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SPATIAL ASSOCIATIONS BETWEEN REDLINING, GENTRIFICATION, AND CANCER RISK FROM AIR TOXICS IN METROPOLITAN ATLANTA, GA

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B.A., North Carolina State University, 2020

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Abstract

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Background: Historic redlining and modern gentrification processes are potential drivers of environmental toxins. Exposure to environmental toxins is a modifiable factor of cancer outcomes. We investigated the associations of historic redlining and gentrification with carcinogenic air toxins. We explored the effect modification of redlining and carcinogenic air toxins by gentrification stage.

Methods: Our study area included 92 census tracts in Atlanta, GA that overlap the area depicted in 1930's Home Owners' Loan Corporation (HOLC) Grade maps. We assigned HOLC Grade to each census tract using redlining scores and measured carcinogenic air pollution using EPA's air toxics cancer risk estimates. Gentrification was characterized using data from the Urban Displacement Project. Spatial Durbin models were used to estimate the direct effect, spillover effect, and total effect on air toxics cancer risk.

Results: Census tracts historically assigned HOLC Grade A had an estimated 61.48 fewer cancer cases due to air toxins compared to HOLC Grade D census tracts. However, there was not a monotonic relationship across HOLC grades. The indirect effects of HOLC grades were more than 12 times larger than the direct effects, demonstrating a strong spatial spillover effect from neighboring counties. There was no apparent pattern of effect modification of redlining by gentrification on air toxics cancer risks.

Conclusions: Our results support that historically and contemporary advantaged neighborhoods are associated with lower air toxics cancer risk. This study highlights the enduring environmental effects of historic redlining cannot be reversed solely by changes in resident demographics, but structural interventions are needed to address sources of air toxins for future generations.

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CHAPTER I: BACKGROUND/LITERATURE REVIEW

1.1. Breast Cancer

Breast cancer is the second most common type of cancer among the United States female population.[1] In the United States, 1 in 8 of all women in the United States will be diagnosed with breast cancer over their lifetimes.[2] Breast cancer is also the second leading cause of cancer death. Breast cancer is categorized into four molecular subtypes based on hormone receptor (HR) and human epidermal growth factor receptor (HER2). Hormone receptor positive (HR+) cancers are those that test positive for estrogen receptor (ER+), progesterone receptor (PR+), or both. Breast cancer cells with higher-than-normal levels of HER2 are called HER2-positive (HER2+). Luminal A (HR+/HER2-) is the most common breast cancer subtype making up 71% of breast cancer cases.[3] This subtype is slower growing and less aggressive compared to the other breast cancer subtypes. It is the most favorable prognosis due to its responsiveness to hormonal therapies. The second molecular subtype, Luminal B (HR+/HER2+) is similar to Luminal A but has a higher proportion of actively dividing cells. As a result of the higher grade, Luminal B is associated with poorer survival compared to Luminal B. HER2-enriched (HR-/HER2+) subtypes are associated with poorer short-term prognosis compared to HR+ breast cancers and HER2+ breast cancer grows and spreads more aggressively than other subtypes. The fourth subtype, triple-negative (HR-/HER2-) has a poorer prognosis than any other subtype, in part because treatment advances have lagged behind other molecular subtypes. Triple-negative subtypes are common in young women, Black women, and women with a *BRCA1* gene mutation.

1.2. Breast Cancer Disparities

Although breast cancer mortality has decreased over the past two decades, racial disparities have persisted.[4] Despite a higher incidence rate among Non-Hispanic White (NHW) compared to Non-Hispanic Black (NHB), the rate of decrease in breast cancer mortality is higher among NHW women compared to NHB women. As a result, there is a gap in breast cancer survival between NHW women and NHB women. From 2014 to 2018, the rate of deaths from breast cancer among NHW women was 19.6 per 100,000 compared to 27.4 per 100,000 among NHB women[4]. Further, the five-year survival rate of NHW women is 91.0 per 100,000 compared to 82.2 per 100,000 among NHB women. The higher rate of cancer death and low five-year survival rate, in part, reflects the disproportionate burden of triple-negative breast cancers among NHB women.[3] Breast cancer disparities may also be due to social determinants of health, including access to medical care, quality of care, and greater comorbidity burden as a result of socioeconomic inequalities. This is supported by several studies which show persistent racial disparities in breast cancer mortality among women participating in clinical trials and receiving equal treatment.[5]

1.3. Breast Cancer Risk Factors

All women are at risk for developing breast cancer but there are several factors related to genetics, lifestyle, and environment that alter the magnitude of risk for individual women. One of the most widely recognized risk factors of breast cancer is family history. Breast cancer risk increases if a first-degree relative has breast cancer at a young age or if there are multiple relatives with breast cancer.[6] Inherited genetic variations in *BRCA1* and *BRCA2* account for 5%-10% of all female breast cancers and 15%-20% of all familial breast cancers.[3] Compared to the general population who have a 10% risk of developing breast cancer by 80 years of age, women with pathogenic variants in *BRCA1* and *BRCA2* have an estimated 70% risk.[7]

Modifiable factors associated with breast cancer risk include lifestyle choices and environmental factors. Modifiable factors are behaviors or exposure that can be changed to raise or lower a person's risk of developing cancer. Many studies have demonstrated women who are physically active have a decreased risk of breast cancer than inactive.[8] Alcohol consumption and tobacco use are behaviors also associated with an increased risk of breast cancer.[3] In general, epidemiological research has not found a clear relationship between environmental pollutants and breast cancer. Animal studies have demonstrated prolonged, high-dose exposure to pesticides and organochlorines can increase mammary tumor development; however, it is inconclusive whether low dose exposures occurring in human environments increase breast cancer risk.[9]

1.4. Air Pollution and Breast Cancer

Metals and Industrial Chemicals

Airborne metals including arsenic, beryllium, cadmium, chromium, nickel, and related compounds, have been determined carcinogenic in humans by the International Agency for Research on Cancer.[10] Nickel and cadmium are metalloestrogens that have documented estrogenic properties which are associated with breast cancer risk.[11] The industrial chemical, benzene, is a classified human carcinogen that remains in the environment at lower levels as a combustion product of natural gas and gasoline. In animal studies, rodents who were exposed to benzene orally or by inhalation showed an increase in mammary tumors.[12] Epidemiological studies have produced mixed results when examining the relationship between breast cancer risk and metals. Cohort data from the California Teachers Study indicated an association between HR- breast cancer subtypes and ambient benzene, cadmium, and arsenic.[13] Results from the Sister Study Cohort identified higher breast cancer risk associated with exposure to mercury, cadmium, and lead.[14] Gaudet et. al. did not find an association between adult cadmium and lead levels in their 2019 meta-analysis.[15]

Nitrogen Dioxide (NO2) and Nitrogen Oxides (NOx)

Levels of Nitrogen Dioxide (NO_2) and Nitrogen Oxides (NO_x) are often used as a marker for traffic-related pollution. Associations between NO_2 and breast cancer risk were found in case-control studies across different exposure periods.[16] One study found that women who lived in their homes for 10 years prior to the study had an increased odds of HR+ breast cancer diagnosis. In cohort studies, positives associations between breast cancer incidence and NO_2 and NO_x were found.[17,18] The Sister Study only found the association with HR+ subtypes; there was no evidence for HR- subtypes.[17]

Particulate Matter (PM)

Particulate matter (PM) is the mixture of solid particles and liquid droplets suspended in the air. Inhalable particles (PM_{10}) have a diameter of 10 micrometers and smaller; fine inhalable particles ($PM_{2.5}$) have a diameter of 2.5 micrometers and smaller. PM can enter the lungs or the bloodstream after inhalation.[19] Prior to the widespread use of PM measurement in environmental studies, Total Suspended Particles (TSP) was commonly used. Western New York Exposures and Breast Cancer case-control study found TSP was associated with 2-fold higher odds of breast cancer at birth.[20] Most cohort studies have not observed a significant positive association between PM and breast cancer risk.[17,18,21,22]

Aggregate Air Pollution Measures

The Environmental Protection Agency (EPA) has two combined air pollutant air measures available at the census tract level, air toxics cancer risk and respiratory hazard index.[23] These measures are constructed from National Air Toxics Assessment (NATA) estimates. The air toxics cancer risk measure is formed from estimated carcinogenic air toxin concentration of 187 hazardous air pollutants, not including ozone, fine particulate matter, and sulfur dioxide. Some examples of better-known air pollutants are benzene formaldehyde, perchloroethylene, and methylene chloride. The air toxics cancer risk is expressed as the number of people out of 1 million who would develop cancer from breathing air toxins alone, assuming a person continuously breathes the air toxin emissions in the area each year over a lifetime, approximately 70 years. Other factors, such as genetics and lifestyle factors, are not considered in these estimates. This risk estimate does not include indoor hazards, contacting or ingesting toxins, and any other ways people might be exposed. Further, the risk represents the number of cases in addition to the number of cancer cases that would arise without being exposed to air toxins.

The respiratory hazard index describes the non-cancer health risk across chemicals that affect the same target or organ system.[23] The respiratory hazard index is expressed as a hazard quotient. A hazard quotient of 1 or lower means it is unlikely for noncancer effects. Hazard quotients greater than 1 mean the potential adverse effects increase, but how much is not known. An assumption of the respiratory hazard index is additive

1.6. Redlining and Gentrification

Redlining was coined by sociologist and civil rights leader John McKnight in 1965 during the Chicago Freedom Movement, a housing and racial justice campaign. McKnight used the term to describe the practice of Chicago financial institutions and the Federal Housing Administration classified, or redlined, neighborhoods as unworthy of mortgage loans based on their racial composition. Redlining emerged in the 1930s after the Federal Home Loan Bank Board and the Home Owners' Loan Corporation assigned grades to neighborhoods and created color-coded “residential security maps” for 239 U.S. cities.[24] Neighborhoods received the highest grade of “A” and shaded green on maps, indicating the area had minimal risks for banks and mortgage lenders. Those neighborhoods receiving the lowest grade of “D” and colored red, were deemed hazardous. HOLC assigned grading based on data collected on the neighborhoods’ quality of housing, the recent history of sale and rent values, and the racial and economic composition of the neighborhood’s residents. Redlining barred Black Americans from owning homes in desirable neighborhoods leading to social, economic, and health disparities.

Although redlining institutionalized racial segregation, the location of redlined areas were a result of migration, economic factors, and race relations. During the early 20th century, manufacturing industries grew and the need for industrial workers increased in metropolitan areas throughout the United States.[25] Large numbers of Black Americans moved to metropolitan areas to fill these positions; this event was named The Great Migration. The increase in population, low housing supply, and racism led to Black Americans living in crowded neighborhoods and substandard housing near industrialized city centers.

Other arms of residential segregation took form during the 1950s. Surbanization and White Flight led to the concentration of predominantly Black neighborhoods in urban centers.[26] The

Highway Act of 1956 granted a federal expansion of highways. Highways were built to pass through predominantly Black neighborhoods, thus destroying Black communities. It was not until 1968, when Congress passed the Fair Housing Act, Title VIII of the Civil Rights Act of 1968 that housing discrimination was federally prohibited.

Today, zoning codes are used by municipalities to determine the ways land is used and how residential neighborhoods develop. In 1982, the City of Atlanta updated its zoning ordinance to the zoning codes still used today.[27] The codes established low residential density in wealthy, predominantly White neighborhoods in the periphery of the city; while higher density areas and mixed-use zones were promoted in predominantly non-White neighborhoods or middle- and low-income areas in the center of the city.

Gentrification is the process of changing characteristics within a neighborhood as a result of an influx of wealthier and White residents moving into the area. This is a market-driven process in which developers and middle or high-income individuals obtain property in historically deprived areas because of increasingly high housing costs throughout metropolitan areas and low property values in disadvantaged neighborhoods.[28] Environmental, or green gentrification, occurs when previously polluted or disenfranchised neighborhoods gain green amenities, attracting wealthier residents.[29] Consequences of gentrification include displacement of low-income residents, increasing rent and taxes, changing community leadership, and conflict between old and new neighbors.[30]

There is a growing body of research investigating the effects of historic redlining on modern-day health outcomes. In California, Chicago, and New York City historically redlined areas were associated with an increased risk of pre-term births.[31-33] Other studies found redlining associated with poor self-reported mental, physical health, cancer incidence.[34,35] Krieger et al.

observed an increased risk of late-stage diagnosis of breast and lung cancer in historically redlined areas.[36]

1.7. Study Aims

AIM 1: To estimate the association of historically redlining in Atlanta, GA with contemporary levels of air pollution

Hypothesis: A decrease in desirability in HOLC Grades will increase the contemporary levels of air pollution with HOLC Grade D having the highest levels of air pollution

AIM 2: To investigate the effect of gentrification on the association between historical redlining and air pollution

Hypothesis: Historically redlined neighborhoods that have gentrified will have lower levels of air pollution compared to historically redlined neighborhoods that are susceptible to present-day low income and susceptible gentrification

CHAPTER II: SPATIAL ASSOCIATIONS BETWEEN REDLINING, GENTRIFICATION, AND CANCER RISK FROM AIR TOXICS IN METROPOLITAN ATLANTA, GA

2.1. Abstract

Background: Historic redlining and modern gentrification processes are potential drivers of environmental toxins. Exposure to environmental toxins is a modifiable factor of cancer outcomes. We investigated the associations of historic redlining and gentrification with carcinogenic air toxins. We explored the effect of modification of redlining and carcinogenic air toxins by gentrification stage.

Methods: Our study area included 92 census tracts in Atlanta, GA that overlap the area depicted in 1930's Home Owners' Loan Corporation (HOLC) Grade maps. We assigned HOLC Grade to each census tract using redlining scores and measured carcinogenic air pollution using EPA's air toxics cancer risk estimates. Gentrification was characterized using data from the Urban Displacement Project. Spatial Durbin models were used to estimate the direct effect, spillover effect, and total effect on air toxics cancer risk.

Results: Census tracts historically assigned HOLC Grade A had an estimated 61.48 fewer cancer cases due to air toxin compared to HOLC Grade D census tracts. However, there was not a monotonic relationship across HOLC grades. The indirect effects of HOLC grades were more than 12 times larger than the direct effects, demonstrating a strong spatial spillover effect from neighboring counties. There was no apparent pattern of effect modification of redlining by gentrification on air toxics cancer risks.

Conclusions: Our results support that historically and contemporary advantaged neighborhoods are associated with lower air toxics cancer risk. This study highlights the enduring environmental effects of historic redlining cannot be reversed solely by changes in resident

demographics, but structural interventions are needed to address sources of air toxins for future generations.

2.2. Introduction

Racial and socioeconomic inequalities of harmful environmental toxins in the United States are well documented.[37-39] Although air quality has improved in the United States over the past decades, communities of color, particularly Black and Hispanic populations, are still exposed to higher levels of air pollution.[40] Environmental disparities persist because sociological, economic, and political factors of structural racism typically evolve over time.

Historical redlining as a measure of structural racism has emerged as an area of interest due to its well-documented and widespread implementation.[24] Historic redlining has shaped current geographic distributions of race and capital in cities across the United States, causing many cities to be racially and economically segregated. Studies have shown redlining to be linked with a variety of health outcomes including pre-term births [31-33],asthma[41], cancer[36], poor self-reported mental and physical health.[34]

Redlining patterns of segregation still continue in the 21st century. However, gentrification is changing these long-standing spatial distributions of neighborhood demographics. Gentrification is the process of changing characteristics within a neighborhood as a result of an influx of wealthier and White residents moving into the area. This is a market-driven process in which developers and middle or high-income individuals obtain property in historically deprived areas because of increasingly high housing costs throughout metropolitan areas and low property values in disadvantaged neighborhoods.[28] Gentrification causes the displacement of Black residents and low-income residents, increasing rent and taxes, changing community leadership, and conflict between old and new neighbors.[30]

The environmental injustices as a result of structural racism lead to health inequities, including breast cancer outcomes. Although national rates of breast cancer mortality have declined in the past two decades, Non-Hispanic Black (NHB) women have a lower survival rate than Non-Hispanic White (NHW) women.[4] Exposure to environmental toxins is a modifiable factor to reduce the risk of breast cancer outcomes. Thus, research in this area can inform policy and place-based interventions to reduce breast cancer mortality disparities in a population caused by higher levels of air pollution.

The geography of race and capital in metropolitan Atlanta, GA is shaped by the practices of historical redlining and gentrification. The spatial patterns of socioeconomic status and race give rise to inequities in cancer outcomes. We hypothesize the segregated landscape of American cities leads to disparities in breast cancer mortality driven by environmental factors and social determinants of health. This study aims to examine the association between historic redlining and contemporary distributions of air pollution in Atlanta, GA—an area with robust racial disparities in breast cancer mortality. We will further investigate the changing effects of residential racial segregation on present-day Atlanta neighborhoods, by examining the association between gentrification and air pollution levels. Finally, to understand whether modern changes in historically redlined areas may change the association with the distribution of air pollution we assessed the interaction between redlining and gentrification stages on air pollution levels.

2.3. Methods

Exposure Assessment

Historical Redlining

The Home Owners' Loan Corporation (HOLC) was a U.S. federal agency that assigned neighborhood grades based on mortgage investment risk across metropolitan areas in the U.S. between 1935 and 1940. We used historic redlining scores for 2010 U.S. census tracts that were made publicly by Meier and colleagues.[42] Redlining scores were calculated from the summed proportion of HOLC grades multiplied by a weighting factor based on the area within each census tract. HOLC grades were assigned a numerical value as follows: 1 for "A" grade, 2 for "B" grade, 3 for "C" grade, and 4 for "D" grade. For this analysis, the scores were grouped into four categories: 1 to 2 "A" grade, 2 to 3 "B" grade, 3 to 3.5 "C" grade, and 3.5 to 4 for "D" grade.

Outcome Assessment

Air toxics cancer risk

To quantify the health risk of air toxins in a given census tract, we used data from the EPA National Air Toxic Assessment (NATA). Specifically, NATA's air toxics cancer risk was our outcome of interest. NATA estimates of air toxin concentration and risk are calculated from 2020 one-year emissions data.[23] The air toxics cancer risk estimates the number of people out of 1 million who would develop cancer from breathing air toxins alone, assuming a person continuously breathes the air toxin emissions in the area each year over a lifetime, approximately 70 years. Other factors, such as genetics and lifestyle factors, are not considered in these estimates. This risk estimate does not include indoor hazards, contacting or ingesting toxins, and any other ways people might be exposed. Further, the risk represents the number of cases in addition to the number of cancer cases that would arise without being exposed to air toxins.

Covariates of Interest

Neighborhood Characteristics

Neighborhood characteristics were derived using publicly available data from the American Community Survey (ACS) and calculated at the census tract level using 5-year estimates with data from 2013-2018.[43] To describe the current social, economic, housing characteristics of our study area, we performed descriptive analyses on the following variables: total population, total housing units, proportion of the population identified as Non-Hispanic Black, percent of population identified as Non-Hispanic White, percentage of college-educated population, median household income, median rent, median home value, proportion of renter-occupied housing units.

Gentrification

Census tracts were assigned categories describing their economic status in 2018 as it relates to the process of gentrification; these categories are "Low Income", "Gentrifying", "Mixed to Moderate Income", "Exclusive", and "Student Population. Data and definitions from the Urban Displacement Project (UDP) were used to construct these categories (Table 1).[44] UDP uses data from the 2013-2018 American Community Survey; 1990, 2010, and 2000 Decennial Census; and 2012-2017 Zillow Home Value and Rent Indices. Under the UDP definition, "a tract gentrified from 1990-2000 or 2000-2017 if the following criteria were met:

1. The tract was vulnerable to gentrification in the base year (1990 for gentrification between 1990 and 2000, or 2000 for gentrification between 2000 and 2017). Vulnerability is defined as tracts with:

2. Below regional median housing values or rents
3. Two or more of the following criteria are met:
    a. Above regional median percent of the population that is low-income
    b. Above regional median percent of the population that is non-white
    c. Above regional median percent of the population that rents
    d. Below regional median percent of the population that is college-educated
4. The tract experienced an above regional median change in percent college-educated population
5. The tract experienced an above regional median percent change in median income
6. The tract experienced above regional median percent change in housing values or rents (otherwise known as a "hot market")
7. For non-urban tracts: tract experienced an above regional median loss in low-income households (absolute loss)"

Statistical Analysis

Descriptive analyses were conducted to summarize modern-day characteristics of areas by HOLC grade. We created census tract choropleth maps to assess the qualitative associations between redlining score quartiles and air toxics cancer risks.

The distribution of air toxins has an expected spillover effect geographically by nature. HOLC grades are also expected to affect HOLC grades of neighboring areas. Thus, the variables of interest are suspected to not be independent in space, but spatially dependent. To confirm overall spatial autocorrelation is present in the data, we performed a Global Moran's I test on the residuals of the aspatial models. The neighbors set was defined using used a standardized 4-kilometer fixed distance spatial weight matrix.

The assumptions from an aspatial linear regression model are violated in the presence of spatial autocorrelation, as evidenced by the Global Moran's I. In order to reduce bias, it is necessary to employ a spatial model. We used a spatial econometric model, the Spatial Durbin model, to estimate the direct and indirect, or spillover effect, of HOLC Grade on air toxics cancer risk. HOLC Grade D was used as the referent group. Additionally, we expect potential spillover of both the outcome and exposures, which aligns with the theoretical data generating process for a Spatial Durbin Model. In the Spatial Durbin model, explanatory variables not only have a direct impact on the dependent variables in the same area, but also may have an indirect influence on the dependent variables in neighboring areas.[45] The direct effect is the average change in the dependent variable in the same area, accounting for the feedback effect from all other areas in the sample. The indirect effect measures the spillover effect, which is the average change in a specific census tract's air toxics cancer risk due to change in the HOLC grade of neighboring census tracts. All statistical analyses and maps were produced using R version 4.1.

2.4. Results

Descriptive Results

The study area is contains ninety-two 2010 census tracts in central Atlanta, GA which represents the neighborhoods drawn in historical redlining maps. Table 2 shows the distribution of demographic and economic characteristics from the five-year period from 2014 to 2018. There is not an even distribution of census tracts among the four historical HOLC Grades. HOLC grade A is comprised of the least number of census tracts (n=7) compared to HOLC grades (n=24, n=32, n=29, respectively). We observed a monotonic decrease in the mean percentage of Non-Hispanic White or college-educated residents, median household income, rent, and home values as HOLC grades decreased in desirability. The mean percentage of Non-Hispanic Black residents and renter-occupied housing units decreased monotonically as HOLC grade desirability increased.

Table 3. shows the distribution of gentrification categories within each HOLC Grade. The gentrification category with the largest number of census tracts was Mixed Moderate/High income (n=38) and the gentrification categories with the fewest census tracts were Student Population (n=6) and Exclusive/High-income (n=8). HOLC Grade A had no census tracts categorized as Low-income, Gentrifying, or Student Population. In contrast, HOLC Grade D had no Exclusive census tracts.

The distribution of the number of cancer cases due to air toxins per 1 million, or air toxics cancer risk, across HOLC Grades grouped by gentrification categories is shown in Figure 1. Overall, census tracts in HOLC Grade A have the lowest air toxics cancer risk and census tracts in HOLC Grade D have the highest air toxics cancer risk—with little variation by gentrification.

HOLC Grade B has the most variability of air toxics cancer risk when stratified by gentrification category.

The spatial distribution of redlining scores in the study area is shown in Figure 2. The distribution of redlining grades in Figure 2 has a few areal differences from the original 1938 HOLC security map due to fitting the data on 2010 census tracts. Most census tracts with high redlining scores (3.5 - 4.0), representing areas deemed "hazardous", are located in western and southwestern areas of the map, while census tracts with the lowest redlining scores. categorized as "best", appear most often in the northern part of the study area.

Figure 3. shows the spatial distribution of gentrification categories in the historically redlined area of Atlanta, GA. A majority of census tracts categorized as low income are located in the southwest of the study area. Mixed moderate to high-income census tracts and exclusive census tracts are located in the northeastern areas of the map. Gentrifying census tracts appear in the western part of the study area and surround the downtown area of Atlanta, which is depicted by an empty space in the middle of the map.

Air toxics cancer risks are mapped across the study area in Figure 4. Census tracts with the highest air toxics cancer risk are located on the western edge area of the study area. Areas with the lowest number of cancer cases per 1 million due to air toxicity alone were located along the periphery in the north, east, and south of the study area.

Spatial Analysis Results

The results of the spatial autocorrelation test of the three aspatial linear relationships are shown in Table 4. The residuals from the empty model including only Air toxics cancer risk had a Global Moran's I of 0.52 (p-value =0.001), indicating moderate spatial dependency. When redlining was added to the model, the Global Moran's I decreased to 0.45 (p-value=0.001). Similarly, the Global Moran's I of the residuals from the model with air toxics cancer risk and gentrification was 0.42 (p-value=0.001). The residuals of the model with a redlining and gentrification interaction term produced a Global Moran's I of 0.35 (0.0009), suggesting that the interaction between redlining and gentrification explains more of the variation of air toxics cancer risk than redlining or gentrification alone.

The spatial Durbin modeling results for the relationship between air toxics cancer risk and redlining are shown in Table 5. The results show the risk difference when each HOLC Grade is compared to HOLC Grade D, "Hazardous". HOLC Grade A census tracts were associated with 4.60 fewer cancer cases per million due to air toxicity alone compared to HOLC Grade B census tracts. The indirect effects of HOLC grades were more than 12 times larger than the direct effects, suggesting a strong spatial spillover effect from neighboring counties. Neighboring HOLC Grade A census tracts were associated with 56.87 fewer cancer cases per million due to air toxicity alone compared to neighboring HOLC Grade D census tracts. The total effects between HOLC Grades air toxics cancer risk do not follow redlining patterns; HOLC Grade B was associated with the highest air toxics cancer risk and HOLC Grade C was associated with the lowest air toxics cancer risk.

The direct effects, indirect effects, and total effects of gentrification and air toxics cancer risk are shown in Table 6. Exclusive census tracts have the lowest direct, indirect, and total effects out of all gentrification categories. Again, the indirect effects are larger than the direct effects of gentrification, demonstrating spillover effects. Student Population census tracts have the highest air toxics cancer risk, followed by mixed moderate to high-income census tract and gentrification tracts.

Lastly, the results from the spatial Durbin model of the relationship between air toxics cancer risk and the interaction between redlining and gentrification are shown in Table 7. When compared to census tracts that were historically HOLC Grade D and were Low Income in 2018 (D-Low Income), census tracts that are C-Gentrifying, D-Mixed Moderate to High income, B-Exclusive, and B- Mixed Moderate to High Income have higher air toxics cancer risks. Census tracts that are A-Mixed Moderate to High Income, C-Exclusive, and A-Exclusive have the lowest air toxics cancer risks compared to D-Low Income. There is no apparent pattern between redlining and gentrification interaction groups and air toxics cancer risks.

2.5. Discussion

In this study, we investigated the association of historic redlining and contemporary gentrification with air toxics cancer risk. Our data shows that census tracts historically assigned HOLC Grade A had a lower air toxics cancer risk than census tracts than HOLC Grade D. However, there was not a monotonic relationship when comparing census tracts with HOLC Grades A, B, and C with HOLC Grades D. When comparing contemporary economic characteristics, exclusive census tracts had the lowest air toxics cancer risk compared to all other census tracts. Notably, there were zero historically HOLC Grade D census tracts that were exclusive and zero HOLC Grade A census tracts that were low-income in 2017. We found census tracts with mixed moderate to high income and gentrifying neighborhoods had a higher air toxics cancer risk compared to low-income census tracts. Moreover, our findings suggest there is a stronger spillover effect from characteristics of neighboring census tracts than characteristics within each census tract. Areas with higher economic status, both historically and contemporary (i.e., HOLC Grade A and exclusive census tracts), were associated with lower air toxin levels in neighboring census tracts. Neighboring census tracts of mixed moderate to high-income census tracts were associated with higher levels of air toxins. We did not find evidence of effect modification by contemporary gentrification categories on the association between air toxics cancer risk in historic redlining and in Atlanta, GA.

To our knowledge, this is the first study to investigate the association between gentrification and air toxics cancer risk. In addition, this is the first study to examine the possible effect modification between historic redlining and gentrification. One previous longitudinal study examined the association between gentrification and the location of Toxic Release Inventory (TRI) facilities in Seattle, WA.[46] Results from the study found areas with the lowest socioeconomic strata overlapped with areas with the riskiest TRI facilities and, the effects of urban development skewed the air pollution burden toward the most socially vulnerable residents.

We hypothesized that as neighborhoods gentrify and increase in social advantage, these areas would implement changes associated with reducing air pollution such as planting trees, increasing green space, or adding bike lanes. However, our results suggested gentrifying areas had higher air toxics cancer risks than low-income and exclusive areas. Two systematic reviews on the relationship between gentrification and health outcomes noted the direction of the relationship was not consistent across the body of literature.[47,48]

Other studies have examined air pollution and cancer risk as outcomes of historic redlining. Namin et. al. investigated the relationship between HOLC Grade and airborne carcinogens using 115 redlining maps across the United States. Their results showed a gradient relationship of airborne carcinogens levels decreasing as desirability increased in HOLC Grade.[49] We found similar effects to Namin et. al.'s study when comparing HOLC Grade A census tracts to HOLC Grade D census tracts. However, we did not observe monotonicity. A potential explanation for the difference in our findings would be our spatial model accounts for spatial spillover effects on air toxics cancer risks from neighboring census tracts, whereas Namin et. al.'s study used an aspatial model. Additionally, differences in our results from other studies could be explained by differences in the study area. The trends of urban development and air pollution across the United States may not be reflective of metropolitan Atlanta. By examining the spatial distribution of carcinogenic air toxins, this research contributes to knowledge about potential pathways to racial disparities in breast cancer mortality caused by historic redlining.

Unequal distributions of air toxins may contribute to racial disparities in cancer outcomes. Discriminatory and unequal access to loans has made it difficult for Black people to move into wealthier, often predominantly White, neighborhoods. In our data, four low-income census tracts were historically HOLC Grade B. The process of gentrification leads to low-income populations being displaced outside of city centers, leading to the suburbanization of low-income communities.

Limitations

There are several limitations to this study. First, this is a cross-sectional, ecological study – thus we cannot infer causality from these results. This study is limited by the census-track level so, we could not account for individual-level factors that contribute to cancer risk. Our study area focused on the area of metropolitan Atlanta that had records of historical redlining which limits the generalizability of our results. Additionally, we were underpowered to detect statistical differences due to the sample size of our study area.

In addition to limitations in study design, our data violates an assumption of casual inference, positivity, when evaluating the effect modification between HOLC grades and gentrification categories. There were no historically HOLC grade A neighborhoods that were present-day low income and no HOLC grade D neighborhoods that were categorized as exclusive. Due to the lasting economic impacts of structural racism, there was a zero probability that every HOLC grade would have neighborhoods in each gentrification category.

We are also limited in our measure of gentrification. Gentrification is a dynamic time-dependent process; thus, our measure of gentrification only describes gentrification in 2017. Our gentrification measure does not capture cultural displacement or infrastructure changes that may induce gentrification, such as the Atlanta Beltline, leading to an underestimation of gentrification.[44]

The limitations of the EPA's NATA dataset should be noted. NATA air toxics cancer risks were estimated using EPA risk assessment models. EPA risk assessment models are not based on human cancer data. Cancer risks were modeled using outdoor air pollution levels of only 180 pollutants with known carcinogenic properties, which does not allow for comprehensive estimates of cancer risk from all potential air toxins. Further, cancer risks were determined for inhalation of air toxins and did not consider other routes of entry into the body.

Conclusions

There is a growing body of research identifying an association between the risk of environmental toxin exposure and cancer risk with patterns of historic redlining. This study investigates how social and economic changes to these historically segregated areas may modify the effect on air toxics cancer risk. Our results support that historically and contemporarily advantaged neighborhoods are associated with lower air toxics cancer risk. Our research does not provide evidence for a consistent pattern of effect modification between historic redlining and air toxics cancer risk. This study highlights the enduring environmental effects of historic redlining cannot be reversed solely by changes in resident demographics or socioeconomic status. Further research on the origins of air toxins is needed to identify interventions to reduce or eliminate air toxin sources.

2.6. References

1. Centers for Disease Control and Prevention. Breast Cancer Statistics. 2021; https://www.cdc.gov/cancer/breast/statistics/index.htm, 2021.
2. National Institutes of Health; National Cancer Institute S, Epidemiology, and End Results Program,. Cancer stat facts: female breast cancer. https://seer.cancer.gov/statfacts/html/breast.html., 2021.
3. American Cancer Society. *Cancer Facts & Figures 2021.* Atlanta: American Cancer Society;2021.
4. U.S. Cancer Statistics Working Group. U.S. Cancer Statistics Data Visualizations Tool, based on 2020 submission data (1999-2018). 2021; www.cdc.gov/cancer/dataviz.
5. Sparano JA, Brawley OW. Deconstructing Racial and Ethnic Disparities in Breast Cancer. *JAMA Oncology.* 2021;7(3):355-356.
6. Yedjou CG, Sims JN, Miele L, et al. Health and Racial Disparity in Breast Cancer. In: Springer International Publishing; 2019:31-49.
7. Kuchenbaecker KB, Hopper JL, Barnes DR, et al. Risks of Breast, Ovarian, and Contralateral Breast Cancer for BRCA1 and BRCA2 Mutation Carriers. *JAMA.* 2017;317(23):2402.
8. Wu Y, Zhang D, Kang S. Physical activity and risk of breast cancer: a meta-analysis of prospective studies. *Breast Cancer Research and Treatment.* 2013;137(3):869-882.
9. Yang KJ, Lee J, Park HL. Organophosphate Pesticide Exposure and Breast Cancer Risk: A Rapid Review of Human, Animal, and Cell-Based Studies. *International journal of environmental research and public health.* 2020;17(14):5030.
10. The International Agency for Research on Cancer. *Air pollution and cancer.* 2013.
11. Aquino NB, Sevigny MB, Sabangan J, Louie MC. The Role of Cadmium and Nickel in Estrogen Receptor Signaling and Breast Cancer: Metalloestrogens or Not? *Journal of Environmental Science and Health, Part C.* 2012;30(3):189-224.
12. Hiatt RA, Brody JG. Environmental Determinants of Breast Cancer. *Annual Review of Public Health.* 2018;39(1):113-133.
13. Garcia E, Hurley S, Nelson DO, Hertz A, Reynolds P. Hazardous air pollutants and breast cancer risk in California teachers: a cohort study. *Environmental Health.* 2015;14(1):14.
14. White AJ, O'Brien KM, Niehoff NM, Carroll R, Sandler DP. Metallic Air Pollutants and Breast Cancer Risk in a Nationwide Cohort Study. *Epidemiology.* 2019;30(1):20-28.
15. Gaudet MM, Deubler EL, Kelly RS, et al. Blood levels of cadmium and lead in relation to breast cancer risk in three prospective cohorts. *International Journal of Cancer.* 2019;144(5):1010-1016.
16. Crouse DL, Goldberg MS, Ross NA, Chen H, Labrèche F. Postmenopausal breast cancer is associated with exposure to traffic-related air pollution in Montreal, Canada: a case-control study. *Environ Health Perspect.* 2010;118(11):1578-1583.
17. Reding KW, Young MT, Szpiro AA, et al. Breast Cancer Risk in Relation to Ambient Air Pollution Exposure at Residences in the Sister Study Cohort. *Cancer Epidemiology Biomarkers & Prevention.* 2015;24(12):1907-1909.
18. Andersen ZJ, Stafoggia M, Weinmayr G, et al. Long-Term Exposure to Ambient Air Pollution and Incidence of Postmenopausal Breast Cancer in 15 European Cohorts within the ESCAPE Project. *Environmental Health Perspectives.* 2017;125(10):107005.

19. United States Environmental Protection Agency. Particulate Matter (PM) Basics. 2021; https://www.epa.gov/pm-pollution/particulate-matter-pm-basics.
20. Bonner MR, Han D, Nie J, et al. Breast cancer risk and exposure in early life to polycyclic aromatic hydrocarbons using total suspended particulates as a proxy measure. *Cancer Epidemiol Biomarkers Prev.* 2005;14(1):53-60.
21. Andersen ZJ, Ravnskjær L, Andersen KK, et al. Long-term Exposure to Fine Particulate Matter and Breast Cancer Incidence in the Danish Nurse Cohort Study. *Cancer Epidemiol Biomarkers Prev.* 2017;26(3):428-430.
22. Hart JE, Bertrand KA, Dupre N, et al. Long-term Particulate Matter Exposures during Adulthood and Risk of Breast Cancer Incidence in the Nurses' Health Study II Prospective Cohort. *Cancer Epidemiology Biomarkers & Prevention.* 2016;25(8):1274-1276.
23. U.S. Environmental Protection Agency. U.S. EPA. National Air Toxics Assessment -- NATA Overview. . 2021; https://www.epa.gov/national-air-toxics-assessment/nata-overview. Accessed January 17, 2022.
24. Robert K. Nelson LW, Richard Marciano, Nathan Connolly, et al. Mapping Inequality. https://dsl.richmond.edu/panorama/redlining/Introduction.
25. Boustan LP. *Competition in the Promised Land: Black Migrants in Northern Cities and Labor Markets.* Princeton University Press; 2017.
26. Boustan LP. Was Postwar Suburbanization “White Flight”? Evidence from the Black Migration*. *Quarterly Journal of Economics.* 2010;125(1):417-443.
27. Plannnig DoC. Atlanta City Design Housing. 2021; https://storymaps.arcgis.com/stories/e91c43ad299a4634add2bed4cf2eca9d.
28. Zukin S. Gentrification: Culture and Capital in the Urban Core. *Annual Review of Sociology.* 1987;13(1):129-147.
29. Cole HVS, Garcia Lamarca M, Connolly JJT, Anguelovski I. Are green cities healthy and equitable? Unpacking the relationship between health, green space and gentrification. *Journal of Epidemiology and Community Health.* 2017:jech-2017-20920.
30. Wilder V, Mirto A-L, Makoba E, Arniella G. The health impact of gentrification. *J Gen Emerg Med.* 2017;4:1981-1991.
31. Nardone AL, Casey JA, Rudolph KE, 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):e0237241.
32. Matoba N, Suprenant S, Rankin K, Yu H, Collins JW. Mortgage discrimination and preterm birth among African American women: An exploratory study. *Health & Place.* 2019;59:102193.
33. Krieger N, Wye GV, Huynh M, et al. Structural Racism, Historical Redlining, and Risk of Preterm Birth in New York City, 2013–2017. *American Journal of Public Health.* 2020;110(7):1046-1053.
34. Nardone A, Chiang J, Corburn J. Historic Redlining and Urban Health Today in U.S. Cities. *ENVIRONMENTAL JUSTICE.* 2020;13(4).
35. Lynch EE, Malcoe LH, Laurent SE, Richardson J, Mitchell BC, Meier HCS. The legacy of structural racism: Associations between historic redlining, current mortgage lending, and health. *SSM - Population Health.* 2021;14:100793.
36. Krieger N, Wright E, Chen JT, Waterman PD, Huntley ER, Arcaya M. Cancer Stage at Diagnosis, Historical Redlining, and Current Neighborhood Characteristics: Breast,

Cervical, Lung, and Colorectal Cancers, Massachusetts, 2001–2015. *American Journal of Epidemiology.* 2020;189(10):1065-1075.
37. Muller C, Sampson RJ, Winter AS. Environmental inequality: The social causes and consequences of lead exposure. *Annual Review of Sociology.* 2018;44:263-282.
38. Liu J, Clark LP, Bechle MJ, et al. Disparities in Air Pollution Exposure in the United States by Race/Ethnicity and Income, 1990–2010. *Environmental Health Perspectives.* 2021;129(12):127005.
39. Clark LP, Millet DB, Marshall JD. National patterns in environmental injustice and inequality: outdoor NO2 air pollution in the United States. *PloS one.* 2014;9(4):e94431.
40. 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. *Environmental Health Perspectives.* 2017;125(9):097003.
41. Nardone A, Casey JA, Morello-Frosch R, Mujahid M, Balmes JR, 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. *The Lancet Planetary Health.* 2020;4(1):e24-e31.
42. Meier HCS, and Mitchell, Bruce C.,. Historic Redlining Scores for 2010 and 2020 US Census Tracts. In. Ann Arbor, MI: Inter-university Consortium for Political and Social Research; 2021.
43. U.S. Census Bureau. 2012-2016 American Community Survey 5-year Estimate Public Use Data. In:2017.
44. Tim Thomas ea. *The Urban Displacement Replication Project.* 2020.
45. LeSage J, Pace RK. *Introduction to spatial econometrics.* Chapman and Hall/CRC; 2009.
46. Abel TD, White J. Skewed riskscapes and gentrified inequities: environmental exposure disparities in Seattle, Washington. *American journal of public health.* 2011;101(S1):S246-S254.
47. Schnake-Mahl AS, Jahn JL, Subramanian S, Waters MC, Arcaya M. Gentrification, neighborhood change, and population health: a systematic review. *Journal of urban health.* 2020;97(1):1-25.
48. Smith GS, Breakstone H, Dean LT, Thorpe RJ. Impacts of Gentrification on Health in the US: a Systematic Review of the Literature. *Journal of Urban Health.* 2020;97(6):845-856.
49. 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. *Social Science & Medicine.* 2020;246:112758.

2.7 Tables

Table 1. Description and Criteria of Gentrification Categories

Gentrification Category	Criteria
Low Income Census tracts in this category exhibit characteristics of stability and affordability to low-income households but could become at risk of gentrification in the future. Low-income tracts have a median household income less than 80% of regional median income.	• Low or mixed low-income in 2018 • Absolute loss of low-income households 2000-2018 • Housing affordable to low- or mixed-income households 2018 • Didn't gentrify 1990-2000 OR 2000-2018 • Marginal change in housing costs OR Zillow home or rental value increases in the 90th percentile between 2012-2018 • Local and nearby increases in rent were greater than the regional median between 2012-2018 OR the 2018 rent gap is greater than the regional median rent gap
Gentrifying This category includes census tracts that are at risk of gentrification, undergoing gentrification, and are in advanced stages of gentrification. Gentrified neighborhoods demonstrate recent housing market change housing stock, and proximity to gentrifying areas.	• Housing affordable to moderate or mixed moderate-income households in 2017 • Increase or rapid increase in housing costs OR above regional median change in Zillow home or rental values between 2012-2017 • Gentrified in 1990-2000 or 2000-2017

Mixed to Moderate Income Census tracts in this category are affordable to moderate-income, mixed moderate-income, and high-income households. Neighborhoods may at risk or in the process of excluding lower-income households. Moderate-income tracts have a median household income between 80-120% of regional median income.	• Moderate, mixed-moderate, mixed-high, high-income tract in 2018 • Housing affordable to middle, high, mixed-moderate, and mixed-high income households in 2018 • Marginal change, increase, or rapid increase in housing costs • Absolute loss of low-income households 2000-2018 • Declining low income in-migration rate 2012-2018 • Median income higher in 2018 than in 2000
Exclusive Exclusive describes census tracts that gave exhibited characteristics of enduring patters of exclusion beyond recent market and demographic changes. Census tracts in this category are unable to be gentrified. High-income tracts have a median household income greater than 120% of regional median income.	• High-income tract in 2000 and 2017 • Affordable to high income households in 2017 • Marginal change, increase, or rapid increase in housing costs
Student Population This category includes census tracts that have college campuses or have a large proportion of students due to their close proximity to college campuses. Neighborhoods with college student populations are more transient and therefore may have different factors influencing their housing market.	• Predominantly student populations due to proximity to college campuses

Table 2. Descriptive Characteristics, 5-year American Community Survey 2014 - 2018

	Grade A "Best"	Grade B "Still Desirable"	Grade C "Definitely Declining"	Grade D "Hazardous"	Total
Total tract count	7	24	32	29	92
Total square miles					
Mean % Non-Hispanic, Black	0.05	0.25	0.36	0.62	0.36
Mean % Non-Hispanic, White	0.85	0.64	0.49	0.26	0.51
Mean % College Educated	0.6	0.5	0.39	0.23	0.41
Median Household Income ($)	181,250	124,821	105,476	77,292	103,929
Median Rent ($)	1,662	1,191	1,034	944	1,070
Median Home Value ($)	730,000	433,850	299,650	149,150	296,000
Mean % Renter-occupied housing units	0.36	0.46	0.52	0.7	0.52

Table 3. Number of census tracts by HOLC Grade and Gentrification

	Grade A	Grade B	Grade C	Grade D	Total
Low-income	0	4	9	10	23
Gentrifying	0	2	5	10	17
Mixed Moderate/High income	3	15	15	5	38
Exclusive/High income	4	3	1	0	8
Student Population	0	0	2	4	6

Table 4. Global Moran's I of residuals for aspatial models

Models	Moran's I	P-value
Air toxics cancer risk	0.52	0.001
Air toxics cancer risk with Redlining	0.45	0.001
Air toxics cancer risk with Gentrification	0.42	0.001
Air toxics cancer risk with Redlining and Gentrification Interaction	0.35	0.0009

Table 5. Redlining Impact Assessment on Air toxics cancer risk, Atlanta, GA

	Direct Effect		Indirect Effect		Total Effect	
	RD	**p-value**	**RD**	**p-value**	**RD**	**p-value**
HOLC Grade A	-4.60	0.22	-56.87	0.79	-61.48	0.78
HOLC Grade B	-0.45	0.96	9.12	0.83	8.96	0.83
HOLC Grade C	-2.53	0.52	-67.66	0.79	-70.19	0.79
HOLC Grade D	Referent		Referent		Referent	

Table 6. Gentrification Impact Assessment on Air toxics cancer risk, Atlanta, GA

	Direct Effect		Indirect Effect		Total Effect	
	RD	**p-value**	**RD**	**p-value**	**RD**	**p-value**
Exclusive	-1.06	0.41	-18.97	0.77	-20.02	0.76
Mixed Moderate to High Income	0.78	0.29	12.59	0.49	13.36	0.48
Gentrifying	0.22	0.83	7.29	0.88	7.511	0.88
Low-income	Referent		Referent		Referent	
Student Population	3.02	0.11	72.61	0.51	75.63	0.50

Table 7. Redlining and Gentrification Interaction Impact Assessment on Air toxics cancer risk, Atlanta, GA

	Direct Effect		Indirect Effect		Total Effect	
	RD	**p-value**	**RD**	**p-value**	**RD**	**p-value**
HOLC Grade A						
Exclusive	-3.28	0.16	5.22	0.92	-8.51	0.91
Mixed Moderate to High Income	-4.26	0.09	-11.96	0.89	-16.22	0.86
Gentrifying	NA	NA	NA	NA	NA	NA
Low Income	NA	NA	NA	NA	NA	NA
Student Population	NA	NA	NA	NA	NA	NA
HOLC Grade B						
Exclusive	0.66	0.71	19.12	0.82	19.78	0.82
Mixed Moderate to High Income	-0.28	0.86	15.42	0.67	15.15	0.68
Gentrifying	0.22	0.99	-28.00	0.84	-27.79	0.84
Low Income	-0.10	0.97	-3.71	0.97	-3.81	0.97
Student Population	NA	NA	NA	NA	NA	NA
HOLC Grade C						
Exclusive	-3.83	0.36	-14.24	0.90	-18.08	0.89
Mixed Moderate to High Income	-1.34	0.33	-24.44	0.71	-25.78	0.71
Gentrifying	2.6	0.51	43.86	0.85	46.47	0.85
Low Income	-0.26	0.85	-13.67	0.79	-13.94	0.79
Student Population	0.57	0.87	98.71	0.68	1.19	0.99
HOLC Grade D						
Exclusive	NA	NA	NA	NA	NA	NA
Mixed Moderate to High Income	3.43	0.09	32.3	0.76	35.74	0.75
Gentrifying	-1.29	0.47	-27.31	0.78	-28.63	0.77
Low Income	Referent		Referent		Referent	
Student Population	4.59	0.23	8.71	0.68	103.3	0.67

NA = no census tracts in redlining-gentrification group

2.8 Figures

Figure 1. Distribution of Air toxics cancer risk across HOLC Grades Stratified by Gentrification Categories

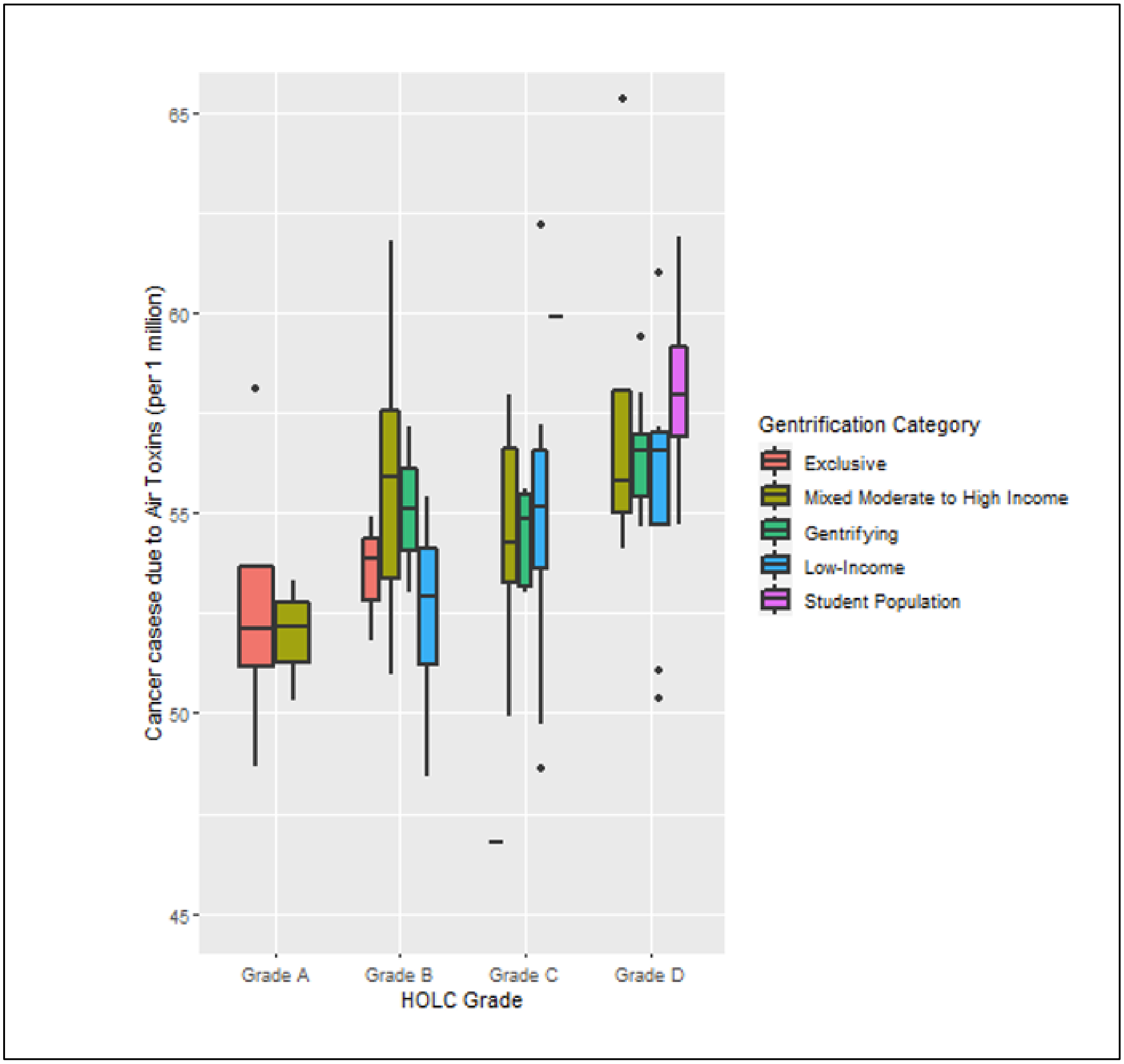


Figure 2. Redlining HOLC Grades Map

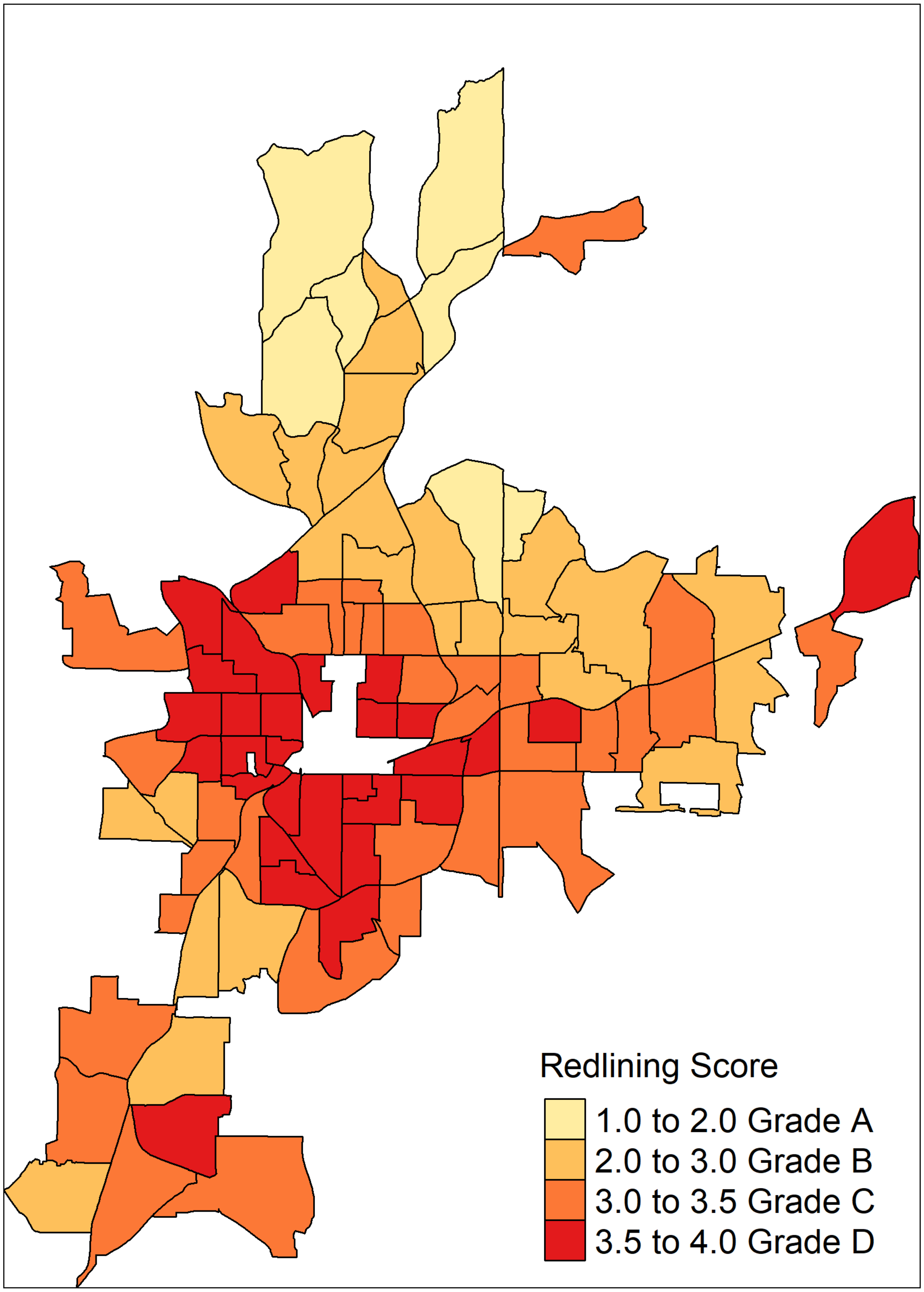


Figure 3. Gentrification Categories, 2018, adapted from Urban Displacement Project

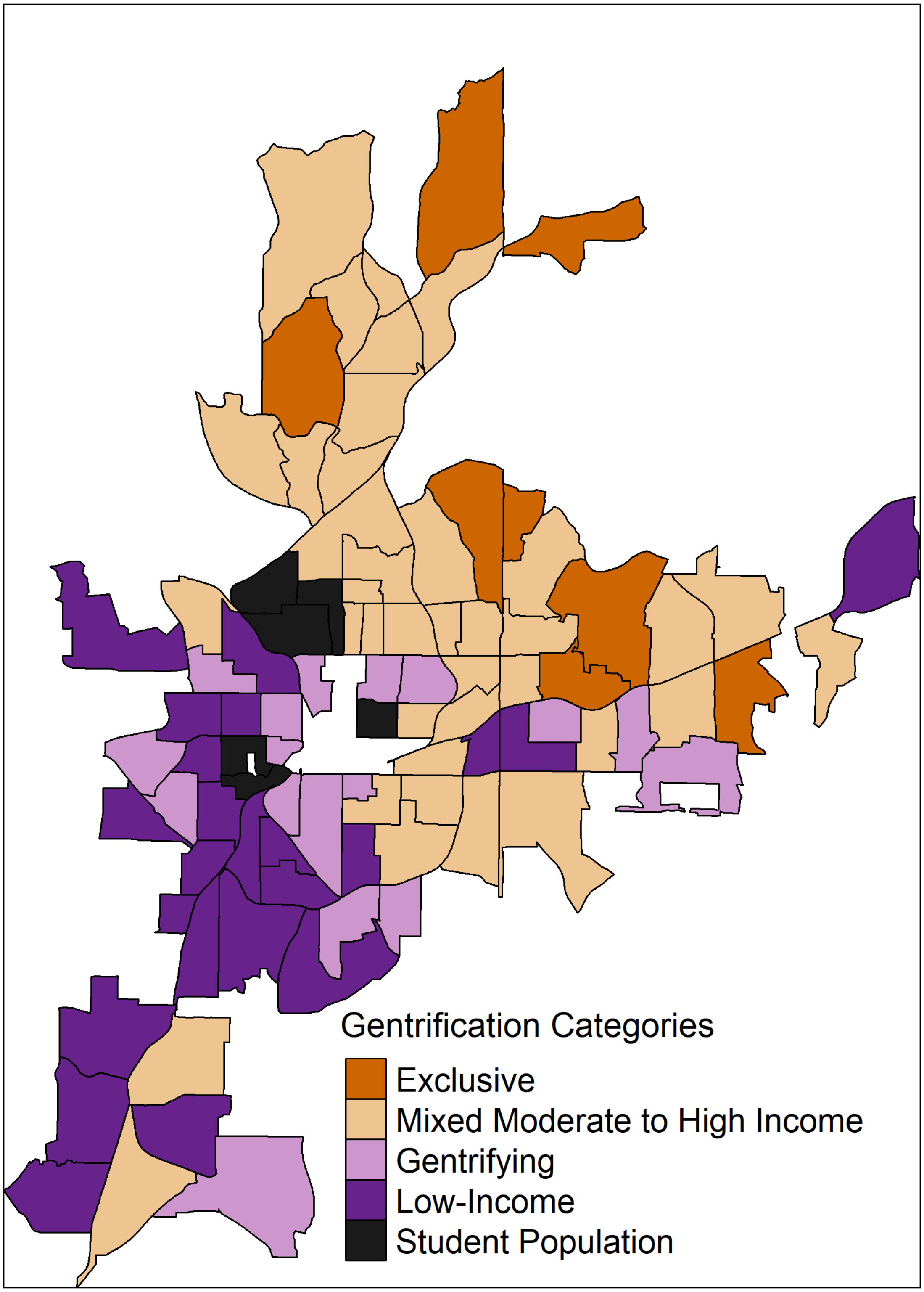
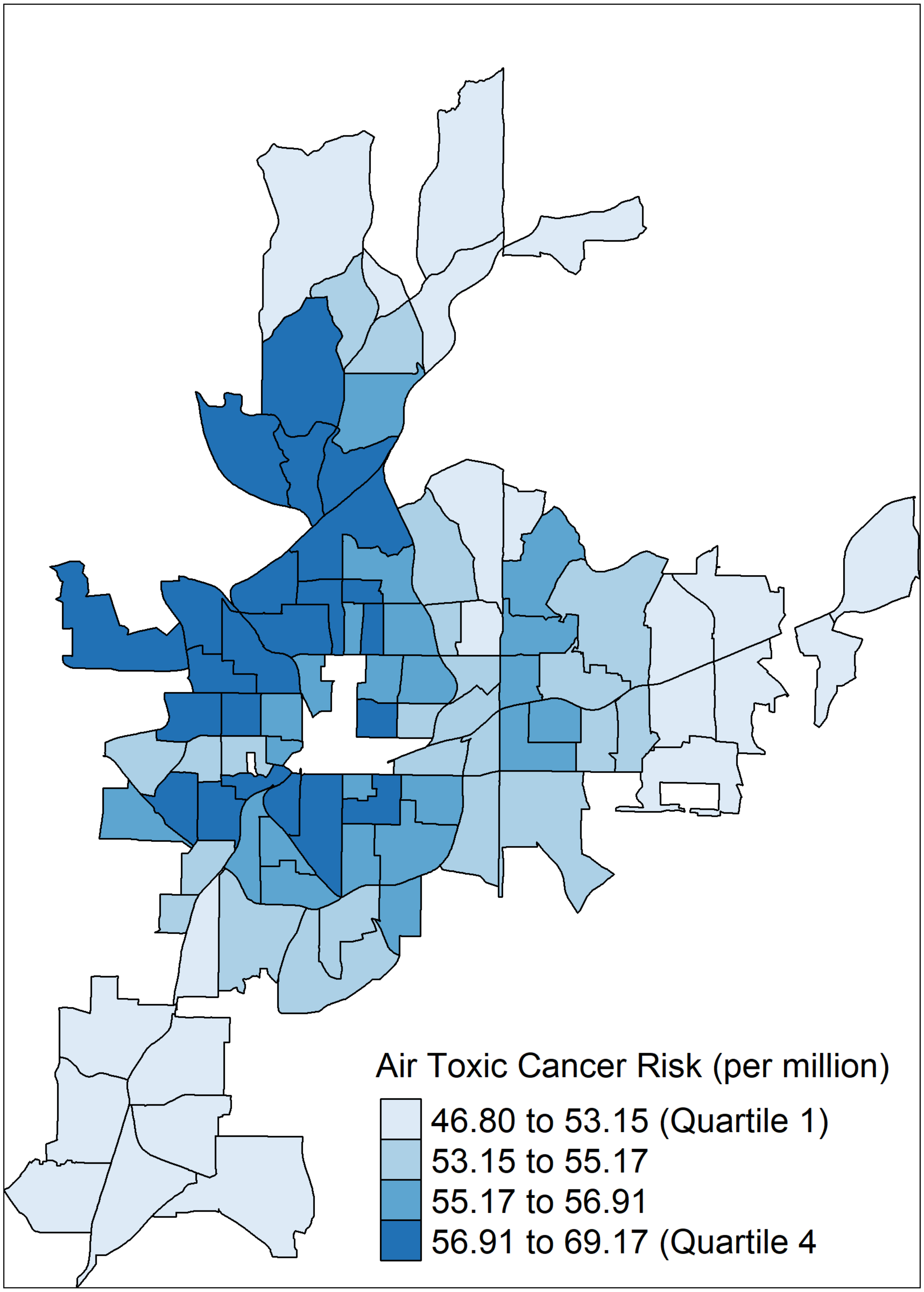


Figure 4. EPA NATA 2020 Air toxics cancer risks Map



Chapter III. Summary, Future Research Directions, Public Health Implications

Summary

This thesis was motivated by a prevailing racial disparity in breast cancer outcomes - the five-year relative survival is lower for Black populations than White populations for most cancers at each stage of diagnosis. Specifically in Atlanta, non-Hispanic Black women at breast cancer diagnosis were younger, with higher stage, and more triple-negative tumors relative to non-Hispanic women. The goal of this study was to examine institutional factors of racism, historical redlining and gentrification, and their relationship with the geographic distribution of air toxics cancer risk that may contribute to the racial disparity in breast cancer outcomes.

Environmental characteristics, such as air pollution levels, are modifiable risk factors for breast cancer outcomes. Often, low-income neighborhoods and communities of color, especially Black communities, have a higher risk of exposure to environmental toxin compared to higher-income or predominantly White communities. In this thesis, there was evidence of differential air toxics cancer risk by historical redlining and modern neighborhoods' socioeconomic status. Neighborhoods with the highest economic status, both historically and present-day, have lower air toxic cancer risk compared to areas with the lowest economic status. While we did not observe an interaction effect between redlining and gentrification, it is important to note that the percentage of exclusive census tracts in each HOLC Grade decreased as desirability decreased, suggesting a relationship between historic redlining and present-day economic neighborhood characteristics.

Future Research Directions

To our knowledge, this is the first study to explicitly connect historic redlining and gentrification processes and their effects on air pollution in Atlanta, GA. It would be important to examine whether the patterns we identified in Atlanta are similar to other cities in the United States, especially cities in different stages of gentrification. To describe the causal relationship between air pollution and racial disparities in breast cancer mortality, studies should identify levels of specific air toxins that are biologically linked to breast cancer. Lastly, research on sources of carcinogenic air toxins is needed to eliminate or reduce air pollution levels. Census tracts with the highest air toxics cancer risk overlapped a railyard in our study area. Future research could estimate the amount of air toxins emitted from industrial sites, like railyards, to guide policy on acceptable emission levels.

Public Health Implications

This study highlights how place-based inequities contribute to racial disparities in health. Neighborhood characteristics influence social and economic factors and environmental exposures as demonstrated in this thesis. Results from this study emphasize environmental policies should be developed targeting areas with historical underinvestment.

Our research question acknowledges the current social issues of gentrification in the context of the history of racially discriminatory policies in Atlanta. Gentrification often occurs in historically redlined neighborhoods due to their attractive location centrally in urban areas coupled with historical underinvestment and low rent prices. Developers, investors, and young career professionals capitalize on gaps in the potential value of properties and the current prices of housing. One method to reduce the burden of gentrification in Atlanta is to expand multi-unit zoning to increase housing supply in areas outside redlined areas with lower air toxics cancer risk. Additionally, officials should evaluate the environmental safety of affordable housing sites to ensure people living in affordable housing are not at risk for higher levels of exposure to environmental toxins.

In conclusion, this study found differences in air toxics cancer risk levels between historic redlining grades and gentrification stages. These results support the need for future research on specific sources of high air pollution levels will inform interventions to reduce air pollution levels. Lastly, the insights gained from this study demonstrate the need to integrate environmental health equity as a goal in urban development when addressing the issue of affordable housing.

CHAPTER IV APPENDICES

Appendix A. Literature Review Chart

Title	Author	Year	Population				Specific Research Questions	Variable Assessment						
			N	Race/Ethnicity	Years	Geographic area		Breast Cancer (BC) or Neighborhood Characteristic (NC)?	BC or NC Variable	What Approach Did They Use?	Air Pollution Measure	Air Pollution Database	Specific Pollutants	Other important variables
Cancer risk from air toxics in relation to neighborhood isolation and sociodemographic characteristics: A spatial analysis of the St. Louis metropolitan area, USA	Ekenga, Yeung, Oka	2019	615 census tracts	Non-White, Hispanic, African American	2011 NATA estimates, 2010-2014 ACS	census tracts	Is neighborhood isolation and sociodemographic characteristics associated with exposure to carcinogenic air toxics?	NC	Neighborhood Isolation	Isolation measures may be interpreted as the probability of a particular population group member meeting another member of the same group within a neighborhood (i.e., census tract). Therefore, the higher the probability, the greater the proportion of that neighborhood's (or census tracts) population who are members of the same group	census tract estimates of lifetime air toxics cancer risk (NATA)	National Air Toxic Assessment (NATA)	NA	% Population non-white, % population African American, % population Hispanic, % population without a high school education, per capita income, median household income, % population poverty, % population unemployed
Environmental Determinants of Breast Cancer	Hiatt, Green Brody	2018	NA	NA	NA	NA	Literature review assessing known and suspected environmental factors that have been associated with breast cancer	BC	NA	Review	NA	NA	NA	NA
Air pollution and Breast Cancer: A Review	White, Bradshaw, Hamra	2018	NA	NA	NA	NA	Literature review examining the epidemiologic evidence regarding the association between air pollution measures and incident breast cancer	BC	NA	Review	NA	NA	NA	NA
Cancer Stage at Diagnosis, Historical Redlining, and Current Neighborhood Characteristics: Breast, Cervical, Lung, and Colorectal Cancers, Massachusetts, 2001–2015	Krieger et al	2020	20808		2001-2015	census tracts	Is historic redlining associated with risk of late-stage diagnosis for breast cancer and lung cancer?	No Air Pollution	HOLC Grade	assigned census tract based on the percentage of the Census Tracts' land area included in any 1937–1938 HOLC area	NA	NA	NA	% population below US poverty line, measures of social spatial polarization, computed using the Index of Concentration at the Extremes (ICE)
Breast Cancer Risk in Relation to Ambient Air Pollution Exposure at Residences in the Sister Study Cohort	Reding et al	2015	47591	NA	2003-2013	Residential address	Is there a relationship between air pollution, namely PM2.5, PM10, and NO2, and risk differences by breast cancer subtype? What is the dose response relationship between long-term exposure and BC incidence?	BC	incidence of breast cancer, breast cancer subtype	cohort study, stratifying by ER/PR and stage	Annual averages of air pollution concentration at home address	not specified	PM2.5, PM10, NO2	Race, educational attainment, smoking status, menopausal hormone therapy, stage, estrogen/progesterone receptor
Metallic Air Pollutants and Breast Cancer Risk in a Nationwide Cohort Study	White et al	2019	50884	NA	2003-2009	census tracts	What is the association between breast cancer risk and airborne exposure to metals, including antimony, arsenic, cadmium, chromium, cobalt, lead, manganese, mercury, nickel, and selenium, considering the metals individually and as a mixture?	BC	BC Incidence	cohort study, medical records and pathology reports	census-tract level concentrations	NATA	antimony, arsenic, cadmium, chromium, cobalt, lead, manganese, mercury, nickel, and selenium,	race, education, annual household income, marital status, parity, census-track level median income, and geographic region
Breast Cancer Risk in Association with Atmospheric Pollution Exposure: A Meta-Analysis of Effect Estimates Followed by a Health Impact Assessment	Gabet et al	2021	NA	NA	1980 -2009	NA	What is the relationship between ambient PM2:5, PM10, and NO2 long-term exposure and breast cancer onset, considering menopausal and hormone responsiveness tumor status?	BC	Breast Cancer incidence	Meta-Analysis and Literature Review	Meta-Analysis and Literature Review	NA	PM2.5, PM10, and NO2	Meta-Analysis and Literature Review
Title	Author	Year	Population				Specific Research Questions	Variable Assessment						

			N	Race/Ethnicity	Years	Geographic area		Breast Cancer (BC) or Neighborhood Characteristic (NC)?	BC or NC Variable	What Approach Did They Use?	Air Pollution Measure	Air Pollution Database	Specific Pollutants	Other important variables
Air pollution and breast cancer risk in the Black Women's Health Study	White et al	2020	41317	Black	1999-2008	individual residential address	What is the relationship between exposure to selected air pollutants and breast cancer risk in a nationwide cohort of U.S. Black women? Is there geographic heterogeneity?	BC	BC diagnosis	Cohort study, Self-report and medical record or pathology record	estimate annual average concentration	Community Model for Air Quality (CMAQ)	PM2.5, NO2, O3	covariate : menopausal status, tumor subtype, invasive or DCIS control: education, smoking status , parity, body mass index , hormone therapy use, geographic region , baseline menopausal status and an interaction term between BMI and menopausal status.
Disparities in Distribution of Particulate Matter Emission Sources by Race and Poverty Status	Mikati et al	2018	All U.S. census blocks	NHW, non-NHW (Black, Hispanic)	2009-2013	census block	Is there a disparity in the characteristics of surrounding residential populations distribution of PM-emitting facilities?	NC	poverty status	annual NEI totals, primary PM2.5, primary PM10	We assigned each facility and its corresponding emissions (in tons per year) census block groups containing a centroid	US EPA National Emissions Inventory (NEI)	PM2.5, PM10	rural–urban commuting area (RUCA) codes,
Separate and Unequal: Residential Segregation and Estimated Cancer Risks Associated with Ambient Air Toxics in U.S. Metropolitan Areas	Morello-Frosch & Jesdale	2006	45,710 tracts (309 metropolitan areas in the continental United States)	NHW, NHB, Hispanics, AI/AN, API	1996 NATA, 2000 census	census tracts	Are racial and economic disparities in estimated cancer risk associated with air toxics are modified by levels of residential segregation in U.S. metropolitan areas?	NC	Residential Segregation	multigroup dissimilarity index (Dm): L12	census tract estimates of lifetime air toxics cancer risk (NATA)	NATA	none	Regional grouping of states, population density, poverty level, Townsend index (proportion of home owner, car owner, living in crowded conditions, unemployed), voter turnout,
Residential Proximity to Industrial Sources of Air Pollution: Interrelationships among Race, Poverty, and Age	Perlin, Wong, & Sexton	2011	3 study areas (Kanawha Valley, Baton Rouge-New Orleans, Baltimore Greater Metro Area)	Black, White	1990	census block group	What is the association of race, poverty status, and age of populations living near industrial sources?	NC	% Age group, % Race, % below poverty	% of race in census block, % of racial age grouping (e.g. Black 0-5 age vs White 0-5), % below poverty of each racial group	proximity to industrial TRI facilities	EPA Toxics Release Inventory (TRI).	NA	% of race, age, age od race, percent below poverty
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	Nardone et al	2020	3696 census tracts	NA	2011-2012	census tracts	What is the association between residential redlining and present-day asthma-related emergency department visits in California?	NC	HOLC Grade	HOLC risk grade of each census	Asthma emergency department visit rate	CalEnviroScreen 3.0	PM2.5, Diesel exhaust particle	3-year average PM2·5 in µg/m3 from 2012–14, and the estimated diesel exhaust particle (DEP) emissions (kg) for a summer day in 2012.21
The legacy of the Home Owners' Loan Corporation and the political ecology of urban trees and air pollution in the United States	Namin et al	2020	115 cities	NA	2001 and 2011	census tracts	Is there a gradient in current levels of exposure to airborne carcinogens and respiratory hazards reflecting the HOLC grade hierarchy?	NC	HOLC Grade	HOLC risk grade of each census	Tree canopy, average respiratory Hazard Index, cancer risk	National Land Cover Database, NATA	NA	population density
Residential Segregation and Racial/Ethnic Disparities in Ambient Air Pollution	Woo et al	2019	3520 respondents	Black, Latino, Asian, White	1990-2011	census block	How do race/ethnicity and racial residential segregation intersect to influence exposure to ambient pollution?	NC	Residential Segregation	index of dissimilarity, a measure of the relative separation of a racial/ethnic minority group from Whites across all census tracts	annual average at census block	EPA Air Quality System	PM2.5, PM10, NO2	(EPA) Air Quality System (AQS)

Title	Author	Year	Population				Specific Research Questions	Variable Assessment						
			N	Race/Ethnicity	Years	Geographic area		Breast Cancer (BC) or Neighborhood Characteristic (NC)?	BC or NC Variable	What Approach Did They Use?	Air Pollution Measure	Air Pollution Database	Specific Pollutants	Other important variables
Assessment of neighborhood-level socioeconomic status as a modifier of air pollution–asthma associations among children in Atlanta	O'Lenick et al	2017	pediatric population; 20-county metropolitan area of Atlanta	NA	2002-2008	ZCTA	How does SES modify the association between air pollution and pediatric asthma?	NC	Socioeconomic level	education, household type, income, poverty, transportation and unemployment, Neighborhood Deprivation Index (NDI), Townsend Index	fusing observational data from available network monitors with pollutant concentration simulations from the Community Multi-Scale Air Quality (CMAQ) emissions-based chemical transport model at 12×12 km grids over Atlanta	Community Multi-Scale Air Quality (CMAQ)	NO2, O3, PM2.5, elemental carbon	asthma ED visit
Socioeconomic and Racial Disparities in Cancer Risk from Air Toxics in Maryland	Apelberg	2005	1,210 tracts	White, African American, Hispanic	1996 NATA, 2000 census	census tract	What is the relationship between tract-level socioeconomic and racial characteristics and estimated cancer risk from exposure to air toxics?	NC	economic and racial makeup	median household income, per capita income, % households owner occupied, %households with public assistance, % living below the poverty level and population ≥ 25 years of age without a high school diploma, % White, %African American, %Hispanic	census tract estimates of lifetime air toxics cancer risk (NATA)	NATA	grouped by emission source: major, area, on-road, nonroad	none
Effect Modification by Community Characteristics on the Short-term Effects of Ozone Exposure and Mortality in 98 US Communities	Bell and Dominci	2008	90 communities	Black	1987-2000 EPA. 1990 and 2000 census	county or set of contiguous counties	Do community-level characteristics explain the heterogeneity across community-specific relative rates or mortality?	NC	County-level descriptor variables	education level, median income, % poverty, % unemployed, %Black, %Urban/rural, % public transportation,	yearly average levels at census track	US EPA Aerometric Information Retrieval Service (ARIS)	ozone, PM10, PM2.5	weather variable (temperature and dew point), % air condition
Race/Ethnicity, Residential Segregation, and Exposure to Ambient Air Pollution: The Multi-Ethnic Study of Atherosclerosis (MESA)	Jones et al	2014	5921 participants across 1147 census tracts	White, Black, Asian, Hispanic	2002-2008	census tract	What are the associations of exposure to ambient air pollution at the household level, with race/ethnicity, neighborhood racial/ethnic composition, and racial/ethnic residential segregation in White, Black, Hispanic and Chinese adults who participated in the MESA study?	NC	racial segregation, G statistic", participant race, % race in tract,	G statistic yields a Z-score for each census tract that estimates the extent to which the racial/ethnic composition in that tract and neighboring tracts deviates from the mean racial/ethnic composition of the county overall.	individual-level annual average estimates	US EPA AQS and MESA monitors	PM2.5 and NOX	self-reported educational attainment, annual family income
Residential Segregation and Racial/Ethnic Disparities in Ambient Air Pollution	Woo et al	2018	3520 participants	Asian, Black, Latino, and White	1990-2011	census block	What are the independent and joint impacts of race/ethnicity and racial residential segregation on inequalities in air pollution exposure?	NC	metropolitan-level racial residential segregation	Dissimilarity Index: measure of the relative separation of a racial/ethnic minority group from Whites across area	annual average concentration	EPA AQS	PM10, PM2.5, NO2	none
Demographic Inequities in Health Outcomes and Air Pollution Exposure in the Atlanta Area and its Relationship to Urban Infrastructure	Servadio et al	2018		African American/non-African American	2006-2016	census tract	How do health outcome disparities compare to inequities in air pollution exposure, the built environment, and demographics?	NC	Demographics	% Race, % age	average NO2/census tract and average PM2.5/census tract	Community Multi-Scale Air Quality model (CMAQ	PM2.5 and NOx	tree canopy, road density, park access, % race, % over 65

Title	Author	Year	Population				Specific Research Questions	Variable Assessment						
			N	Race/Ethnicity	Years	Geographic area		Breast Cancer (BC) or Neighborhood Characteristic (NC)?	BC or NC Variable	What Approach Did They Use?	Air Pollution Measure	Air Pollution Database	Specific Pollutants	Other important variables
Metallic air pollutants and breast cancer Heterogeneity	Kersovich et al	2019	696 cases		2005-2008 cases, 2002 NATA	census tract	Do airborne heavy metal associations differ by tumor ER/PR status?	BC	Breast tumor ER/PR status	ER/PR-positive or ER/PR-negative	Total ambient concentrations	NATA	antimony, arsenic, beryllium, cadmium, chromium, cobalt, lead, manganese, mercury, nickel and selenium	Individual: age at diagnosis, race, education, household income, BMI, age at first birth, # of live births, menopausal status Neighborhood: income, education, occupation, public assistance unemployment, female-headed households with children
New spatially continuous indices of redlining and racial bias in mortgage lending: links to survival after breast cancer diagnosis and implications for health disparities research		2016	1010 cases	Black	2002-2011	ZCTA	What is the association between in mortgage lending and redlining, and breast cancer survival among Black American women?	No Air Pollution	Racial bias in lending, Modern Redlining,	estimate the odds ratio for denial of a mortgage application from a Black applicant compared to denial of a White applicant; odds of denial of the mortgage application for individuals inside the filter, as compared to individuals outside the filter	NA	NA	NA	survival time post diagnosis for breast cancer, stage at diagnosis, loan to income ratio, age group, population density
Air Pollution, Clustering of Particulate Matter Components, and Breast Cancer in the Sister Study: A U.S.-Wide Cohort	White et al	2019	49,771 participants	White, non-White	2003-2009	individual address	What is the relationship between air pollution, PM components, and breast cancer risk in a United States-wide prospective cohort?	BC	BC characteristics	cohort study, DCIS or invasive; ER+PR+ invasive or ER-PR- invasive	Annual averages of air pollution concentration	EPA AQS	PM10, PM2.5, NO2, component [elemental carbon (EC), organic carbon (OC), nitrate (NO−3), sulfate (SO2−4), Al, As, Br, Cd, Ca, Co, Cr, Cu, Fe, K,Mn, Na, S, Si, Se, Ni, V, and Zn]	age at baseline, race, education, household income, census tract income, smoking status marital status, BMI, Parity, Mammography screening past 24 months, Family history, menopausal status
Long-term Particulate Matter Exposures during Adulthood and Risk of Breast Cancer Incidence in the Nurses' Health Study II Prospective Cohort	Hart et al	2016	3416 participants	not specified	1993-2011	individual address	What is the association between PM and measures of distance to roadway with the risk breast cancer incidence in the prospective cohort?	BC	incidence	cohort study, risk of overall breast cancer, and hormone receptor–specific sub-types (ER+/PR+ and ER-/PR-)	48-month average moving average and cumulative average, residential roadway proximity categories.	not specified	PM10, PM2.5, PM2.5 and PM10	menopausal status, age, race, and calendar year
Postmenopausal breast cancer is associated with 11996- exposure to traffic-related air pollution in Montreal, Canada: a case-control study	Crouse et al	2010	383 cases, 416 controls	not specified	1996-1997	centroid	Is the incidence of postmenopausal breast cancer associated with exposure to urban air pollution?	BC	incidence of postmenopausal breast cancer	case-control study	mean annual concentration	Environment Canada's National Air Pollution Surveillance network	NO2	reproductive history, educational attainment, family history of breast cancer, age at menarche, smoking and alcohol consumption, body mass index, and home address (and duration of residence at that address), occupational exposures, median household income and percentage of adults who did not complete high school
Ambient air pollution is associated with the increased incidence of breast cancer in US	Wei, Davis, and Bina	2011	199 counties	not specified	1973-2007 incidence, 1940-2008 EPA	county	What is the association between emissions of air pollutants and incidence rates of female breast cancer in the U.S.? How do time trends and regional variations affect the association?	BC	time trend of breast cancer incidence	Age-adjusted incidence rates, compare more industrialized US states to less industrialized US states	Total emissions, Emission density	US EPA Geographic Area Air Data	CO, NOx, VOC, SO2, PM10	2000 US standard population
Defining gentrification for epidemiologic research: A systematic review	Bhavsar, Kumar, and Richman	2020	36 reports	NA	2007–2020	NA	What relationships between gentrification, health, and determinants of health have been examined in research? How do articles quantitively define phenotype gentrification?	NC	gentrification	Systematic Review	NA	NA	NA	NA

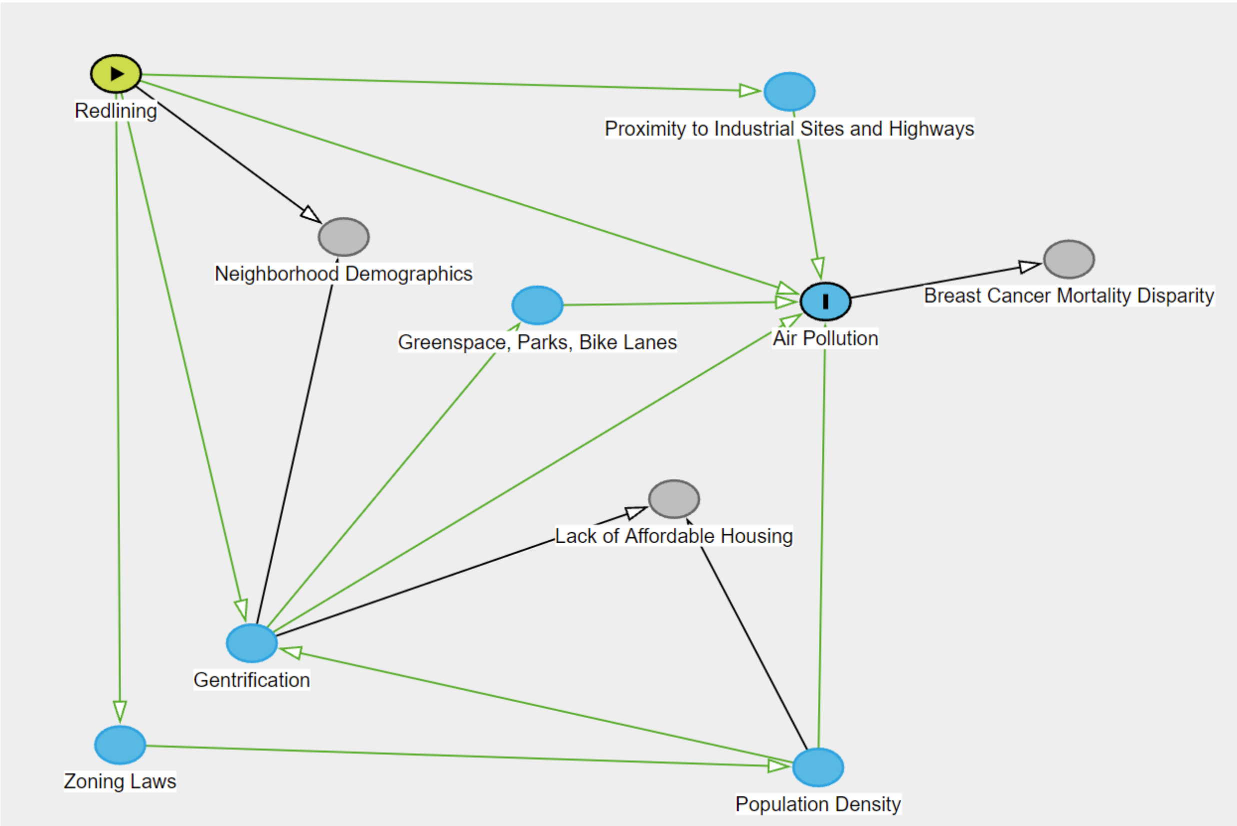
Title	Author	Year	Population				Specific Research Questions	Variable Assessment						
			N	Race/Ethnicity	Years	Geographic area		Breast Cancer (BC) or Neighborhood Characteristic (NC)?	BC or NC Variable	What Approach Did They Use?	Air Pollution Measure	Air Pollution Database	Specific Pollutants	Other important variables
Residential Racial Composition, Spatial Access to Care, and Breast Cancer Mortality among Women in Georgia	Russell, Kramer, Cooper, Thompson, and Arriola	2011	1,159 cases	Black, White	1999-2003	census tract	What is the association between neighborhood residential racial composition and breast cancer mortality among Black and White breast cancer patients in Georgia? Does spatial access to cancer care mediate this association?	NC	metropolitan isolation index (isolation of minority communities to other groups across metropolitan space)	% Black, % poverty	NA	NA	NA	survival time post diagnosis for breast cancer, age at diagnosis, cancer stage at diagnosis, course of treatment, marital status, local availability of cancer treatment and care
Skewed Riskscapes and Gentrified Inequities: Environmental Exposure Disparities in Seattle, Washington	Abel and White	2011	568 census block groups	Black, Asian, White	1990-2007	census block	What is the distribution of Seattle's industrial air toxic exposure risk? What is the relationship between the distribution and gentrification of neighborhoods?	NC	gentrification	upward socioeconomic transformation of urban neighborhoods by income, housing values, education, and occupational levels.	relative risk characterization of 90 toxic release inventory (TRI) facilities	US EPA Risk Screening Environmental Indicators (RSEI)	none	% White, % Black, % Asian, % College Educated, % Professional/managerial, % age 25-34, median household income, median rent, median house value, %nonfamily households, %poverty, %owner-occupied
The legacy of the Home Owners' Loan Corporation and the political ecology of urban trees and air pollution in the United States	Namin, Xu, Zhou, and Beyer	2020	115 HOLC areas	NA	2001 and 2011	HOLC areas	1) Is there a systematic disparity in contemporary spatial distributions of tree canopy that corresponds with HOLC categories, across US cities? 2) To what extent, if at all, are HOLC grades associated with increases or decreases in tree canopy over time (from 2001 to 2011)? 3) Is there a gradient in current levels of exposure to airborne carcinogens and respiratory hazards reflecting the HOLC grade hierarchy?	NC	historic redlining	HOLC grades	tree canopy, average respiratory Hazard Index	National Land Cover Database, US EPA NATA	none	population density

Author	Year	Spatial approach	Statistical approach	Results
Ekenga, Yeung, Oka	2019	Spatial clustering	relative risks from log-binomial regression models	Air toxic hot spots were independently associated with neighborhoods with high levels of poverty and unemployment and low levels of education. Census tracts with the highest levels of both racial isolation of Blacks and economic isolation of poverty were more likely to be located in air toxic hotspots than those with low combined racial and economic isolation (RR=5.34; 95% CI: 3.10–9.22).
Hiatt, Green Brody	2018	Literature Review	Literature Review	NA
White, Bradshaw, Hamra	2018	Literature Review	Literature Review	NA
Krieger et al	2020	none	Poisson regression	Models for the total effect of HOLC grade, adjusted for race/ethnicity and sex/gender (where appropriate), showed a pattern of increased risk of late-stage diagnosis in redlined and yellow areas for women with breast cancer (risk ratio (RR)red = 1.07, 95% confidence interval (CI): 0.98, 1.17
Reding et al	2015	verified pollution concentration using regionalized universal kriging model derived from regulatory monitors	Cox proportional hazards models	Although breast cancer risk overall was not associated with PM2.5 [HR = 1.03; 95% confidence intervals (CI), 0.96–1.11], PM10 (HR = 0.99; 95% CI, 0.98–1.00), or NO2 (HR = 1.02; 95% CI, 0.97–1.07), the association with NO2 differed according to ER/PR subtype (P = 0.04).
White et al	2019	none	multivariable Cox proportional hazards, weighted quantile sum	Postmenopausal breast cancer risk was elevated for mercury (hazard ratio [HR]=1.3, 95% confidence interval [CI]: 1.1–1.5), cadmium (HR=1.1, 95%CI: 0.96–1.3), and lead (HR=1.1, 95%CI: 0.98–1.3).
Gabet et al	2021	Meta-Analysis and Literature Review	Meta-Analysis and Literature Review	The meta-analytical RR of breast cancer was 1.014 (95% CI:0.929, 1.106) for a 10-lg=m3 increase in exposure to PM2:5 without correction for publication bias
White et al	2020	none	Cox proportional hazards models	Higher exposure to NO2 or O3 was not associated with a higher risk of breast cancer. For PM2.5, although we observed no association overall, there was evidence of modification by geographic region for both ER and premenopausal breast cancer risk.
Mikati et al	2018	distance-based"centroid-containment"assignment	Absolute Burden and proportional Burden, sensitivity analysis	For PM2.5, those in poverty had 1.35 times higher burden than did the overall population, and non-Whites had 1.28 times higher burden. Black populations, specifically, had 1.54 times higher burden than did the overall population.
Morello-Frosch & Jesdale	2006	NA	Poisson regression	After controlling for tract-level SES measures, increasing segregation amplified the cancer risks associated with ambient air toxics for all racial groups combined [highly segregated areas: relative cancer risk (RCR) = 1.04; 95% confidence interval (CI), 1.01–107; extremely segregated areas: RCR = 1.32; 95% CI, 1.28–1.36].
Perlin, Wong, & Sexton	2011	EPA's Population Estimation and Character-ization Tool, area weighting method	Pair-wise Chi-squared analyses	Compared with White children, a substantially higher proportion of African-American children 5 years of age or younger lived in poor households that were located in relatively close proximity to one or more industrial sources of air pollution.
Nardone et al	2020	Census tract choropleth maps	ordinary least squares regression models	The proportion of the population that was non-Hispanic black and Hispanic, the percentage of the population living in poverty, and diesel exhaust particle emissions all significantly increased as security map risk grade worsened (p<0·0001)

Author	Year	Spatial approach	Statistical approach	Results
Namin et al	2020	NA	Beta regression, Linear regression	Moreover, the results show that overall, grades A and B neighborhoods are exposed to less airborne carcinogens and respiratory health hazards compared to grades C and D. An association between airborne carcinogens and HOLC grade is also observed.
Woo et al	2019	Uni-versal kriging, land-use regression	linear regression models using ordinary least squares	The difference between minorities and Whites in exposure to all three types of air pollution was most pronounced in metropolitan areas with high levels of residential segregation.
O'Lenick et al	2017	none	logistic regression	We generally observed stronger associations between air pollution and pediatric asthma in extremely low SES neighborhoods compared with areas of higher SES. (Particularly consistent across SES indicators for NO2).
Apelberg	2005	none	linear regression model	Census tracts in the highest quartile defined by the fraction of African American residents were three times more likely to be high risk (> 90th percentile of risk) than those in the lowest quartile (95% confidence interval, 2.0–5.0). Census tracts in the lowest quartile of socioeconomic position, as measured by various indicators, were 10–100 times more likely to be high risk than those in the highest quartile.
Bell and Dominci	2008	none	constrained distributed lag model, mixed-effects meta-regression, Bayesian hierarchical model	Higher effect estimates were associated with higher unemployment, fraction of the Black/African American population, and public transportation use and with lower temperatures or prevalence of central air conditioning.
Jones et al	2014	none	Mixed-effect models	Participants in neighborhoods with more than 60% Hispanic populations were exposed to 8% higher PM2.5 and 31% higher NOX concentration compared with those in neighborhoods with less than 25% Hispanic populations. Participants in neighborhoods with more than 60% White populations were exposed to 5% lower PM2.5and 18% lower NOX concentrations compared with those in neighborhoods with less than 25% of the population identifying as White.
Woo et al	2018	land-use regression	linear regression	In general, metropolitan-level segregation is significantly associated with higher levels of exposure to all three ambient air pollutants, above the influence of race/ethnicity
Servadio et al	2018	Conditionally autoregressive (CAR) models, spatial autocorrelation (Moran's I)	linear regression	Areas with majority African American populations are significantly associated with higher exposure to both air pollutants.
Kersovich et al	2019	none	logistic regression model	Comparing the highest and lowest quintiles, higher concentrations of antimony (odds ratio [OR]: 1.8, 95% confidence interval [CI]: 0.9, 3.7, P-trend: 0.05), cadmium (OR: 2.3, 95% CI: 1.2, 4.4, P-trend: 0.04) and cobalt (OR: 2.0, 95% CI: 0.9, 4.4, P-trend: 0.04) were associated with ER/PR-negative breast cancer.
	2016	adaptive spatial filtering (ASF)	Cox proportional hazards regression	For breast cancer specific mortality, the redlining index was associated with a lower hazard rate (HR 0.76 [0.59, 0.98]). The racial bias index and race and ethnicity adjusted redlining index were not significantly associated with breast cancer specific mortality.
White et al	2019	land-use regression	Cox proportional hazards regression	PM2:5 and NO2 were associated with breast cancer overall [HR = 1:05 (95% CI:0.99, 1.11) and 1.06 (95% CI:1.02, 1.11) bur not invasive cancer. Invasive breast cancer was associated with PM2:5 only in the Western United States [HR = 1:14 (95% CI:1.02, 1.27)] and NO2 only in the Southern United States [HR = 1:16 (95% CI:1.01, 1.33)].
Hart et al	2016	calculated the distance from each address to the nearest street segments	Time-varying Cox proportional hazards	There was little evidence of an increased risk of breast cancer (or any of the receptor-specific subtypes) overall or by menopausal status with PM exposure. There was, however, a suggestion of increased risks among women living <50 m of the largest road type (HR = 1.60; 95% CI, 0.80-3.21) or within <50 m of the two largest road types (1.14; 95% CI, 0.84-1.54) compared with women living farther (≥200 m) away.
Crouse et al	2010	land-use regression	logistic regression	For each increase of 5 ppb NO2 estimated in 1996, the adjusted odds ratio was 1.31 (95% confidence interval, 1.00–1.71). Although the size of effect varied somewhat across periods, we found an increased risk of approximately 25% for every increase of 5 ppb in exposure.
Wei, Davis, and Bina	2011	none	linear regression	Emissions of nitrogen oxides, carbon monoxide, sulfur dioxide, and volatile organic compounds were shown to be positively correlated with breast cancer incidence.
Bhavsar, Kumar, and Richman	2020	Systematic review	Systematic review	NA
Russell, Kramer, Cooper, Thompson, and Arriola	2011	gravity-based modeling	Cox proportional hazards models	Residential racial composition had a small but significant association with breast cancer mortality (hazard ratios [HRs]=1.04–1.08 per 10%increase in the percent of Black tract residents). Individual race did not moderate this relationship, and spatial access to care did not mediate it.
Abel and White	2011	principal components analysis	factorial social ecology	A cluster of air toxic exposure inequality and socioeconomic inequity converged in 1 area of south-central Seattle. Minority and working-class residents were more concentrated in the same neighborhoods near Seattle’s worst industrial pollution risks.
Namin, Xu, Zhou, and Beyer	2020	none	linear regression	Results indicate a clear gradient in tree canopy by HOLC grade, with better neighborhood grades associated with significantly higher percentage of tree canopy coverage. The pattern also exists for airborne carcinogens and respiratory hazards, with worse neighborhood grades associated with significantly higher hazards exposure.

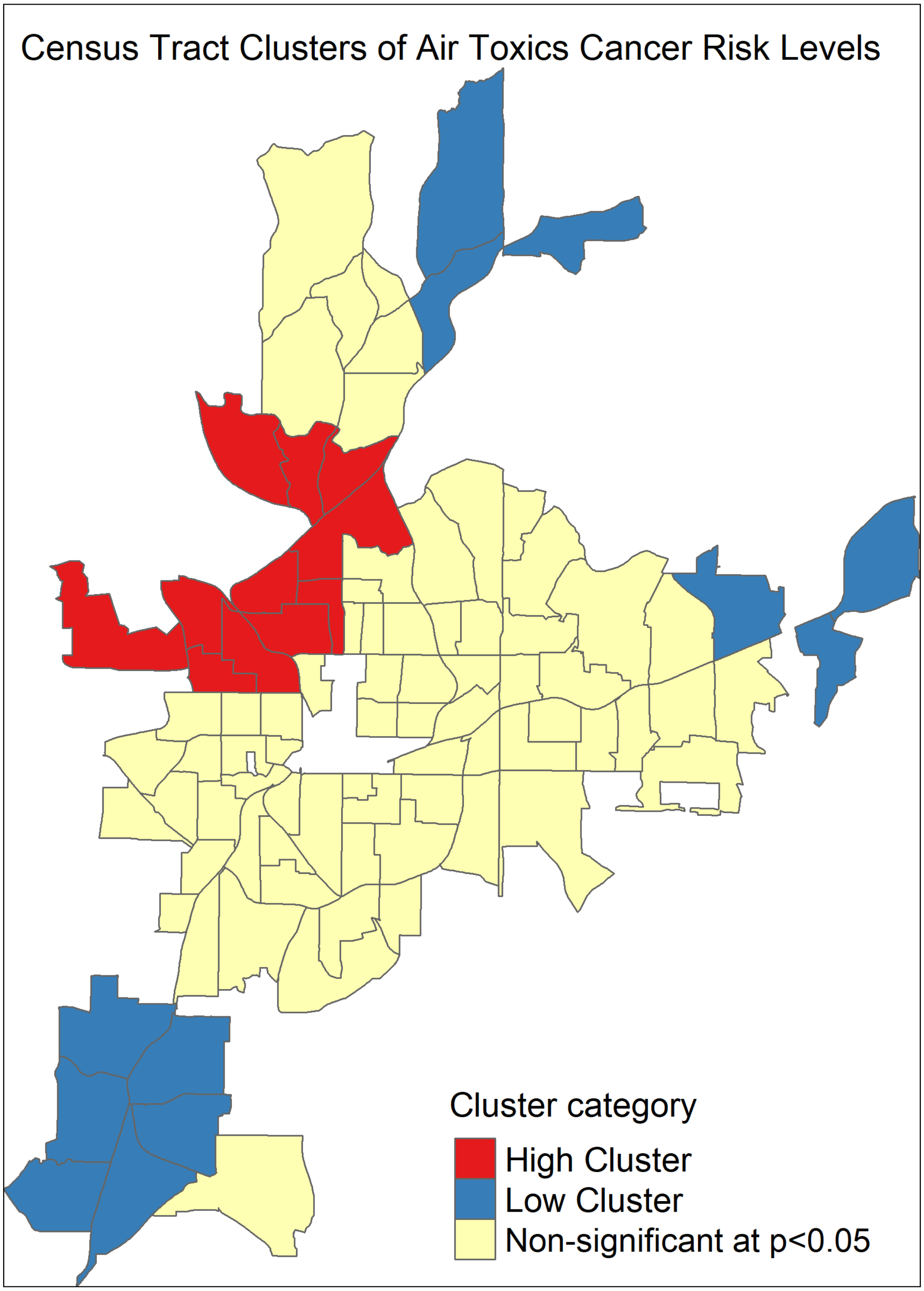
Appendix B. Directed Acyclic Graph (DAG)

Directed acyclic graph (DAG) of the association between historic redlining (exposure) and air pollution (outcome)



APPENDIX C. LISA Map

Local Indicators of Spatial Association (LISA) maps of air toxics cancer levels



APPENDIX D. Aspatial Linear Model Results

Appendix D1. Aspatial Risk Differences of Redlining on Air Toxic Cancer Risk, Atlanta, GA

	RD	95% CI
Intercept	56.29	(54.48, 58.11)
HOLC Grade A	-4.03	(-6.79, -1.27)
HOLC Grade B	-1.19	(-3.53, 1.14)
HOLC Grade C	-2.32	(-4.59, -0.04)
HOLC Grade D	Referent	Referent

Appendix D2. Aspatial Risk Differences of Gentrification on Air Toxic Cancer Risk, Atlanta, GA

	RD	95% CI
Intercept	53.99	(53.37, 55.60)
Exclusive	-1.65	(-4.29, 0.99))
Mixed Moderate to High Income	-1.04	(1.00, 3.08)
Gentrifying	-1.08	(-1.61, 3.76)
Low Income	Referent	Referent