Behind the Concrete Curtain: Restrictive Zoning and Neighborhood Air Quality*

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February 1, 2026

Preliminary draft. Please do not cite without permission.
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Abstract

We identify municipal zoning as a key institutional channel through which historical housing discrimination translates into contemporary environmental inequality. Exploiting quasi-experimental variation at HOLC ("redlining") boundaries, we use historical grades as an instrument for present-day zoning status for 39 of the largest cities in the USA. The first stage reveals a strong and monotonic relationship: areas assigned lower historical grades are significantly more likely to be zoned for multi-family use today. Our 2SLS estimates indicate that multi-family zoning causally increases annual $PM_{2.5}$ concentrations by 0.7 to 1.2 $\mu g/m^3$, or about 7 to 12 percent relative to the sample mean. These results suggest that zoning regulations are an important contributor to current disparities in pollution exposure.

JEL Codes: I14, N92, Q53, R31

*We would like to thank Robert French, Dustin Frye, Rhiannon Jerch, Daniel Phaneuf, Christopher Timmins, and seminar participants at MEA Annual Meeting, Tsukuba University, UW-Madison for helpful comments. All mistakes are our own.

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1 Introduction

Disparities in exposure to environmental hazards across racial and socioeconomic groups are a persistent and defining feature of the American landscape. Residents of minority and low-income communities suffer from systematically higher levels of air pollution, leading to adverse outcomes in health, human capital, and economic mobility (Bailey et al. (2017); Chay and Greenstone (2005); Currie (2011); Gillingham and Huang (2024); Isen et al. (2017)). Recent work confirms that these exposure gaps, although narrowing over time, have remained remarkably persistent (Colmer et al. (2020, 2024); Currie et al. (2023); Jbaily et al. (2022)). While a vast literature has explored potential drivers, from discriminatory steering, income-based sorting to the strategic siting of polluters (Banzhaf and Walsh (2008); Banzhaf et al. (2019); Cain et al. (2024); Christensen and Timmins (2022, 2023); Depro et al. (2015); Lin et al. (2024)), the role of foundational government institutions in perpetuating these disparities remains a key open question for public economics.

This paper investigates one such institution: municipal zoning ordinances. We ask whether modern zoning ordinances, which dictate land use at a granular level, serve as one of the primary mechanisms channeling the legacy of historical housing discrimination into contemporary environmental inequality. The core empirical challenge in answering this question is the profound endogeneity of zoning codes. The same unobserved economic and political factors that determine whether a neighborhood is zoned for single-family homes versus multi-family apartments—such as resident income, political capital, and proximity to industry—are also directly correlated with pollution levels. A simple regression of pollution on zoning would therefore yield biased estimates, making it difficult to isolate the causal effect of land-use policy itself.

To overcome this challenge, we utilize an instrumental variable strategy that leverages the historical "Residential Security Maps"—commonly known as "redlining maps"—created by the Home Owners' Loan Corporation (HOLC) in the 1930s. These maps, which graded neighborhoods on a four-tier scale from "A" (Best) to "D" (Hazardous), effectively institutionalized racial and ethnic discrimination in the housing market and have been shown to have had persistent effects on segregation, human capital accumulation, and housing investment (Aaronson et al. (2021, 2023); Fishback et al. (2023, 2024)). Our identification strategy posits that these almost-century-old assessments, while having no direct effect on current air pollution, strongly influenced the trajectory of land-use regulation. Crucially, while recent evidence suggests the direct effect of the HOLC maps on historical mortgage lending was limited (Fishback et al. (2023, 2024)), we argue their primary long-run legacy was in codifying a discriminatory heuristic that became embedded in subsequent local land-use law. Specifically, we argue that the quasi-arbitrary boundaries drawn by HOLC appraisers created a sharp discontinuity in the long-run likelihood of a parcel being zoned for less restrictive uses, such as multi-family housing.

This research design is implemented using a newly constructed dataset that spatially merges historical HOLC maps with 2024 zoning ordinances and high-resolution satellite data on fine particulate matter ($PM_{2.5}$) for 39 of the largest U.S. cities (Figure 1). Our unit of analysis is a small land polygon, each possessing a uniform historical HOLC grade and a uniform contemporary zoning code. This granular approach allows us to precisely estimate the effects of zoning at a hyper-local level, often comparing adjacent parcels that fell on opposite sides of a historical HOLC boundary.

We document three results. First, we document a strong first stage: a lower historical HOLC grade significantly increases the probability that a parcel is zoned for multi-family use today. Second, our two-stage least squares (2SLS) estimates show that zoning has a large and causal effect on environmental exposure. We find that land zoned for multi-family residences has substantially higher concentrations of $PM_{2.5}$ than land zoned for single-family use. Our 2SLS estimates imply that multi-family zoning raises annual PM2.5 concentrations by roughly $0.7 - 1.2$ $\mu g/m^3$ (about $7\% - 12\%$ of the mean), with larger effects in historically "C"- and "d"-graded marginal neighborhoods. The results are robust to a host of controls on demographics, historical urban and industrial landscapes. Our estimates suggest that zoning policies account for a significant share of the observed relationship between historical redlining and current pollution disparities.

This paper makes three primary contributions to the literature. First, we contribute to the environmental justice literature by identifying restrictive zoning as a key institutional mechanism through which inequality is created and sustained. Our findings reinforce the growing consensus that places—not demographic characteristics per se—determine pollution exposure (Colmer et al. (2020); Currie et al. (2023); Heblich et al. (2021); Lyubich (2025)). We provide clear evidence that institutional forces—in this case, restrictive land-use regulations—are a primary driver sorting disadvantaged groups into these more polluted places, thereby creating the exposure gap. Second, we contribute to the growing literature on the long-term consequences of historical institutions

(Nunn (2009)) by tracing the specific pathway through which the infamous HOLC maps continue to impact resident welfare today. Finally, we add a new dimension to the urban and public economics literature on restrictive zoning. While the classic string of work explores its effects on the housing market equilibrium (Fischel (1978); Glaeser et al. (2005); Hsieh and Moretti (2019); Pollakowski and Wachter (1990); Rollet (2025)), and other research connects it to racial segregation (Kulkarni and Malmendier (2022); Monarrez and Schönholzer (2023); Rothwell and Massey (2010); Sahn (2025); Shertzer et al. (2016, 2022)), we are the first to establish its causal role in determining environmental pollution exposure. Our findings suggest that contemporary debates over zoning reform are not only central to housing policy but are also a critical lever for advancing environmental justice.

The remainder of the paper proceeds as follows. Section 2 discusses the institutional history of HOLC and zoning in the U.S. Section 3 describes our data construction. Section 4 outlines the empirical strategy. Section 5 presents the results, and Section 6 concludes.

2 Background

To understand the modern relationship between land use and pollution in the U.S., one must look to two of the most influential urban policies of the 20th century: the federal practice of "redlining" and the local implementation of zoning. This section provides the historical context for both institutions.

2.1 Redlining

The HOLC was a federal agency created in 1933 as part of the New Deal to stabilize the housing market, which had been devastated by the foreclosure crisis, by refinancing mortgages in default (Hillier (2005); Jackson (1987)). Between 1935 and 1940, HOLC created "Residential Security Maps" for over 200 U.S. cities to standardize the assessment of mortgage lending risk in its existing portfolio (Michney (2022)). Appraisers graded neighborhoods into four categories: "A" (Best, green), "B" (Still Desirable, blue), "C" (Definitely Declining, yellow), and "D" (Hazardous, red) (e.g., Figure 2).

While these grades were ostensibly based on housing stock, sales activity, and economic indicators, the appraisers' area descriptions revealed that racial and ethnic composition were primary determinants. Neighborhoods with even small minority populations—particularly Black residents and immigrant communities—were systematically graded "D" and outlined in red, with little to no weight given to other factors. This practice became part of what was known as "redlining."

The HOLC's own records provide stark illustrations of the discriminatory undertone of this practice. For instance, in Madison, Wisconsin, the Area D2 was graded "Hazardous" with appraisers noting that it was the "most troublesome area in city" due to its "predominating foreign population" of Italian immigrants. An even more explicit example is the nearby Area D3, where the list of "Detrimental Influences" begins with a single word: "Negroes," followed only by "Proximity to business section." These official records demonstrate that racial and ethnic composition was not merely a confounding factor but was often the primary, explicitly stated determinant of a neighborhood's perceived investment risk.

It is important to note that, although often treated by many as a blueprint for nationwide housing policy in contemporary discussions, the HOLC maps were not originally created to guide future development or mortgage lending in any official capacity. Their stated purpose was internal—to help HOLC staff manage the agency's existing loans and real estate holdings (Hillier (2003b); Michney and Winling (2020); Michney (2022)). The intended audience for those maps had always been limited to the HOLC staff; and its message could be seen as a mere reflection of the common sentiment among real estate professionals, the likes of whom created the HOLC maps (Harriss (1951); Hillier (2003a,b)). Consistent with this limited initial scope, recent empirical work finds that the direct causal effect of the HOLC maps on the subsequent geography of mortgage lending has been rather small (Hillier (2003a); Fishback et al. (2023, 2024)). This historical context is central to our identification strategy. The limited direct influence of the maps on historical capital investment and development lends credibility to the exclusion restriction—it is less likely that the map boundaries are correlated with many other unobserved historical factors that could independently influence modern pollution levels.

Nevertheless, the limited direct effect on lending does not render the HOLC maps powerless. Their primary influence was arguably more subtle but ultimately more durable: they codified and legitimized racially discriminatory appraisal practices, which were then actively promoted and diffused through the public and private real estate sectors (Woods (2012)). As a result, the maps served as a focal point that shaped decades of subsequent development patterns of public urban policymaking (e.g., zoning ordinances) and private practices (e.g., restrictive covenants), even if the direct lending channel is found to be weak (Jones-Correa (2000)). Indeed, an extensive literature has documented significant, negative long-run consequences of redlining on segregation and intergenerational mobility—although the effects seem to wane after the successful reform of federal lending policies since 1968 (Aaronson et al. (2021, 2023); Faber (2020); Glaeser and Vigdor (2012)). It is through this powerful, indirect channel of shaping norms and subsequent policymaking that we argue the HOLC maps are a relevant instrument for contemporary zoning. Our study builds on this literature by investigating a novel channel through which these historical assessments persist: their influence on subsequent land-use laws.

2.2 Zoning Ordinances in the United States

Zoning ordinances are local government regulations that dictate how land can be used and developed. The practice emerged in the early 20th century, and its constitutionality was affirmed by the Supreme Court in 1926 (Village of Euclid v. Ambler Realty Co. (1926)). The primary stated purpose of zoning was to protect public health, safety, and property values by separating incompatible land uses—for instance, to keep industrial factories away from residential homes (e.g., Figure 3).

However, from its inception, zoning was also used to enforce socioeconomic and racial segregation (Rothstein (2017); Troesken and Walsh (2019)). The most common form of land-use regulation in the U.S. is single-family zoning, which prohibits the construction of denser housing types like duplexes or apartment buildings. Economists have shown that such restrictive or "exclusionary" zoning inflates housing prices (Glaeser et al. (2005)) and limits housing supply, effectively preventing lower-income households from moving into certain neighborhoods. Historical research has also demonstrated a strong correlation between the early adoption of racial zoning ordinances and subsequent patterns of segregation (Shertzer et al. (2016, 2018)). Because zoning shapes local public goods and amenities—school access, open space, transit frictions—it can move communities along the tipping margin, linking land-use regulation to segregation via Tiebout sorting (Banzhaf and Walsh (2013); De Silva et al. (2024)).

While redlining and zoning were separate legal regimes—one federal and informal, the other local and statutory—they were motivated by similar objectives and operated in parallel. Our central hypothesis is that these institutions did not merely co-exist but were causally linked, with historical redlining practices shaping the restrictive zoning ordinances that govern these same neighborhoods today. This is consistent with historical evidence that local land-use law internalized—and then perpetuated—segregative forces (Shertzer et al. (2016)). We build on this by tracing a specific channel from 1930s assessments to contemporary zoning and pollution.

3 Data

3.1 Land-use Regulation Data

Our analysis starts with the 77 largest U.S. cities, as ranked by population in the 2020 Census. We collect contemporary land use data by obtaining digitized zoning ordinance maps (in effect for the year 2024) from public municipal government databases. For historical data, we use the digitized Residential Security Maps, which are sourced from the University of Richmond's Digital Scholarship Lab (Nelson et al. (2023)). We then spatially integrated these datasets to create a harmonized shapefile linking historical HOLC grades to contemporary zoning codes for each land polygon. Due to limitations in data availability and implementation of zoning laws, our final analytical sample includes 39 of the original 77 cities for which both data sources are complete and available.

Analysis requires official land-use codes spanning decades for the same plot of land, the boundary of which almost never aligns perfectly. To create a spatially consistent dataset linking historical assessments to contemporary land use, we intersect the historical HOLC maps with the 2024 zoning maps via the "Spatial Join" tool on ArcGIS Pro. This geoprocessing step defines our unit of analysis: a land polygon characterized by a single historical HOLC grade and a uniform contemporary zoning code. We trim the map by deleting newer development areas that have not been evaluated by HOLC. Each resulting polygon represents a unique area defined by both its historical HOLC grade and its single, contemporary zoning code. For our analysis, we also need to measure the land-use characteristics of the immediate surroundings. We capture this by generating a three-meter buffer around each polygon and recording the zoning designations of all adjacent or intersecting polygons. We then record the zoning codes of all adjacent polygons that fall within or intersect this buffer zone, creating a comprehensive variable of neighboring land-use patterns.

In addition to the spatial overlay, we exploit the qualitative "area description" sheets that accompany each HOLC map. For each graded area, we extract text from several fields—"detrimental influences", "clarifying remarks", "infiltration of", "negro yes or no", and "foreign-born nationality"—and concatenate them into a single passage. Using a text-classification procedure based on a leading commercial large language model (Gemini 2.5 Pro), we then construct three binary indicators: whether the description explicitly mentions: (1) a major point pollution source (e.g., industrial plants, coal yards, or railroads), (2) a general nuisance (e.g., odors or sewage), and (3) the presence of minority or foreign-born residents as a reason for the area's grade. We attach these indicators to the HOLC–zoning polygons and use them as controls in our preferred specifications, allowing us to distinguish the role of historical industrial layout, nuisance siting, and racial decomposition from the long-run effect of zoning itself.

3.2 Pollution and Other Data

We augment the land-use dataset with high-resolution environmental and demographic data. To measure air pollution, we use satellite-derived annual average concentrations of $PM_{2.5}$ from the Atmospheric Composition Analysis Group at Washington University in St. Louis, which are available at a spatial resolution of $0.01° \times 0.01°$ (Shen et al. (2024)). We calculate the mean 2021-2023 $PM_{2.5}$ level for each analytical polygon, providing a contemporary measure of pollution exposure for local residents.

To link pollution exposure to resident characteristics, we source block-level statistics from the U.S. Census Bureau using the "tidycensus" package in R. As census block boundaries do not perfectly align with our land-use polygons, we use the interpolate_pw function to create a population-weighted spatial interpolation. This procedure enables the calculation of our primary outcome variable: the population-weighted pollution exposure for each unique land polygon. It also allows us to estimate the demographic composition for each polygon, including key variables such as minority population share, renter share, median household income, educational attainment, and age.

In addition to contemporary pollution and demographic data, we incorporate three sources of historical data designed to capture baseline differences in the built environment and industrial activity. First, we use the Historical Settlement Data Compilation for the United States (HISDAC), which provides gridded information on the number of unique structures and total built floor area at a $250m \times 250m$ resolution for the year 1930 (Ahn et al. (2024)). We spatially join these pixels to our analysis polygons to construct two controls: the intensive (aggregate floor area) and extensive (number of unique structures) margins of urban built-up in 1930.

Second, we draw on establishment-level transcriptions of the United States Census of Manufactures for 1929–1935 (Vickers and Ziebarth (2023)). Using the reported locations and industry codes, we geolocate each manufacturing establishment and assign it to a 1 km $\times$ 1 km grid aligned with the distance band commonly used in hedonic literature (e.g., Davis (2011); Grislain-Letrémy and Katossky (2014); Hanna (2007)). For a set of pollution-intensive industries, we then compute in each grid cell (1) the intensive margin (total value of product output) and (2) extensive margin (number of distinct establishments) of industrial built-up in the pre-World-War-II era. We then spatially join these gird cells to our analysis polygons to construct the two industrial controls.

Lastly, we incorporate two additional datasets digitized by Weiwu (2024). The first is a shapefile of U.S. historical non-Interstate roads, constructed by re-aligning modern roads to be consistent with the historical maps digitized from Shell Atlases in 1951 and 1956. The second is a shapefile of planned U.S. Interstate Highways in 1947, digitized from a Public Roads Administration map. While they do not reflect infrastructure immediately prior to the creation of HOLC maps, these datasets represent the earliest available digitized national-level data on U.S. road infrastructure. We construct two controls via a spatial analysis of these datasets and our analysis polygons: (1) distance to the closest historical local road and (2) distance to the closest planned historical Interstate Highway.

Together with the controls constructed using HOLC map transcriptions, our eight historical controls holistically summarize the intensive and extensive margins of urban development around the creation of the HOLC maps. They allow us to compare polygons that are similar in their pre-HOLC built environment and early manufacturing intensity, thereby sharpening our interpretation of the variation in zoning generated by historical HOLC grades.

3.3 Summary Statistics

Table 1 presents descriptive statistics for our primary analytical sample of 311,906 land polygons across our sample cities, stratified by historical HOLC grade. The data reveal a sharp socioeconomic gradient that aligns with the historical hierarchy established nearly a century ago. Grade A polygons are characterized by the highest socioeconomic status, with a median household income of $\$124,628$ and a non-Hispanic White population share of 62%. In contrast, Grade D polygons exhibit a median income of roughly half that amount ($\$64,913$) and a White population share of 30%. We observe a similarly striking disparity in housing tenure: the renter share doubles from 30% in Grade A areas to 59% in Grade D areas. These baseline differences in contemporary demographics underscore the endogeneity of neighborhood sorting and the necessity of our instrumental variable strategy to isolate the regulatory mechanism.

The "Variables of Interest" panel offers a descriptive preview of our first-stage and reduced-form relationships. We observe a strict monotonic increase in regulatory land-use restriction moving up the HOLC hierarchy: only 13% of Grade A areas is currently zoned for multi-family use, compared to 37% of Grade C and 51% of Grade D areas. This regulatory constraint correlates with observed environmental outcomes, as Grade A areas benefit from the lowest average annual $PM_{2.5}$ concentrations (9.40 $\mu g/m^3$), while Grade C and D areas suffer from elevated exposure (10.24 $\mu g/m^3$ and 10.02 $\mu g/m^3$). To further illustrate the distributional nature of this chasm, Figure 4 plots the cumulative distribution functions of pollution exposure by demographic status. Panel 4a shows that the pollution distribution for non-white majority neighborhoods first-order stochastically dominates that of white majority neighborhoods, indicating systematically higher exposure. Panel 4b reveals a similar pattern by income.

Finally, the "Historical Built Environment" panel of Table 1 highlights the importance of conditioning on pre-existing industrial geography to satisfy the exclusion restriction. Grade D areas historically contained the highest intensity of manufacturing activity, with an average 1935 manufacturing output of $\$5,059$ per polygon compared to just $630 in Grade A areas (in 1935 U.S. dollars). By explicitly controlling for these historical industrial baselines, our identification strategy isolates the regulatory legacy of redlining from the persistence of early 20th-century industrial corridors.

4 Empirical Framework

To estimate the causal effect of land-use regulations on environmental outcomes, we specify a set of regression models. In all specifications, the unit of analysis is a land polygon i located in city c.

Our outcome variable, $PM_{2.5ic}$, is the average annual $PM_{2.5}$ concentration for that polygon. The primary explanatory variable of interest, MultiFamily_{ic}, is an indicator variable equal to one if the polygon is zoned for multi-family housing, and zero otherwise. To control for any time-invariant unobserved factors at the city level (such as geography, climate, or broad economic structure), all models include a full set of city fixed effects, denoted δ_c.

Throughout, we also control for a rich set of polygon-level covariates, collected in the vector X_{ic}. This vector includes contemporary demographic variables constructed from the Census—minority share, renter share, median household income, educational attainment, and age. It also includes the eight historical controls described in Section 3. These covariates enter all OLS and 2SLS specifications unless otherwise noted. However. for expositional simplicity, we suppress X_{ic} in the notation of equations.

4.1 OLS Specification

We first establish a baseline OLS model, shown in Equation (1), to quantify the correlation between zoning and pollution:

$$\text{PM}_{2.5ic} = \beta_0 + \beta_1 \text{MultiFamily}_{ic} + \delta_c + \epsilon_{ic} \tag{1}$$

However, a causal interpretation of the OLS estimate $\hat{\beta}_1$ from Equation (1) is not credible due to the endogeneity of zoning. Zoning laws are the outcome of complex economic and political processes. Unobserved factors, such as resident income levels, political influence, historical land-use patterns, and proximity to infrastructure, are likely correlated with both the probability of a multi-family zoning designation and local pollution levels. This omitted variable bias will render the OLS estimate inconsistent. For example, if zoning for multi-family housing is more likely in areas that are already polluted for other reasons, $\hat{\beta}_1$ would be an overestimation of the effect. Conversely, if such zoning occurs in dense downtown areas that have less industrial pollution, $\hat{\beta}_1$ could be an underestimation.

4.2 2SLS Specification

To overcome this endogeneity, we employ a two-stage least squares (2SLS) instrumental variable strategy, using a polygon's historical HOLC grade as a source of quasi-random variation in its contemporary zoning status. To ensure the robustness of our findings, we construct three distinct specifications for our instrumental variable set, $\mathbf{Z}_{ic}$:

1. **Categorical Instrument (Preferred):** Our primary instrument set consists of five indicator variables, one for each historical HOLC grade (A, B, C, D, and commercial/industrial). This flexible specification allows for non-linear effects of the historical grades on modern zoning.

2. **Linear Instrument:** We construct a single linear instrument by converting the HOLC grades to a numeric score from 0 ("Commercial/Industrial") to 4 ("A"). This specification tests the assumption of a linear relationship.

3. **Binary Instrument:** We create a single binary instrument equal to one if a polygon was in a "Desirable" area (Grades A, B, or C) and zero if it was in an "Undesirable" area (Grade D or commercial/industrial). This specification tests a simplified version of our core hypothesis without risking over-identification.

The 2SLS model, using one of these three instrument sets, is specified in the following two stages:

First Stage:

$$\text{MultiFamily}_{ic} = \alpha_0 + \alpha_{\mathbf{1}}' \mathbf{Z}_{ic} + \delta_c + \mu_{ic} \tag{2}$$

In the first stage, described in Equation (2), we regress the endogenous $\textbf{MultiFamily}_{ic}$ indicator on one of the instrument sets $\mathbf{Z}_{ic}$ and city fixed effects. This stage isolates the variation in modern zoning that is plausibly explained only by the historical HOLC designations. The strength of this relationship is formally tested via the first-stage F-statistic.

Second Stage:

$$\text{PM}_{2.5ic} = \beta_0 + \beta_1 \widehat{\text{MultiFamily}}_{ic} + \gamma_c + \nu_{ic} \tag{3}$$

In the second stage, shown in Equation (3), we regress the pollution outcome on the predicted values of multi-family zoning, $\widehat{MultiFamily}_{ic}$, from the first stage. The resulting coefficient, $\hat{\beta}_1$, provides a consistent estimate of the local average treatment effect (LATE) of multi-family zoning on air pollution.

Endogenous neighborhood sorting and regulatory decision-making are a first-order concern in this setting, as place-based policies can induce Tiebout sorting and neighborhood tipping (Banzhaf and Walsh (2013)). Our strategy uses quasi-arbitrary historical HOLC boundaries to isolate exogenous variation in zoning rules that subsequently shape amenities and sorting, rather than contemporaneous amenity shocks. The validity of this estimate rests on the exclusion restriction—the historical HOLC boundaries affect modern pollution only through their impact on contemporary zoning and land use. This assumption is bolstered by historical evidence suggesting the maps' stated purposes as well as the actual audience reached were internal, and that their direct effects on private mortgage markets were limited (Hillier (2003b,a); Michney (2022); Fishback et al. (2023, 2024)). Our strategy posits that the maps' primary long-run impact was not through capital allocation nor other major neighborhood development forces associated with $PM_{2.5}$ emissions, but through the durable codification of segregationist norms, which were then institutionalized in local policies like zoning. This provides a strong basis for the instrument's relevance while lending credibility to the exclusion restriction, given the nearly one-century gap and the focus on hyperlocal variation at the boundaries.

Our historical controls further bolster the exclusion restriction by blocking the relevant "persistence channel" formalized by Casey and Klemp (2021). As they demonstrate, historical instruments often influence modern outcomes through serial correlation in local characteristics rather than the treatment alone. By conditioning on historical urban build-up intensity—the primary vector for such persistence—we absorb much of the persistent variation in density and industrial geography that both plausibly influenced HOLC grading and modern $PM_{2.5}$ levels directly. In other words, our estimates rely on a conditional exclusion restriction by comparing polygons that were similar in their pre-period built and industrial environments, thereby reducing concerns that the instrument is proxying for long-standing industrial corridors or dense downtown cores rather than the redlining-induced evolution of zoning codes (Imbens and Wooldridge (2009)). This design ensures that our instrument captures the regulatory shock of zoning rather than the inertia of long-standing industrial geography.

4.3 Mechanism: Proximity to Pollution Sources

Our primary hypothesis for why multi-family zones would exhibit higher pollution levels is their systematic co-location with pollution-generating land uses. Historically, zoning has been used to link population density with neighborhood composition (Monarrez and Schönholzer (2023); Sahn (2025); Shertzer et al. (2016)). Following similar insights from literature (Shertzer et al. (2018); Zirogiannis et al. (2023)), we propose that a key mechanism in our setting is the spatial sorting of residential zones relative to major pollution sources—in this case, the commercial and industrial zones (CIs). These non-residential zones often increase local traffic, concentrate combustion-intensive activities, and serve as employment hubs that attract residents to denser housing corridors, jointly raising steady-state $PM_{2.5}$ exposure.

To test this mechanism, we follow Shertzer et al. (2018) by estimating a linear probability model that examines whether multi-family zones are more likely to be located near CIs. As in that study, this part of the analysis is best interpreted as descriptive evidence, rather than a robust causal estimate. In particular, it gauges whether pollution-generating CIs are more likely to cluster near multi-family zones. We specify the following model:

$$\text{ProxCI}_{ic} = \gamma_0 + \gamma_1 \text{ZoneType}_{ic} + \delta_c + \omega_{ic} \tag{4}$$

where the dependent variable, ProxCI_{ic}, is a measure of the polygon's proximity to major pollution sources: 1) distance to the closest freeway, 2) an indicator for being immediately adjacent to at least one CI within a $3km$ radius, and 3) share of adjacent zones ($< 3km$) that are CIs. The primary variable of interest, ZoneType_{ic}, is an indicator for a specific zoning designation in polygon i and city c. A positive and significant estimate for γ_1 would provide evidence consistent with our proposed spatial sorting mechanism.

5 Results

We first present the OLS estimates of Equation (1) in Table 4. Column (1) shows a correlation that yields a counterintuitive negative coefficient. After including city fixed effects (δ_c) in Column (2), the coefficient for MultiFamily flips to positive. While this aligns with our hypothesis, the magnitude is small, and the estimate is almost certainly biased by unobserved variables that jointly determine zoning and pollution. The instability of these estimates across specifications highlights the severe omitted variable bias discussed in Section 4.1, confirming that OLS is insufficient for estimating the causal effect.

The validity of our IV strategy hinges on the relevance of the historical HOLC grades in predicting modern zoning. The first-stage results, corresponding to Equation (2), are displayed in Table 2. These regressions confirm a strong relationship between the historical HOLC instruments ($\mathbf{Z}_{ic}$) and contemporary multi-family zoning. In Column (1), a one-unit increase in the HOLC grade score (i.e., from Grade D to C) is associated with a 13.0 percentage point decrease in the probability that a polygon is zoned for multi-family use. In Column (2), the indicator specification reveals a clear gradient across grades: relative to the omitted category, Grade A and Grade B areas are substantially less likely to permit multi-family housing (-28.1 and -19.1 percentage points, respectively), while the Grade C coefficient is small and statistically indistinguishable from zero. Finally, Column (3) shows that within the marginal sample of B/C/D areas, historically Grade D polygons are 17.0 percentage points more likely to be zoned for multi-family use today. Together, these patterns demonstrate the relevance of HOLC grades for modern zoning status.

The strong first-stage relationship between HOLC grades and multi-family zoning is robust to the inclusion of the historical controls. When we add the HISDAC and Census of Manufactures controls to Equation (2), the coefficients on the HOLC instruments are almost unchanged and the first-stage F-statistics remain well above conventional thresholds, exceeding 2,000 in all cases. This pattern indicates that historical HOLC grades predict modern multi-family zoning even after conditioning on fine-grained measures of pre-HOLC development and early manufacturing intensity, consistent with our interpretation of the maps as codifying a durable zoning heuristic rather than merely tracing pre-existing industrial corridors.

Table 4 presents the 2SLS estimates of β_1 from Equation (3). In our preferred specification (Column (4)), which uses the full set of HOLC grade indicators as instruments and includes city fixed effects and demographic controls, we find that a multi-family zoning designation causally increases a polygon's annual average $PM_{2.5}$ concentration by around 1.1 $\mu g/m^3$. This estimate is statistically significant and nearly 20 times larger than the OLS estimate from Column (2), suggesting a strong downward bias in the naive regression. This result is robust across our alternative instrument specifications. As shown in Columns (5) and (6), using the linear HOLC score or the binary "Desirable" indicator as the instrument yields similar and statistically significant point estimates. The stability of the coefficient provides strong confidence in our central finding.

Augmenting the second stage with the historical HISDAC and Census of Manufactures controls and clustering standard errors at the city level yields a modest but informative change in the estimated effect of multi-family zoning on $PM_{2.5}$ (Table 4). Relative to our baseline estimate in Column (4) of Table 3 (1.1 $\mu g/m^3$), the coefficient remains economically meaningful but declines as we add successively richer historical controls: the estimate falls from 0.9 $\mu g/m^3$ with demographic controls only to 0.7 $\mu g/m^3$ in our most demanding specification, an attenuation of roughly 13% to 33%. Across specifications, the implied effect ranges from 0.7 to 1.2 $\mu g/m^3$ (about 7%–12% of the sample mean). City-level clustering substantially increases uncertainty relative to the baseline, but the estimates remain statistically distinguishable from zero. We interpret this pattern as evidence that part of the raw HOLC-to-pollution relationship reflects persistent differences in historical built-up and industrial intensity, which the added controls now absorb. The remaining variation, which we exploit for identification, is more plausibly tied to the redlining-induced evolution of local land-use regulation. Substantively, however, the message is unchanged: even after conditioning on these historical baselines, multi-family zoning continues to have a quantitatively important causal effect on neighborhood air quality.

As a further robustness check, we probe the sensitivity of our findings within progressively narrower "marginal" samples and alternative instrument definitions. First, Table 5 restricts the sample to historically C and D graded neighborhoods and uses the Grade D indicator as the instrument, thereby comparing parcels that HOLC already deemed substandard and limiting contrasts with more "desirable" areas. In this subset, the estimated effect of multi-family zoning remains sizable across specifications, ranging from 1.2 to 1.6 $\mu g/m^3$, and remains statistically significant through Column (4). In the most demanding specification that additionally controls for the historical road network (Column (5)), the point estimate is similar in magnitude (1.4 $\mu g/m^3$) but becomes imprecisely estimated, consistent with reduced power in the restricted sample rather than a qualitatively different effect.

Two additional robustness tables extend this exercise to slightly broader marginal definitions and alternative instrument sets. Table 6 expands the marginal sample to B/C/D neighborhoods while continuing to instrument multi-family zoning with the Grade D indicator; the estimated effect remains stable, between 1.0 and 1.4 $\mu g/m^3$, and is statistically significant across all specifications. Table 7 instead instruments with two indicators (i.e., one for Grade B and C), shifting identifying variation to differences between "better" (B/C) and "worse" (D) neighborhoods within the same B/C/D sample. The resulting estimates are a bit smaller but still economically meaningful and statistically significant, ranging from 0.7 to 1.1 $\mu g/m^3$. Taken together, these robustness checks show that our central conclusion does not hinge on comparisons involving the full HOLC grading range or on a single instrument construction. Across multiple marginal samples and instrument definitions, multi-family zoning is consistently associated with higher contemporary $PM_{2.5}$ exposure.

Table 8 provides strong support for our proposed spatial sorting mechanism specified in Equation (4). We find a clear and statistically significant pattern of land-use co-location. The coefficients in Column (1) are negative, indicating that single-family residential zones are systematically located further away from commercial and industrial (CI) zones. Conversely, the positive coefficients in Column (2) show that multi-family residential zones are significantly more likely to be adjacent to these pollution-generating areas. This evidence is consistent with exisiting findings where historical development patterns have sorted denser housing into corridors with greater proximity to commercial activity and its associated pollution (Shertzer et al. (2016, 2018)).

6 Conclusion

This paper establishes a causal link between the discriminatory housing policies of the 1930s and present-day environmental inequality. We show that the historical practice of redlining did not merely leave a legacy of disinvestment but also fundamentally shaped the subsequent regulatory landscape. By utilizing historical HOLC maps as an instrument, we demonstrate that modern zoning ordinances, a widely used planning tool mostly associated with debates around urban density, have become a primary institutional channel through which the intent of redlining was preserved and translated into the disproportionate siting of pollution in marginalized communities. Our design conditions not only on contemporary demographics but also on detailed measures of the pre-HOLC built environment and early manufacturing activity, strengthening the case that the variation we exploit reflects the long-run regulatory imprint of redlining rather than persistent industrial geography.

The magnitude of this effect is not only statistically significant but also economically large. Our preferred 2SLS estimate indicates that a multi-family zoning designation causally increases annual $PM_{2.5}$ concentrations by 0.7 $\mu g/m^3$, an increase of approximately 7 percent relative to the sample mean. To place this in context, we compare our estimate to the effects of the Clean Air Act. Currie et al. (2023) estimate that $PM_{2.5}$ levels fell by roughly 1.2 $\mu g/m^3$ in nonattainment counties after the 2005 $PM_{2.5}$ standard, and more generally conclude that the CAA explains over 60% of the Black–White convergence in exposure since 2000. Novel high-resolution estimates by Sager and Singer (2025) imply a more conservative 0.4 $\mu g/m^3$ reduction over five years—placing our zoning LATE between 0.6× and 1.8× the effect of a representative federal emission reduction policy. Taken together, these comparisons suggest that land-use decisions at neighborhood margins are a major obstacle to achieving healthy levels of clean air in the United States.

The pollutant we study is a primary driver of negative health outcomes, reduced labor productivity, and lower lifetime earnings. Our finding that zoning creates meaningful, localized differences in $PM_{2.5}$ concentrations means that these land-use policies are actively contributing to disparities in human capital and economic mobility. Thus, the pollution exposure gaps we document are not merely statistical artifacts but represent significant welfare losses that are disproportionately borne by residents in historically disadvantaged neighborhoods. For instance, Deryugina et al. (2019) find that a 1 $\mu g/m^3$ increase in daily $PM_{2.5}$ exposure raises elderly mortality by 0.69 per million over the subsequent three days.

Our results also contribute directly to the literature on the long-term consequences of historical institutions by illustrating a clear case of path dependence. Our analysis shows how a quasi-formal historical institution—the HOLC maps—can become embedded in the formal, durable legal framework of a city. This demonstrates that historical events do not exist in a vacuum; rather, they can durably alter development paths by shaping the very rules and regulations that govern modern economic life.

The policy implication of this research is direct. As cities across the United States grapple with severe housing shortages, many are considering reforms to restrictive single-family zoning. Our findings caution that blind support for density, while potentially beneficial for housing affordability (Liao (2024); Rollet (2025)), could result in introducing dis-amenities that are not distributionally neutral (Duranton and Puga (2020); Freemark (2023)). Heightened exposure to $PM_{2.5}$ has been shown to degrade labor productivity and mental stability (Chang et al. (2016); Herrnstadt et al. (2021)), which are signs of a community that attracts discussions of re-development. Simply allowing for greater density in historically redlined areas, without corresponding investments in pollution abatement and green infrastructure, risks reinforcing the very environmental disparities these neighborhoods have endured for generations. Our findings suggest that housing policy and environmental policy are not separate domains but are deeply intertwined—addressing one without considering the other may result in a suboptimal outcome, especially when upzoning overlaps with heavy traffic or commercial and industrial activity

Lastly, our analysis opens several avenues for future research. While we focus on a key pollutant, the institutional channel we identify likely affects a wider array of socioeconomic and environmental outcomes, such as urban inequality, flood risk, and access to green space (Weiwu (2024)). Furthermore, the quasi-experimental variation provided by HOLC boundaries could be used to explore how zoning has impacted other measures of well-being, from health outcomes to intergenerational mobility. By illuminating the critical role of local land-use law, this study underscores that the architecture of persistent inequality in air pollution is built upon historical foundations, and that dismantling it requires not only addressing present-day symptoms but also reversing the damages coming from foundational institutions themselves.

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A Appendix Figures and Tables

Figure 1: Map of Cities Included in the Analysis

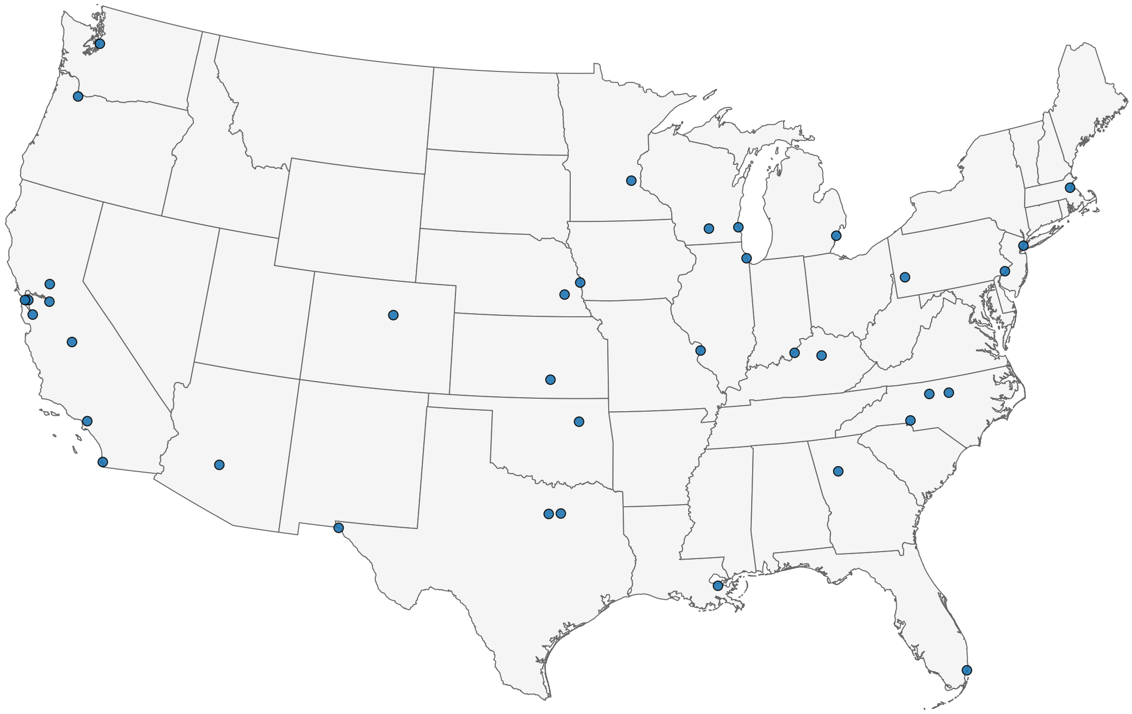


Figure 2: HOLC grades in Madison, WI

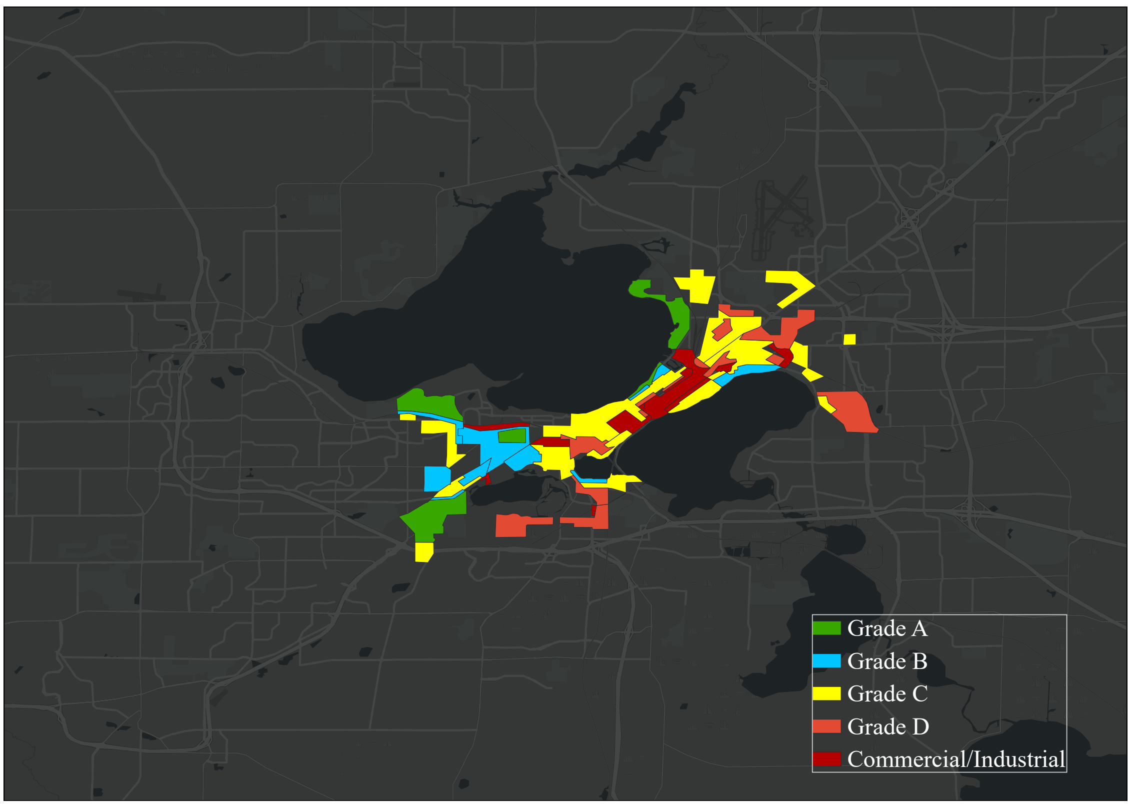


Figure 3: Zoning Ordinances in Madison, WI

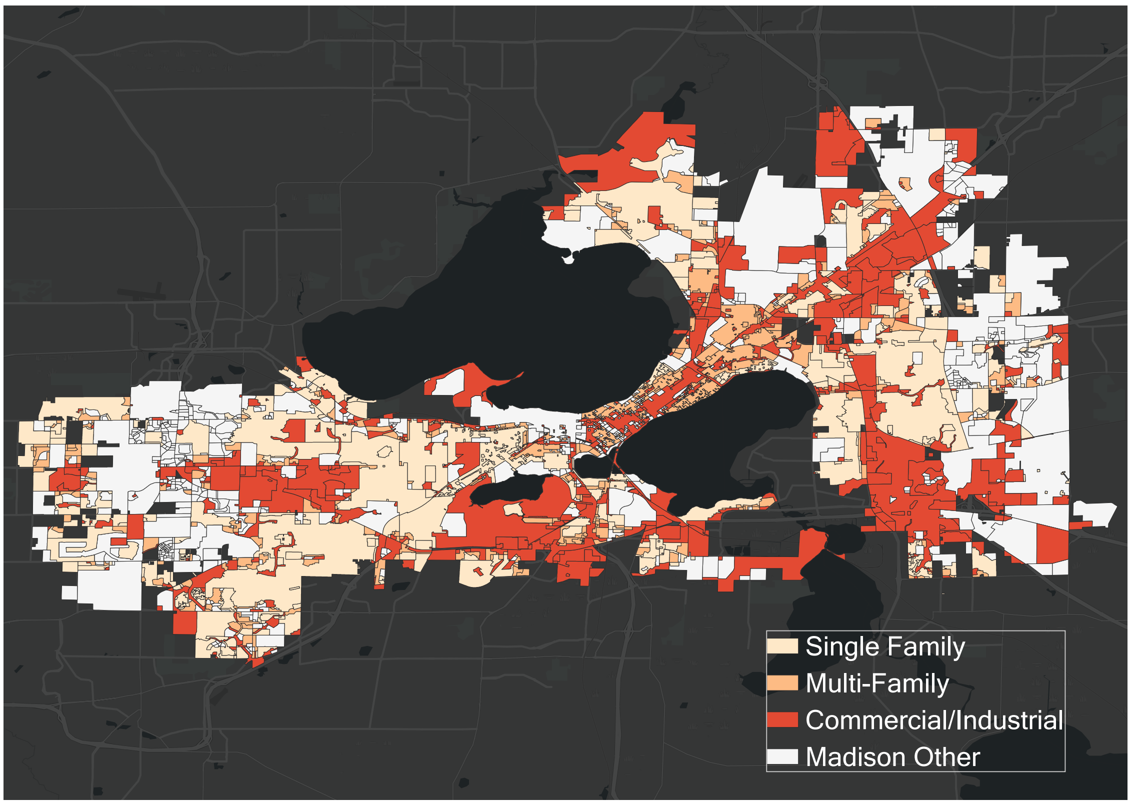
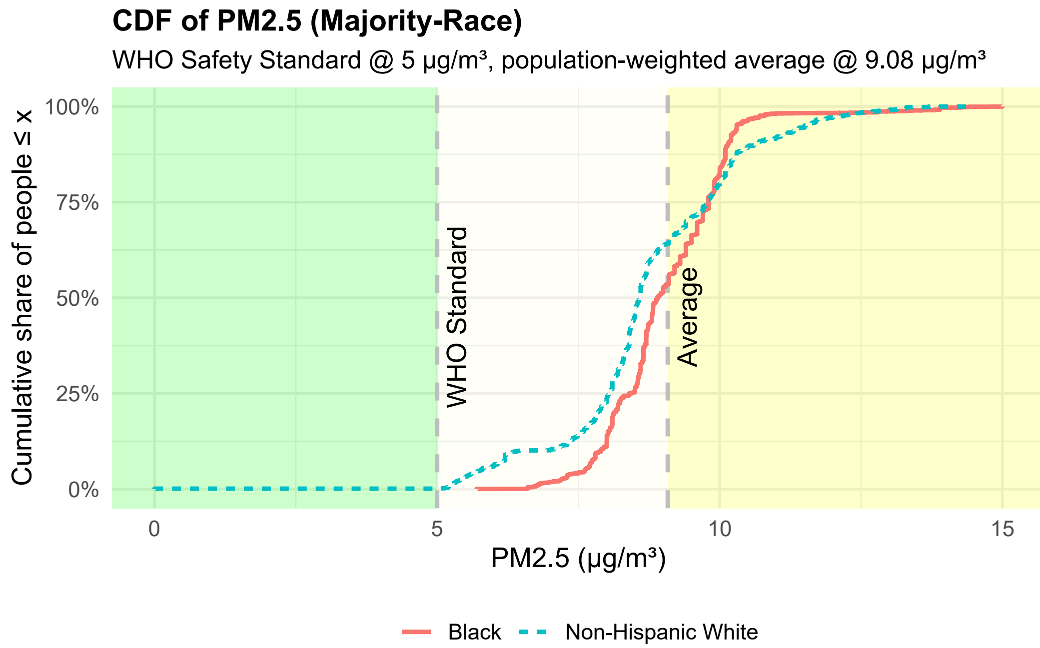
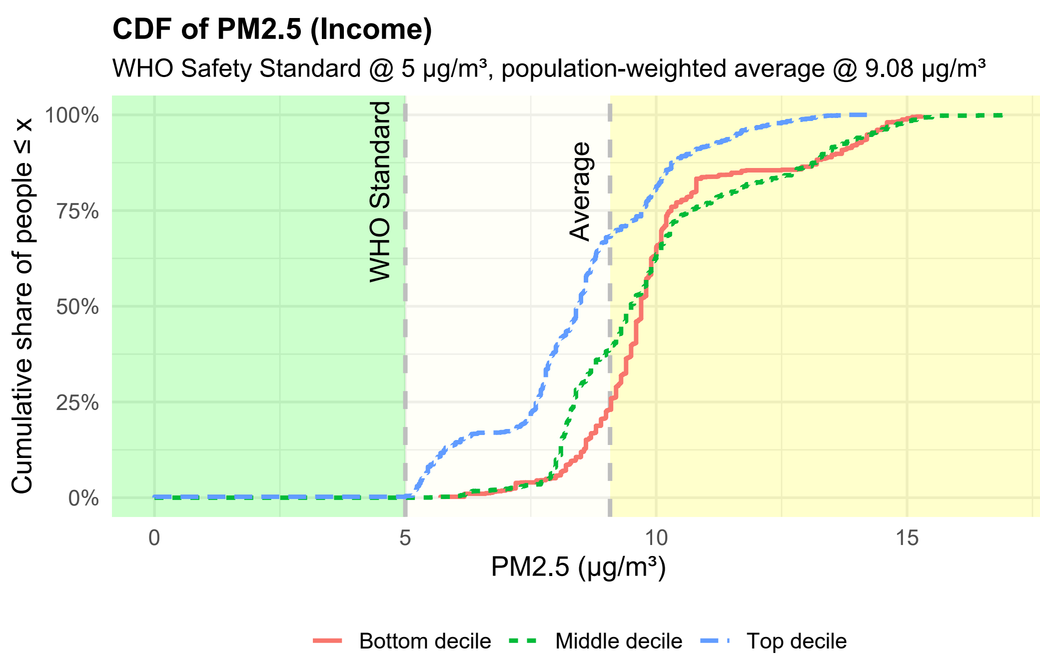


Figure 4: Cumulative Distribution of Pollution Exposure



(a) By Racial Share



(b) By Income Decile

Notes: The figure plots the cumulative distribution functions (CDFs) of population-weighted $PM_{2.5}$ exposure at the polygon level. Panel A stratifies the sample by majority race/ethnicity, comparing polygons with a non-Hispanic White majority (share > 50%) to those with a minority majority. Panel B stratifies the sample by polygon-level median household income decile. In both panels, the distribution for the disadvantaged group (Minority or Lowest Income) is shifted to the right, indicating first-order stochastic dominance in pollution exposure.

Table 1: Summary Statistics by HOLC Grade

Variable	**Grade A**		**Grade B**		**Grade C**		**Grade D**		**Whole Sample**	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Variables of Interest										
PM2.5 ($\mu g/m^3$)	9.40	1.65	9.83	1.90	10.24	2.11	10.02	1.74	10.06	1.98
Multi-family Zoning Share	0.13	0.33	0.22	0.42	0.37	0.48	0.51	0.50	0.37	0.48
Neighborhood Characteristics										
Median HH Income ($)	124,628	70,010	91,863	55,905	68,050	42,210	64,913	38,947	75,841	49,409
Non-Hispanic White Share	0.62	0.29	0.45	0.31	0.31	0.29	0.30	0.28	0.35	0.30
Black Share	0.21	0.30	0.27	0.34	0.34	0.36	0.32	0.33	0.31	0.35
Renter Share	0.30	0.22	0.40	0.23	0.52	0.24	0.59	0.22	0.50	0.25
Bachelor+ Share	0.60	0.27	0.43	0.28	0.31	0.27	0.30	0.26	0.35	0.28
Unemployment Share	0.05	0.06	0.07	0.08	0.08	0.09	0.08	0.09	0.08	0.08
Area (m^2)	14,703	98,983	9,736	64,073	7,172	56,497	7,386	58,017	8,150	60,992
Total Population	52	340	62	567	56	561	64	665	60	581
Historical Built Environment										
Built-up Records	3.89	34.78	6.25	71.31	5.57	58.70	5.23	43.59	5.47	56.49
Floor Area (m^2)	644	6,054	852	8,062	716	6,667	667	5,725	721	6,689
Manuf. Count	0.01	0.33	0.00	0.54	0.00	0.42	0.01	0.42	0.00	0.44
Manuf. Output ($)	630	39,327	3,437	406,029	1,975	369,664	5,059	412,070	3,210	378,011
Observations	16,678 (5%)		62,028 (20%)		147,919 (47%)		77,816 (25%)		311,906	

Notes: The table reports the means and standard deviations for neighborhood characteristics of individual land polygons from the following data sources: 2021–2023 satellite-derived $PM_{2.5}$ concentrations (Shen et al. (2024)), the American Community Survey (2024), contemporary municipal zoning maps, and historical data from the 1930 HISDAC (Ahn et al. (2024)) and $1929-1935$ Census of Manufactures. The unit of analysis is the land polygon created by the intersection of historical HOLC maps (Nelson et al. (2023)) and 2024 municipal zoning boundaries. Pollution exposure is calculated as the mean annual concentration within each polygon. Multi-family zoning is an indicator variable equal to one if the polygon's contemporary zoning designation permits multi-family residential use. Demographic characteristics are spatially interpolated to the polygon level using block-group data from the ACS; racial share is defined as the percentage of the population. Historical structure and manufacturing estimates are derived from gridded settlement data representing the unique built-up environment circa 1935. The sample includes all polygons within the 39 cities in our analysis sample for which complete zoning and historical data are available.

Table 2: First-stage Results

	Multi-family Zoning		
	(1)	(2)	(3)
HOLC Grades	-0.130^{**}		
	(0.059)		
Grade A		-0.281^{***}	
		(0.041)	
Grade B		-0.191^{***}	
		(0.048)	
Grade C		-0.031	
		(0.071)	
Grade D		0.091	0.170^{**}
		(0.127)	(0.083)
City FE	Yes	Yes	Yes
Observations	311,906	311,906	287,763
Sample	All	All	B,C,D

Notes: City-level clustered standard errors are in parentheses.
***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

Table 3: Regression Results: OLS vs 2SLS

	Annual $PM_{2.5}$ Level					
	OLS	OLS	2SLS	2SLS	2SLS	2SLS
	(1)	(2)	(3)	(4)	(5)	(6)
Multi-family Zoning	-0.857^{***}	0.053^{***}	1.167^{***}	1.077^{***}	1.261^{***}	1.565^{***}
	(0.007)	(0.002)	(0.035)	(0.019)	(0.023)	(0.037)
Mean $PM_{2.5}$	10.05	10.05	10.05	10.05	10.05	10.05
City FE	No	Yes	No	Yes	Yes	Yes
Census Controls	No	Yes	No	Yes	Yes	Yes
F-stat			4,447	1,714	5,716	2,812
Observations	312,697	272,908	312,697	272,908	272,908	272,908

Notes: The instrument set for columns (3)-(4) is a full set of HOLC grade indicators. Column (5) uses the linear HOLC score as the instrument. Column (6) uses the binary "Desirable" indicator.
***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

Table 4: Effect of Multi-Family Zoning on PM2.5

	Annual $PM_{2.5}$ Level				
	(1)	(2)	(3)	(4)	(5)
Multi-Family Zoned	1.153**	0.936**	0.830**	0.788**	0.722**
	(0.547)	(0.394)	(0.364)	(0.337)	(0.298)
City FE	Yes	Yes	Yes	Yes	Yes
Demographics	No	Yes	Yes	Yes	Yes
Historical Nuisances	No	No	Yes	Yes	Yes
Historical Built Environment	No	No	No	Yes	Yes
Historical Road Network	No	No	No	No	Yes
Kleibergen-Paap rk Wald F	5.0	6.6	8.9	9.9	9.4
Cragg-Donald F	19428	11796	10339	8126	7312
Observations	311906	272908	253387	253387	253387
Instrument	Grades	Grades	Grades	Grades	Grades

Notes: City-level clustered standard errors are in parentheses.
***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

Table 5: Effect of Multi-Family Zoning on PM2.5 – Marginal HOLC Areas

	Annual $PM_{2.5}$ Level				
	(1)	(2)	(3)	(4)	(5)
Multi-Family Zoned	1.626*	1.212*	1.388*	1.406*	1.367
	(0.847)	(0.730)	(0.816)	(0.858)	(0.936)
City FE	Yes	Yes	Yes	Yes	Yes
Demographics	No	Yes	Yes	Yes	Yes
Historical Nuisances	No	No	Yes	Yes	Yes
Historical Built Environment	No	No	No	Yes	Yes
Historical Road Network	No	No	No	No	Yes
Kleibergen-Paap rk Wald F	3.9	6.7	13.7	10.5	7.8
Cragg-Donald F	3971	2582	995	1146	846
Observations	225735	194190	189251	189251	189251
Sample	C, D	C, D	C, D	C, D	C, D
Instrument	Grade D	Grade D	Grade D	Grade D	Grade D

Notes: City-level clustered standard errors are in parentheses.
***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

Table 6: Effect of Multi-Family Zoning on PM2.5 – Marginal HOLC Areas

	Annual $PM_{2.5}$ Level				
	(1)	(2)	(3)	(4)	(5)
Multi-Family Zoned	1.358**	1.043*	1.057*	1.099*	1.018*
	(0.690)	(0.586)	(0.607)	(0.639)	(0.620)
City FE	Yes	Yes	Yes	Yes	Yes
Demographics	No	Yes	Yes	Yes	Yes
Historical Nuisances	No	No	Yes	Yes	Yes
Historical Built Environment	No	No	No	Yes	Yes
Historical Road Network	No	No	No	No	Yes
Kleibergen-Paap rk Wald F	4.2	6.5	10.3	9.6	9.7
Cragg-Donald F	8,584	5,654	3,697	3,399	2,881
Observations	287,763	250,722	240,266	240,266	240,266
Sample	B, C, D	B, C, D	B, C, D	B, C, D	B, C, D
Instrument	Grade D	Grade D	Grade D	Grade D	Grade D

Notes: City-level clustered standard errors are in parentheses.
***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

Table 7: Effect of Multi-Family Zoning on PM2.5 – Marginal HOLC Areas

	Annual $PM_{2.5}$ Level				
	(1)	(2)	(3)	(4)	(5)
Multi-Family Zoned	1.120*	0.862*	0.765*	0.772*	0.685*
	(0.637)	(0.451)	(0.442)	(0.459)	(0.395)
City FE	Yes	Yes	Yes	Yes	Yes
Demographics	No	Yes	Yes	Yes	Yes
Historical Nuisances	No	No	Yes	Yes	Yes
Historical Built Environment	No	No	No	Yes	Yes
Historical Road Network	No	No	No	No	Yes
Kleibergen-Paap rk Wald F	4.0	5.0	11.1	8.3	6.8
Cragg-Donald F	7,300	4,758	3,973	3,504	3,211
Observations	287,763	250,722	240,266	240,266	240,266
Sample	B, C, D	B, C, D	B, C, D	B, C, D	B, C, D
Instruments	Grade B+C	Grade B+C	Grade B+C	Grade B+C	Grade B+C

Notes: City-level clustered standard errors are in parentheses.
***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

Table 8: Mechanism Results

	Residential-Single (1)	Residential-Multi (2)	Commercial/Industrial (3)
Commercial/Industrial	−0.167***	0.060***	0.084***
	(0.007)	(0.002)	(0.005)
# of Commercial/Industrial	−0.104***	0.035***	0.053***
	(0.010)	(0.004)	(0.003)
City FE	Yes	Yes	Yes
Observations	312,697	312,697	312,697

Notes: City-level clustered standard errors are in parentheses.
***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.