters.

ⁱChild opportunity index (COI; 0–100; 5-year estimates; 2013–2017), comprising of 3 domains (i.e., Education, Health and Environment, and Social and Economic), was defined as the percentile score of overall child opportunity index. *Education opportunities* include school poverty rate (eligibility for free or reduced-price lunch), teacher experience, student math proficiency level, student reading proficiency level, number of licensed early childhood education centers, number of high-quality early childhood education centers, early childhood education participation, high school graduation rate, AP course enrollment, college enrollment nearby, and adult education attainment; *Health and Environmental Opportunities* include access to healthy food, access to green space, walkability, housing vacancy rate, hazardous waste dump counts, index of industrial pollutants, average levels of airborne PM_{2.5}, ozone levels, extreme heat exposure, and health insurance coverage; *Social and Economic opportunities* include high-skill employment, poverty rate, public assistance rate, homeownership rate, median household income, employment rate, single household, and proximity to employment.

^jChi-square tests were conducted to compare the proportion of gentrifying neighborhoods between historical redlining and other neighborhoods.

Table 2

Average annual trends of air pollutants near NYC schools over 10 years (2009–2018): Effect of historical redlining ($N_{\text{schools}} = 1,462$).

Air pollutants	Average annual percent change (APC), [%]		
	Overall ^a	Redlined neighborhoods ^b	Other neighborhoods ^b
N_{data}	14,620	7220	7400
BC, $m^{-1} \times 10^{-5}$	-4.40**	-4.11**	-4.69**
PM _{2.5} , $\mu\text{g}/\text{m}^3$	-3.92**	-3.82**	-4.11**
NO ₂ , ppb	-2.76**	-2.66**	-2.76**
NO, ppb	-6.20**	-5.73**	-6.67**
			P-value for interaction ^c
			14,620
			<0.01
			<0.01
			0.60
			<0.01

NYC: New York City; BC: Black carbon; PM_{2.5}: Particulate Matter < 2.5 μm ; NO₂: Nitrogen dioxide; NO: Nitric oxide; Other neighborhoods include best (A), still desirable (B), and definitely declining (C) neighborhoods based on the Home Owners' Loan Corporation (HOLC)

Average percent changes (%) in air pollutant concentration are presented per year.

Multivariable linear regression in generalized estimating equation (GEE) models with robust standard errors were used

** p-value < 0.01.

^a Models were adjusted for historical redlining and O₃ (adjusted model)

^b Models adjusted for O₃

^c A multiplicative interaction term (year of monitoring \times historically redlined) was included in the adjusted model.