Zoning and Neighborhood Air Quality: Evidence from HOLC Boundaries*

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May 3, 2026

Preliminary draft. Please do not cite without permission.
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Abstract

Does exclusionary zoning contribute to environmental inequality? We examine how municipal residential zoning relates to local air pollution exposure across 39 major U.S. cities. As zoning is endogenous to neighborhood amenities, we instrument for present-day zoning status using historical Home Owners' Loan Corporation redlining boundaries. To separate the regulatory legacy of redlining from pre-existing neighborhood characteristics captured by the HOLC maps, we control extensively for pre-period manufacturing activity, transportation networks, and other historical proxies for local pollution sources. The first stage is strong and monotonic: areas assigned lower historical grades are more likely to permit multi-family housing today. Our preferred 2SLS estimates indicate that areas permitting multi-family housing experience about 1.2 $\mu g/m^3$ higher annual $PM_{2.5}$ exposure (13% of the sample mean). These estimates reflect long-run equilibrium differences in exposure across zoning regimes shaped by historical redlining, rather than the short-run effect of rezoning a particular neighborhood.

JEL Codes: I14, N92, Q53, R31

*For helpful comments and discussions, we would like to thank Spencer Banzhaf, Robert French, Dustin Frye, Rhiannon Jerch, Daniel Phaneuf, Christopher Timmins, and seminar participants at CESifo, MEA Annual Meeting, Tsukuba University, University of Wisconsin-Madison. We gratefully acknowledge financial support from the Wisconsin Alumni Research Foundation.

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1 Introduction

Disparities in exposure to environmental hazards across racial and socioeconomic groups are well documented. Residents of minority and low-income communities experience systematically higher levels of air pollution, which has direct and indirect consequences for health, human capital, and economic mobility (Bailey et al., 2017; Chay and Greenstone, 2005; Currie, 2011; Gillingham and Huang, 2024; Isen et al., 2017). While recent environmental policies have reduced pollution significantly, the gaps between groups persist (Colmer et al., 2020, 2024; Currie et al., 2023; Jbaily et al., 2022). Recent papers point to mechanisms such as income-based sorting, discriminatory steering, and the siting of polluting facilities (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). Less is known about the role of local institutions in shaping how pollution exposure is distributed across residents.

This paper focuses on one such institution: municipal zoning. We ask whether contemporary zoning affects environmental inequality. We focus on one prominent form of exclusionary zoning: single-family zoning. In many cities, single-family zoning is paired with occupancy rules that restrict unrelated cohabitation, which can raise the effective cost of renting (e.g., by limiting roommate arrangements) and exclude lower-income households even when the housing stock remains unchanged. This feature matters for sorting: even renters who value clean air may be priced out of high-amenity neighborhoods when their feasible choice set is limited to apartments or legally constrained roommate arrangements.

Rather than isolating the short-run effect of a marginal zoning change, we focus on how zoning regimes are associated with long-run differences in pollution exposure. This equilibrium interpretation follows directly from the data environment: constructing harmonized parcel-scale zoning data is feasible for a contemporary cross-section, whereas building a historical zoning panel would be a quixotic mission requiring the recovery, digitization, and harmonization of archived ordinances and maps from each locality. Multi-family areas may exhibit higher pollution levels through a combination of channels, including higher density and proximity to commercial and industrial land uses, which we test explicitly. In this land-use configuration, restrictive zoning may buffer single-family neighborhoods from industrial activity while concentrating denser residential development near more polluted commercial and industrial corridors. The central empirical challenge is that zoning is endogenous: the same unobserved economic and political forces that determine whether an area is zoned for single-family or multi-family use—including resident income, political capital, and proximity to industry—are also correlated with pollution.

To address this endogeneity, we use an instrumental variables strategy based on the historical "Residential Security Maps" ("redlining maps") created by the Home Owners' Loan Corporation (HOLC) in the 1930s. HOLC graded neighborhoods on a four-tier scale from "A" (Best) to "D" (Hazardous). A growing literature shows that these maps had persistent effects on segregation, human capital accumulation, and housing investment (Aaronson et al., 2021, 2023; Fishback et al., 2023, 2024). Our identifying assumption is that HOLC boundaries shifted the long-run trajectory of land-use regulation, but do not directly determine pollution today except through zoning. Recent evidence suggests that the maps had limited direct effects on mortgage lending at the time (Fishback et al., 2023, 2024). We interpret this as consistent with a different long-run legacy: HOLC grades and boundaries provided a durable, discriminatory heuristic that became embedded in local land-use law. In our setting, the key variation comes from the quasi-arbitrary boundaries drawn by HOLC appraisers, which generate discontinuities in the long-run probability that adjacent parcels are zoned for less restrictive uses, including multi-family housing.

We implement this design using a newly constructed dataset that merges historical HOLC maps and urban built-environment records with 2024 zoning ordinances and high-resolution satellite measurements of fine particulate matter ($PM_{2.5}$) for 39 of the largest U.S. cities (Figure A1). The unit of analysis is a small land polygon with a uniform HOLC grade and a uniform contemporary zoning designation. This spatial resolution allows us to compare parcels on opposite sides of an HOLC boundary within the same city and neighborhood environment.

We document four results. First, we show that HOLC grades are strongly predictive of contemporary land use: relative to Grade D areas, historically higher-graded polygons are more likely to be zoned residential today and less likely to be zoned commercial or industrial. Second, when we condition on current residential areas, we find a strong first-stage effect: lower HOLC grades substantially increase the probability that a parcel permits multi-family housing today. Third, our 2SLS estimates indicate large differences in residents' pollution exposure across areas with different zoning regimes. In our preferred full-sample specification, which uses the linear HOLC grade score ("Grades") as the instrument, areas permitting multi-family housing exhibit annual $PM_{2.5}$ exposure that is about 1.2 $\mu g/m^3$ higher. Alternative full-sample specifications using HOLC grade indicators yield similarly positive and statistically significant effects, while the estimates are larger still in the more comparable B/C/D and C/D samples. Finally, our results are robust to the inclusion of a rich set of controls, including contemporary demographics and detailed historical measures of the built environment, manufacturing activity, transportation networks, and the presence of environmental hazards in the HOLC descriptions. Together, these findings suggest that zoning is an important institutional channel through which historical discrimination is linked to present-day exposure to pollution.

We contribute to three distinct literatures. First, we provide a novel institutional mechanism for the environmental justice literature. Zoning structurally anchors pollution exposure to specific places, validating recent findings that geography, rather than demographics *per se*, drives exposure gaps (Colmer et al., 2020; Currie et al., 2023; Heblich et al., 2021; Lyubich, 2025). Second, we contribute to the literature on the long-run consequences of historical institutions (Nunn, 2009; Favilukis and Song, 2023) by tracing a highly specific administrative pathway: HOLC maps affect modern welfare primarily by durably shaping local land-use laws. Third, we contribute to urban and public economics research on restrictive land-use regulation. While classic work emphasizes effects on housing market equilibria (Duranton and Puga, 2023; Fischel, 1978; Glaeser et al., 2005; Hsieh and Moretti, 2019; Pollakowski and Wachter, 1990; Rollet, 2025; Song, 2025) and more recent work links zoning to segregation (Kulkarni and Malmendier, 2022; Monarrez and Schönholzer, 2023; Rothwell and Massey, 2010; Sahn, 2025; Shertzer et al., 2016, 2022), we show that zoning is strongly associated with differences in environmental pollution exposure. This suggests that zoning reform is not only a housing policy lever, but also a potentially important instrument for 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: HOLC and the Evolution of Zoning

To interpret the relationship between zoning and pollution in modern U.S. cities, it is useful to situate our setting in the history of two major twentieth-century institutions: the federal practice of "redlining" and the local adoption of zoning. This section briefly reviews each and clarifies why the HOLC maps provide plausibly exogenous variation in contemporary land-use regulations.

2.1 Redlining and Identification

HOLC was created in 1933 as part of the New Deal to stabilize the housing market by refinancing mortgages in default (Hillier, 2005; Jackson, 1987). Between 1935 and 1940, HOLC produced "Residential Security Maps" for over 200 U.S. cities to standardize the assessment of mortgage lending risk in its existing portfolio (Michney, 2022). Neighborhoods were graded into four categories: "A" (Best, green), "B" (Still Desirable, blue), "C" (Definitely Declining, yellow), and "D" (Hazardous, red) (e.g., Panel 1a).

Although these grades were ostensibly based on housing quality, sales activity, and other economic indicators, the accompanying area descriptions make clear that racial and ethnic composition was often central to the assessment. Neighborhoods with even small minority populations–particularly Black residents and immigrant communities–were systematically graded "D," with little weight given to other factors. This practice became known as "redlining."

The HOLC records illustrate the explicit nature of this discrimination. For example, in Madison, Wisconsin, 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. In the nearby Area D3, the list of "Detrimental Influences" begins with a single word: "Negroes," followed only by "Proximity to business section." These records underscore that racial and ethnic composition was not merely correlated with HOLC grades; it was frequently the stated basis for the appraisal.

Despite their prominence in contemporary discussions, the HOLC maps were not originally intended as a blueprint for future development or mortgage lending policy. Their stated purpose was 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 was limited to HOLC staff, and the maps reflected appraisal norms that were already widespread among real estate professionals (Harriss, 1951; Hillier, 2003a,b). Consistent with this limited scope, recent empirical work finds that the direct causal effect of HOLC maps on the subsequent geography of mortgage lending was relatively small (Hillier, 2003a; Fishback et al., 2023, 2024). This context is important for our identification strategy: if the maps had only limited direct influence on capital investment and lending, then the boundaries themselves are less likely to proxy for other unobserved historical shocks that independently determine modern pollution.

At the same time, limited direct effects on lending do not imply that the HOLC maps were inconsequential. Some argue that the maps codified and legitimized discriminatory appraisal practices and helped diffuse them through both public and private real estate institutions (Woods, 2012). In this way, the maps could shape subsequent urban policy (e.g., zoning) and private practices (e.g., restrictive covenants), even if the direct lending channel was weak (Jones-Correa, 2000). A large literature documents persistent consequences of redlining for segregation and intergenerational mobility, with evidence that these effects attenuate after reforms to federal lending policy beginning in 1968 (Aaronson et al., 2021, 2023; Faber, 2020; Glaeser and Vigdor, 2012). Our study builds on this work by focusing on a distinct mechanism: the role of HOLC assessments in shaping the evolution of local land-use regulation.

2.2 Zoning Ordinances in the United States

Zoning ordinances are local government regulations that restrict how land can be used and developed. The practice emerged in the early twentieth century, and its constitutionality was affirmed by the Supreme Court in 1926 (Village of Euclid v. Ambler Realty Co., 1926). Zoning was justified as a public-health and land-use planning tool, designed to separate incompatible uses, such as keeping heavy industry away from residential areas (e.g., Panel 1b).

From the beginning, however, zoning was also used to enforce socioeconomic and racial segregation (Cui, 2024; Fischel, 2004; Rothstein, 2017; Troesken and Walsh, 2019). The most common form of land-use regulation in the United States is single-family zoning, which prohibits denser housing types such as duplexes and apartment buildings. Economists have shown that restrictive or "exclusionary" zoning restricts housing supply and increases housing prices (Glaeser et al., 2005), thereby preventing lower-income households from moving into higher income, high-amenity neighborhoods. Historical work further documents a strong relationship between early racial zoning ordinances and later segregation patterns (Cui and Been, 2025; Shertzer et al., 2016, 2018). By shaping access to local public goods and amenities–such as schools, open space, and transit–zoning can push neighborhoods toward tipping points that reinforce segregation through Tiebout sorting (Banzhaf and Walsh, 2013; De Silva et al., 2024).

While redlining and zoning were distinct legal regimes–one federal and largely informal, the other local and statutory–they evolved under overlapping objectives and often operated in parallel. Our central hypothesis is that HOLC-era neighborhood assessments contributed to the formation and persistence of restrictive zoning regimes that continue to govern these areas today. This view is consistent with historical evidence that segregative land-use frameworks are highly persistent: early zoning choices become embedded in subsequent plans, capitalized into land values, and reinforced by administrative norms that favor stability (Shertzer et al., 2016; Twinam, 2018). We build on this evidence by tracing a specific pathway from 1930s HOLC assessments to contemporary zoning stringency and, in turn, differences in neighborhood air quality. This perspective emphasizes that modern zoning patterns reflect long-run institutional persistence and spatial sorting, rather than the effects of contemporaneous policy changes in isolation.

3 Data

3.1 Land-use Regulation Data

We begin with the 77 largest U.S. cities by population in the 2020 Census. For each city, we collect digitized zoning ordinance maps in effect in 2024 from municipal government sources. Compiling comparable zoning data at this scale is difficult because: 1) zoning is highly local; 2) municipal geospatial files are often unavailable; and 3) many ordinances are accessible only through official documents or gated by parcel-query portals and commercial data providers. Our final dataset, therefore, required collecting parcel-scale zoning codes city by city, parsing each municipality's zoning ordinance rule book, and harmonizing local codes into common land-use categories. We use a flagship commercial large language model (Gemini 2.5 Pro) to assist in interpreting ordinance text and mapping zoning codes to common classifications, followed by manual review of city-specific classifications and development standards. We link these maps to the digitized HOLC "Residential

Security Maps," obtained from the University of Richmond's Digital Scholarship Lab (Nelson et al., 2023). Due to variation in zoning-map availability and completeness, our final sample includes 39 cities for which both the HOLC maps and 2024 zoning maps can be consistently assembled.

Historical HOLC areas and contemporary zoning districts rarely align. We therefore construct a spatially harmonized dataset by intersecting HOLC polygons with 2024 zoning polygons. This intersection defines the unit of analysis: a land polygon characterized by a single HOLC grade and a single contemporary zoning designation. We classify each zoning code into mutually exclusive categories–including residential, commercial, industrial, mixed-use, and other uses–and, for residential districts, code the level of permitted residential density using dimensional requirements such as minimum lot size, building height, and the set of housing types allowed by-right. Our primary zoning indicator equals one for zoning districts that permit multi-family residential structures and zero for districts restricted to single-family residential use. We restrict our attention to areas covered by the HOLC maps, trimming out newer development that was not graded in the 1930s. Because polygon intersections can generate very small edge fragments, we further drop polygons in the bottom five percent of the area distribution. The resulting dataset provides a granular link between historical HOLC assessments and present-day land-use regulation.

Our analysis also requires information on the surrounding land-use environment. For each polygon, we construct measures of adjacent zoning by recording the zoning designations of neighboring polygons. These variables allow us to characterize the local land-use mix around each parcel and to test mechanisms related to proximity to commercial and industrial zoning.

In addition to the HOLC grades themselves, we use the qualitative "area description" sheets that accompany each HOLC map. For each graded area, we extract text from several fields–including "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 the same commercial large language model, we construct three binary indicators capturing 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., smoke, odors or sewage), and (3) 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 (e.g., Panel 1c).

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, St. Louis, available at a spatial resolution of $0.01^\circ \times 0.01^\circ$ (Shen et al., 2024). We assign pollution to each polygon using the mean $PM_{2.5}$ level over $2021-2023$, which provides a contemporary measure of local air quality.

To link pollution exposure to resident characteristics, we obtain block-level demographic statistics in the year 2024 from the U.S. Census Bureau using the `tidycensus` package in R. Because census block boundaries do not align with zoning polygons, we use the `interpolate_pw` function to construct population-weighted interpolations. This procedure yields our primary demographic controls: polygon-level demographic measures, including minority population share, renter share, median household income, educational attainment, and age. We then restrict the final polygon dataset to locations with at least one resident. Polygons are not uniform in size, so in our regressions we weight by population (and, in alternative specifications, by area).

In addition to contemporary outcomes and demographics, we incorporate three sources of historical data designed to capture baseline differences in the pre-HOLC built environment and industrial geography. First, we use the Historical Settlement Data Compilation for the United States (HISDAC), which provides gridded measures of the number of unique structures and total built floor area at a $250m \times 250m$ resolution for 1930 (Ahn et al., 2024). We spatially join these pixels to our analysis polygons to construct two controls capturing the extensive margin (number of structures) and intensive margin (total floor area) of urban development.

Second, we use establishment-level transcriptions of the U.S. Census of Manufactures for $1929-1935$ (Vickers and Ziebarth, 2023). We geolocate establishments and aggregate them to a $1km \times 1km$ grid, consistent with the distance scale commonly used in hedonic work (e.g., Davis, 2011; Grislain-Letrémy and Katossky, 2014; Hanna, 2007). For a set of pollution-intensive industries, we compute in each grid cell (1) the intensive margin (total value of output) and (2) the extensive margin (number of establishments). We then spatially join these grid measures to our analysis polygons.

Third, we incorporate digitized maps of historical U.S. transportation networks, which strongly shape urban development and industrial location (Barsanetti, 2026; Duranton and Turner, 2012).

These include: (i) a shapefile of historical non-Interstate large local roads, constructed by re-aligning modern roads to match Shell Atlases from 1951 and 1956; (ii) a shapefile of planned U.S. Interstate Highways in 1947, digitized from a Public Roads Administration map (Weiwu, 2024); and (iii) a shapefile of U.S. transcontinental railroads in 1911 (Atack, 2023). From these data, we construct three distance controls: distance to the nearest large local road, distance to the nearest planned Interstate Highway, and distance to the nearest railroad.

Together with the controls constructed from HOLC area descriptions, these historical measures summarize pre-existing differences in development intensity, industrial activity, and transportation access around the time the HOLC maps were produced (e.g., Panel 1d). Conditioning on these baselines allows us to isolate the regulatory legacy of HOLC assessments from the underlying industrial geography of early twentieth-century cities.

3.3 Summary Statistics

Table 1 reports descriptive statistics for our analytical sample of 263,734 residential land polygons across the 39 cities, stratified by HOLC grade. The data exhibit a sharp socioeconomic gradient that correlates with the historical grading hierarchy. Grade A polygons have the highest contemporary socioeconomic status, with a median household income of $121,582 and a non-Hispanic White population share of 60%. In contrast, Grade D polygons have a median income of $64,215 and a White population share of 29%. Housing tenure differs sharply across grades: the renter share rises from 31% in Grade A areas to 58% in Grade D areas.

The "Variables of Interest" panel provides a descriptive preview of the first stage and exposure gradients in the residential sample. Consistent with our identifying variation, the probability of multi-family zoning rises monotonically as HOLC grades decline: only 12% of Grade A polygons are zoned for multi-family use, compared to 38% of Grade C and 51% of Grade D polygons. These zoning differences coincide with meaningful differences in pollution exposure. Population-weighted $PM_{2.5}$ exposure is lowest in Grade A and B areas (8.96 $\mu g/m^3$ and 8.80 $\mu g/m^3$), and rises further in Grade C and D areas (9.09 $\mu g/m^3$ and 9.27 $\mu g/m^3$). Figure A2 further illustrates these disparities. Panel A2a shows that the pollution distribution for non-white majority neighborhoods first-order stochastically dominates that of white majority neighborhoods. Panel A2b shows a similar pattern by income.

Finally, the "Historical Built Environment" panel highlights the importance of conditioning on pre-existing industrial geography. Grade D polygons historically contained substantially higher manufacturing intensity, with average 1935 manufacturing output of $5,059 per polygon compared to $630 in Grade A polygons (in 1935 U.S. dollars). These controls allow us to separate the long-run regulatory legacy of HOLC assessments from the persistence of early industrial location.

4 Empirical Framework

Our empirical analysis proceeds in two steps. First, using the full polygon sample, we descriptively examine how HOLC grades and the historical land-use proxies captured in our data are associated with contemporary zoning categories. Second, our main IV analysis restricts attention to residential land polygons and estimates how residential zoning regimes differ in the localized pollution exposure borne by residents. The unit of analysis in the main specifications is a residential land polygon i in city c. The outcome, $\text{PM}_{2.5,ic}$, is the mean annual $\text{PM}_{2.5}$ concentration assigned to polygon i. In our baseline regressions, each polygon is weighted by its total population, so the coefficients should be interpreted as differences in the pollution exposure borne by residents rather than equal-weighted spatial differences across parcels. The main explanatory variable, MultiFamily_{ic}, is an indicator equal to one if polygon i is zoned for multi-family residential use and zero if it is zoned for single-family use. All specifications include city fixed effects, δ_c, to absorb time-invariant differences across cities such as geography, climate, and baseline industrial structure. We also control for a rich set of polygon-level covariates, collected in the vector X_{ic}. These include contemporary demographic variables (minority share, renter share, median household income, educational attainment, and age) and the historical controls described in Section 3.

4.1 OLS Specification

Before turning to the residential-sample IV analysis, we estimate descriptive regressions of indicators for contemporary business, commercial, industrial, and residential zoning on HOLC grades and the historical covariates described in Section 3. These estimates are not intended to be causal. Rather, they summarize whether and how strongly the historical land-use environment captured in our data is associated with contemporary zoning patterns.

We then begin with the baseline OLS relationship:

$$\text{PM}_{2.5,ic} = \beta_0 + \beta_1 \text{MultiFamily}_{ic} + X_{ic}'\gamma + \delta_c + \epsilon_{ic}. \tag{1}$$

This regression provides a descriptive benchmark, but $\hat{\beta}_1$ does not have a credible causal interpretation. Zoning is an equilibrium outcome of local political and economic processes, and unobserved factors such as neighborhood income, political influence, historical land-use patterns, and proximity to infrastructure are likely correlated with both zoning designations and pollution levels. This perspective implies that our estimates reflect long-run equilibrium differences across zoning regimes rather than the immediate effect of a zoning change in isolation.

4.2 2SLS Specification

To address endogeneity, we use a two-stage least squares strategy that instruments for contemporary zoning with historical HOLC grades. Let $\mathbf{Z}_{ic}$ denote the instrument set. We consider three variants.

1. **Categorical instrument:** indicators for each HOLC grade excluding Grade D (A, B, C).
2. **Linear instrument:** a numeric score ranging from 0 (D) to 3 (A).
3. **Binary instrument:** an indicator for "marginally desirable" areas (B or C) or an indicator for "undesirable" areas (D).

The first stage is:

$$\text{MultiFamily}_{ic} = \alpha_0 + \alpha_1' Z_{ic} + X_{ic}'\gamma + \delta_c + \mu_{ic}. \tag{2}$$

The second stage is:

$$\text{PM}_{2.5,ic} = \beta_0 + \beta_1 \widehat{\text{MultiFamily}}_{ic} + X_{ic}'\gamma + \delta_c + \nu_{ic}. \tag{3}$$

The 2SLS coefficient $\hat{\beta}_1$ can be interpreted within a standard local average treatment effect framework. However, because zoning is an equilibrium outcome that co-evolves with land use, transportation infrastructure, and industrial location, we interpret our estimates as capturing reduced-form differences in pollution exposure across areas subject to different zoning regimes, rather than the partial equilibrium effect of a marginal zoning change.

The identifying assumption is a conditional exclusion restriction: conditional on city fixed effects and the covariates in X_{ic}, HOLC grades affect modern $PM_{2.5}$ only through their impact on contemporary zoning. This assumption is consistent with historical evidence that the HOLC maps were produced for internal use and had limited direct effects on subsequent mortgage lending and private capital allocation (Hillier, 2003b,a; Michney, 2022; Fishback et al., 2023, 2024). Our interpretation is that the maps' more durable legacy was institutional: the grades captured neighborhood characteristics that later shaped planning and land-use regulation.

Endogenous neighborhood sorting remains a first-order concern in this setting, as place-based policies can induce Tiebout sorting and neighborhood tipping (Banzhaf and Walsh, 2013). Our design exploits variation at HOLC boundaries to isolate variation in zoning rules that is plausibly orthogonal to contemporaneous amenity shocks. To address concerns that HOLC grades proxy for persistent industrial geography, we condition on a rich set of pre-period built-environment and manufacturing controls. This approach follows the logic of Casey and Klemp (2021), who emphasize that historical instruments may affect modern outcomes through serial correlation in local characteristics rather than through the treatment alone. By controlling for pre-HOLC development intensity and manufacturing activity, we absorb a primary channel through which HOLC grades could be correlated with modern pollution even in the absence of zoning. Our estimates therefore compare polygons with similar pre-period built and industrial environments, reducing the risk that the instrument captures long-standing industrial corridors rather than the long-run evolution of zoning (Imbens and Wooldridge, 2009).

4.3 Mechanism: Proximity to Pollution Sources

Why are areas permitting multi-family housing associated with higher exposure to $PM_{2.5}$? Multi-family zoning may be associated with higher pollution through residential density and congestion-related emissions (Carozzi and Roth, 2023). We hypothesize that this pollution penalty is not merely a byproduct of residential density, but the result of deliberate spatial sorting engineered by local land-use law. Historically, zoning has been used to link population density with neighborhood composition (Monarrez and Schönholzer, 2023; Sahn, 2025; Shertzer et al., 2016). We conjecture that multi-family zones are more likely to be located near commercial and industrial (CI) zones, effectively serving as a "buffer" between single-family neighborhoods and noxious CI activity. Following related work (Shertzer et al., 2018; Zirogiannis et al., 2023), we examine whether multi-family zoning clusters near commercial and industrial zones, which can increase traffic, concentrate combustion-intensive activity, and raise steady-state $PM_{2.5}$ exposure.

To formalize this co-location hypothesis, we estimate the following descriptive specification:

$$\text{ProxCI}_{ic} = \gamma_0 + \gamma_1 \text{ZoneType}_{ic} + \delta_c + \omega_{ic}, \quad (4)$$

where ProxCI_{ic} measures proximity to potential pollution sources (i.e., CI zones), and ZoneType_{ic} denotes the polygon's land-use designation. A positive estimate of γ_1 would indicate that multi-family zones are systematically closer to CI land uses.

5 Results

We begin with descriptive evidence on broader contemporary land-use patterns. Unless otherwise noted, statements about statistical significance below refer to the wild-bootstrap p-values as reported in the table notes. Table B1 shows that HOLC grades remain strongly associated with current zoning categories. Relative to Grade D polygons, historically higher-graded areas are significantly more likely to be zoned residential today and significantly less likely to be zoned commercial or industrial, while business zoning shows little systematic relationship with HOLC grade. Among the historical controls, polygons whose HOLC descriptions explicitly mention pollution sources are more likely to be zoned industrial and less likely to be zoned residential today. These patterns motivate our main focus on the residential sample, where we ask how zoning differences translate into pollution-exposure gaps borne by residents.

Turning to the residential sample, Table 2 reports the first-stage relationship in Equation (2). The HOLC instruments strongly predict contemporary multi-family zoning in the expected direction. In Column (1), a one-unit increase in the HOLC grade score (e.g., from D to C) reduces the probability that a polygon permits multi-family housing by 8.4 percentage points. Column (2) reveals a clear gradient across grades: relative to Grade D, Grade A, Grade B, and Grade C polygons are 25.7, 16.0, and 5.4 percentage points less likely to be zoned for multi-family use. Column (3) shows a similar ordering within the marginal sample of B/C/D, where Grade B and

Grade C polygons are 15.7 and 5.1 percentage points less likely than Grade D polygons to permit multi-family housing. Column (4) indicates that within the more marginal C/D sample, Grade D polygons are 4.6 percentage points more likely than Grade C polygons to permit multi-family housing. Instrument strength is strong in the full sample and remains adequate in the broader marginal sample, though weaker in the narrow C/D design.

Table 3 reports the population-weighted OLS and 2SLS estimates of β_1 from Equation (3). Column (1) shows a negative unconditional correlation between multi-family zoning and $PM_{2.5}$. Once we include city fixed effects in Column (2), the coefficient becomes positive, but we cannot interpret the OLS coefficients causally due to the endogeneity of zoning. In our preferred specification (Column (6)), which uses the linear HOLC grade score ("Grades") as the instrument and includes city fixed effects and the full set of controls, areas permitting multi-family housing exhibit annual $PM_{2.5}$ exposure that is higher by 1.2 $\mu g/m^3$. This estimate is statistically significant, economically large, and much larger than the corresponding OLS estimate, implying that naive regressions understate the exposure burden associated with multi-family zoning. Consistent with the interpretation in Section 4, we view this coefficient as an estimate of long-run equilibrium exposure differences across zoning regimes rather than the immediate effect of a zoning change in isolation. Columns (3) and (4) show that the alternative residential-sample specification using HOLC grade indicators also produces positive estimates of 1.2 and 0.9 $\mu g/m^3$.

To contextualize the magnitude of this exposure penalty, it is useful to benchmark it against major federal environmental interventions. For perspective, the 2005 tightening of the National Ambient Air Quality Standards reduced $PM_{2.5}$ by approximately 1.2 $\mu g/m^3$ in nonattainment counties (Currie et al., 2023). Novel high-resolution estimates by Sager and Singer (2025) imply a more conservative 0.4 $\mu g/m^3$ reduction over five years. Our preferred 2SLS estimate is therefore of a similar order of magnitude as the gains from one of the most significant air-quality interventions in recent U.S. history. Furthermore, applying the mortality-dose response estimates from Deryugina et al. (2019) (an increase in elderly mortality of 0.69 per million per 1 $\mu g/m^3$) and Ebenstein et al. (2017) (a decrease in life expectancy of 0.064 year per 1 $\mu g/m^3$), a chronic exposure difference of this magnitude implies substantial hidden mortality and human-capital costs borne disproportionately by renters and low-income households.

For comparison, Appendix Table B2 reports area-weighted spatial estimates. In the fully controlled 2SLS specifications, these polygon-level coefficients remain positive and statistically significant, equaling 0.9 $\mu g/m^3$ under the categorical HOLC-grade instrument and 0.9 $\mu g/m^3$ under the preferred Grades instrument. These estimates are smaller than the corresponding resident-weighted estimate under the preferred Grades specification, indicating that the effect of zoning is not limited to the spatial allocation of pollution across land area. Instead, multi-family housing appears to be disproportionately concentrated in more polluted locations where more people are exposed, so the personal exposure burden exceeds what the average spatial footprint alone would imply.

Appendix Table B3 shows how the weighted 2SLS estimate evolves as we add progressively richer controls when using the preferred Grades instrument. The point estimate attenuates from 1.9 $\mu g/m^3$ in the baseline specification to 1.2 $\mu g/m^3$ in the most demanding model. We interpret this attenuation as evidence that part of the raw HOLC–pollution relationship reflects pre-existing industrial geography and built-form differences that are absorbed by the historical controls. Crucially, however, the estimate remains positive, economically meaningful, and statistically significant under wild-bootstrap inference throughout. In the most demanding specification, the implied effect is about 13% of the sample mean (9.1 $\mu g/m^3$), confirming that the long-run regulatory imprint of zoning has a substantial effect on resident exposure.

We next examine robustness within progressively narrower "marginal" samples and alternative instrument definitions. Table B4 restricts the sample to B/C/D neighborhoods and uses the linear HOLC grade score as the instrument. The estimated effect ranges from 1.4 to 2.1 $\mu g/m^3$ and is statistically significant in every specification. Appendix Table B5 instead uses indicators for Grades B and C as instruments within the same B/C/D sample; the resulting estimates remain positive and statistically significant, ranging from 1.1 to 2.1 $\mu g/m^3$. Finally, Appendix Table B6 restricts attention to the narrowest C/D margin and uses a Grade D indicator as the instrument. Here, the estimated effect is larger, ranging from 2.2 to 4.0 $\mu g/m^3$. Interpreted through the lens of a Local Average Treatment Effect, these results suggest that the marginal parcels whose zoning regimes are most strongly shifted by HOLC-grade variation are also those where zoning differences are associated with the largest modern-day exposure gaps.

Finally, Table 4 examines the spatial sorting mechanism in Equation (4) using an indicator for whether a polygon borders any commercial or industrial (CI) zone. We find a clear historical gradient: relative to Grade D polygons, higher HOLC grades (A–C) are significantly less likely to border CI zones. Consistent with this co-location channel, single-family zoning is associated with less CI adjacency, while multi-family zoning is associated with more CI adjacency. In Columns (1) and (2), these relationships remain statistically significant under weak-IV-robust wild-bootstrap Anderson–Rubin inference. Taken together, these results support a spatial mechanism in which exclusionary land-use regimes protect single-family neighborhoods by systematically concentrating higher-density, multi-family housing near industrial and commercial corridors, thereby increasing the pollution exposure borne by their residents (Shertzer et al., 2016, 2018).

6 Conclusion

This paper establishes land-use regulation as a primary institutional channel translating historical housing discrimination into contemporary environmental inequality. Using quasi-experimental variation at HOLC boundaries, we show that areas graded poorly in the 1930s are substantially more likely to be zoned for multi-family use today, and that these zoning differences are associated with meaningful differences in residents' pollution exposure. Netting out baseline urban geography and infrastructure, we show that this regulatory imprint is associated with substantially higher modern-day $PM_{2.5}$ exposure for the residents who live there.

More broadly, the results illustrate a form of path dependence in which a quasi-formal historical institution–the HOLC maps–became embedded in the formal legal and administrative structure of cities. Historical assessments can persist not only through capital allocation and neighborhood sorting, but also through durable policy rules that continue to govern land use decades later.

The policy implications are immediate. As the United States faces a historic housing shortage, a growing coalition of policymakers and economists has championed the dismantling of exclusionary single-family zoning. While increasing allowed density can improve affordability (Anagol et al., 2021; Liao, 2024; Rollet, 2025), our findings caution that zoning reform and urban density may not be distributionally neutral when new housing is concentrated in places already exposed to traffic and commercial/industrial activity (Carozzi and Roth, 2023; Duranton and Puga, 2020; Freemark, 2023). Because historical land-use regimes systematically relegated multi-family housing to the perimeters of industrial and heavy-traffic corridors, allowing more density only within existing multi-family zones may expose more residents to environmental hazards. If efforts to improve housing affordability are not paired with targeted environmental remediation and the upzoning of high-amenity, single-family neighborhoods, density reforms may risk exacerbating the very environmental inequalities it inherited from the 1930s. Housing policy and environmental policy are therefore complements, not substitutes, in efforts to reduce inequality in pollution exposure.

Finally, our design opens several directions for future work. The institutional channel we identify may affect a broader set of outcomes, including flood risk and access to green space (Weiwu, 2024). The same HOLC boundary variation could also be used to study how zoning regimes relate to downstream measures of well-being, including health and intergenerational mobility. More generally, the results underscore that persistent inequality in environmental exposure is shaped by durable local institutions, and that reversing it likely requires policy changes that address both current conditions and the historical roots of land-use rules.

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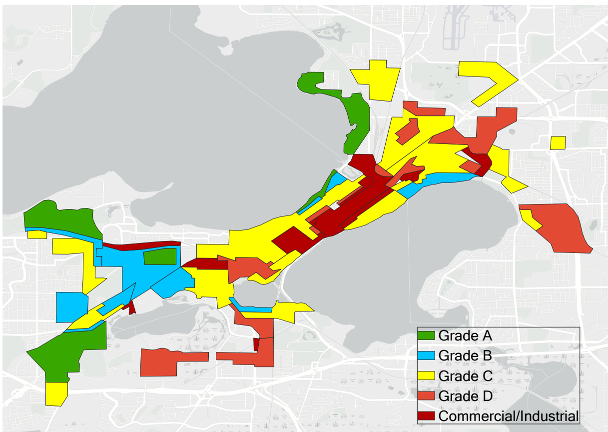
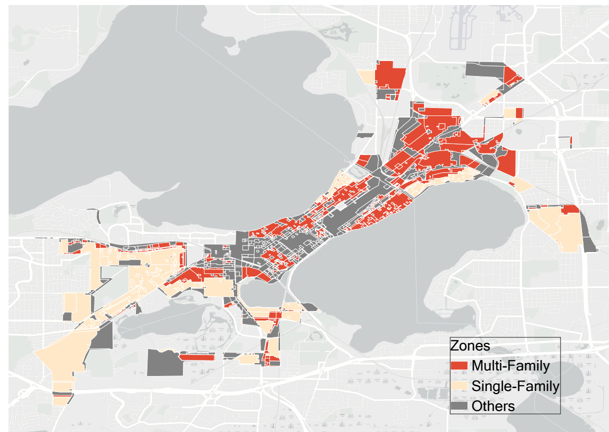
Figure and Tables

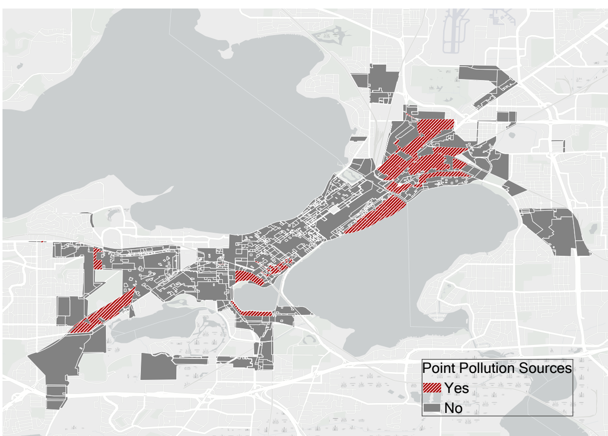
Figure



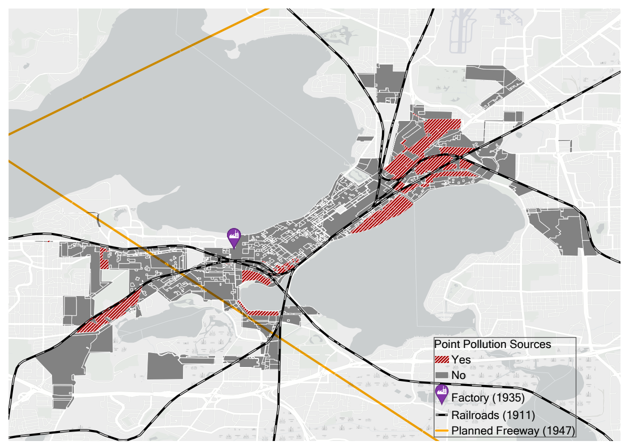
(a) HOLC Map



(b) Zoning Ordinances



(c) HOLC Map Description



(d) Historic Controls

Figure 1: Maps of Madison, WI

Notes: Panels illustrate the construction of the analysis dataset using Madison, WI as an example. Panel (a) shows historical HOLC neighborhood grades (A–D and commercial/industrial). Panel (b) shows the 2024 zoning map, grouped into single-family residential, multi-family residential, and commercial/industrial categories. Panel (c) displays the text-based indicators for historical pollution sources extracted from HOLC area-description sheets. Panel (d) illustrates historical baseline controls (pre-HOLC built intensity, manufacturing activity, and transportation networks) used to account for the baseline urban development landscape.

Tables

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										
Pop Weighted PM2.5 ($\mu g/m^3$)	8.96	1.50	8.80	1.57	9.09	1.78	9.27	1.82	9.06	1.73
Multi-family Zoning Share	0.12	0.33	0.22	0.41	0.38	0.49	0.51	0.50	0.37	0.48
Neighborhood Characteristics										
Median HH Income ($)	121,582	71,009	88,400	54,289	67,791	42,060	64,215	38,807	74,653	48,681
Non-Hispanic White Share	0.60	0.30	0.43	0.31	0.30	0.29	0.29	0.28	0.34	0.30
Black Share	0.23	0.31	0.29	0.35	0.34	0.36	0.31	0.33	0.32	0.35
Renter Share	0.31	0.22	0.41	0.23	0.52	0.24	0.58	0.22	0.50	0.24
Bachelor+ Share	0.58	0.27	0.43	0.28	0.30	0.27	0.29	0.26	0.34	0.28
Unemployment Share	0.05	0.07	0.07	0.08	0.08	0.09	0.09	0.09	0.08	0.08
Area (m^2)	17,395	107,701	11,285	69,089	8,268	60,832	8,853	63,743	9,560	66,224
Total Population	62	370	72	612	65	605	78	731	70	634
Historical Built Environment										
Built-up Records	4.61	37.88	7.26	76.98	6.44	63.24	6.28	47.91	6.43	61.38
Floor Area (m^2)	763	6,593	989	8,700	827	7,182	802	6,293	848	7,267
Manuf. Count	0.01	0.36	0.01	0.58	0.00	0.45	0.01	0.46	0.00	0.48
Manuf. Output (1935 $)	738	42,856	4,009	438,589	2,287	398,525	6,117	453,559	3,788	411,084
Dist. Interstate (km)	3.44	1.93	3.28	2.16	3.12	2.51	2.15	2.34	2.92	2.42
Observations	14,032 (5%)		53,160 (20%)		127,270 (48%)		64,225 (24%)		263,734	

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)), 1929 − 1935 Census of Manufactures, and 1947 U.S. national Interstate highway plan (Weiwu (2024)). 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 in the residential-only sample. Pollution is assigned to each polygon as the mean annual $\text{PM}_{2.5}$ concentration within the polygon; summary statistics for pollution exposure are population-weighted. Multi-family zoning is an indicator variable that equals 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 Zoned			
	(1)	(2)	(3)	(4)
HOLC Grades	−0.084***			
	(0.011)			
Grade A		−0.257***		
		(0.028)		
Grade B		−0.160***	−0.157***	
		(0.027)	(0.027)	
Grade C		−0.054***	−0.051***	
		(0.019)	(0.019)	
Grade D				0.046**
				(0.019)
City FE	Yes	Yes	Yes	Yes
Demographics	Yes	Yes	Yes	Yes
Historical Nuisances	Yes	Yes	Yes	Yes
Historical Built Environment	Yes	Yes	Yes	Yes
Historical Road Network	Yes	Yes	Yes	Yes
Kleibergen-Paap rk Wald F	54.0	30.5	17.6	6.3
Cragg-Donald F	4,503	1,581	1,537	372
Hansen J		6.6	3.7	
Observations	216,946	216,946	205,770	161,910
Sample	All	All	B, C, D	C, D

Notes: The unit of observation is a HOLC–zoning intersection polygon in the residential-only sample. The dependent variable is an indicator for whether a polygon's 2024 zoning permits multi-family residential structures by-right. Column (1) uses a linear HOLC grade score as the instrument; Column (2) uses HOLC grade indicators; Column (3) restricts to B/C/D polygons and uses HOLC Grade B and Grade C indicators; Column (4) restricts to C/D polygons and uses a Grade D indicator. All specifications use analytical weights equal to the polygon's total population. City fixed effects and the control sets shown in the table are included as indicated. Kleibergen–Paap rk Wald F and Cragg–Donald F are reported for instrument strength; Hansen J is reported when over-identification is relevant. City-level clustered standard errors are in parentheses. P-values are from city-clustered wild bootstrap inference with 10,000 replications. Significance stars reflect these bootstrap p-values.
***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 (1)	OLS (2)	2SLS (3)	2SLS (4)	2SLS (5)	2SLS (6)
Multi-family Zoned	−0.400	0.032	1.171*	0.922**	1.938***	1.168***
	(0.215)	(0.051)	(0.785)	(0.364)	(0.506)	(0.358)
Mean PM2.5	9.06	9.06	9.06	9.06	9.06	9.06
City FE	No	Yes	No	Yes	No	Yes
Demographics	No	Yes	No	Yes	No	Yes
Historical Nuisances	No	Yes	No	Yes	No	Yes
Historical Built Environment	No	Yes	No	Yes	No	Yes
Historical Road Network	No	Yes	No	Yes	No	Yes
Kleibergen-Paap rk Wald F			25.5	30.5	17.9	54.0
Cragg-Donald F			3,986	1,581	8,241	4,503
Observations	263,734	216,946	263,734	216,946	263,734	216,946
Instrument			A, B, C	A, B, C	Grades	Grades

Notes: The unit of observation is a HOLC–zoning intersection polygon in the residential-only sample. The dependent variable is polygon-level mean annual $PM_{2.5}$ (2021–2023 average), in $\mu g/m^3$. "Multi-family zoned" equals one if the polygon's 2024 zoning permits multi-family residential structures by-right. Columns (1)–(2) report OLS; Columns (3)–(6) report 2SLS. Columns (3)–(4) use HOLC grade indicators as instruments; Columns (5)–(6) use a linear HOLC grade score as the instrument. All specifications use analytical weights equal to the polygon's total population. City fixed effects and the control sets shown in the table are included as indicated. Kleibergen–Paap rk Wald F and Cragg–Donald F are reported for instrument strength. City-level clustered standard errors are in parentheses. P-values are from city-clustered wild bootstrap inference with 10,000 replications. Significance stars reflect these bootstrap p-values.

***Significant at the 1 percent level.

**Significant at the 5 percent level.

*Significant at the 10 percent level.

Table 4: Mechanism Results

	Commercial/Industrial		
	(1)	(2)	(3)
Residential-Single	-0.739^{*}		
	(0.494)		
Residential-Multi		0.445^{*}	
		(0.238)	
HOLC Grade A			-0.139^{***}
			(0.036)
HOLC Grade B			-0.092^{***}
			(0.027)
HOLC Grade C			-0.043^{**}
			(0.015)
City FE	Yes	Yes	Yes
Demographics	Yes	Yes	Yes
Historical Nuisances	Yes	Yes	Yes
Historical Built Environment	Yes	Yes	Yes
Historical Road Network	Yes	Yes	Yes
Kleibergen-Paap rk Wald F	2.3	8.7	
Cragg-Donald F	2,098	5,980	
Observations	187,671	187,671	187,671
Sample	All	All	All
Instrument	Grades	Grades	

Notes: The unit of observation is a HOLC–zoning intersection polygon in the full HOLC–zoning sample. The dependent variable is an indicator equal to one if the polygon borders at least one commercial/industrial (CI) zoned neighboring polygon. The endogenous regressor is the polygon's zoning designation: single-family in Column (1), multi-family in Column (2), and HOLC grade indicators (A/B/C) in Column (3). Columns (1) and (2) use a linear HOLC grade score as the instrument; Column (3) is estimated by OLS. All specifications include city fixed effects, demographic controls, historical nuisance indicators, historical built-environment controls, and historical road-network controls. City-level clustered standard errors are in parentheses. P-values in Columns (1) and (2) are from weak-IV-robust wild-bootstrap Anderson–Rubin inference with 10,000 replications. P-values in Column (3) are from city-clustered wild bootstrap inference with 10,000 replications. Significance stars reflect these bootstrap p-values.
***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

Appendices

A Additional Figures

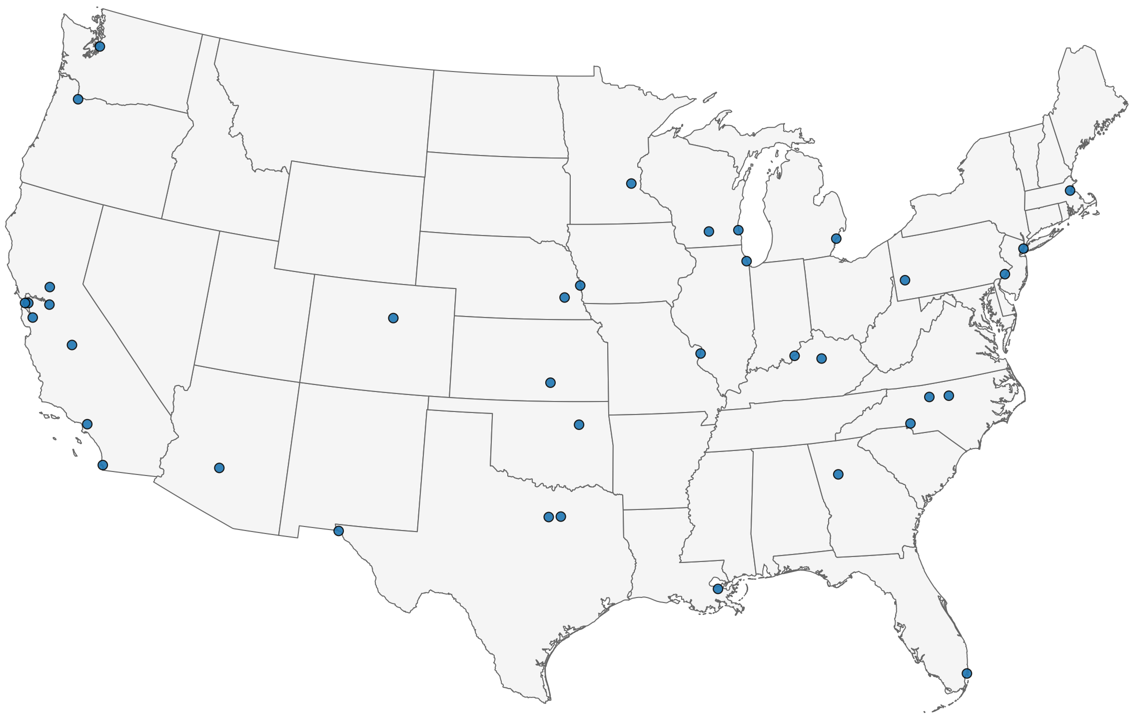
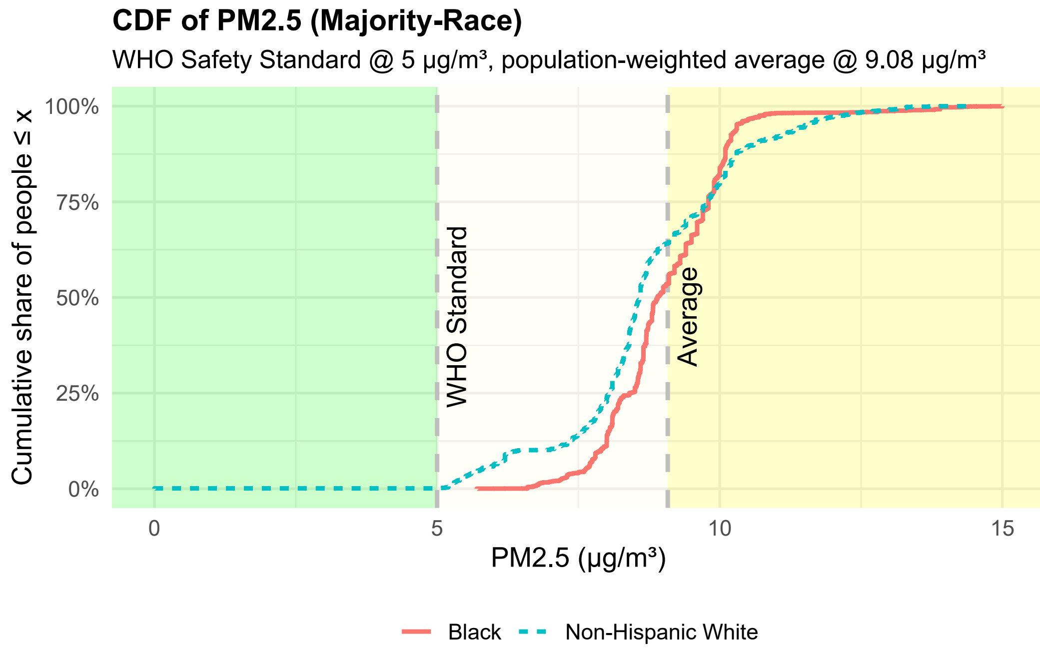


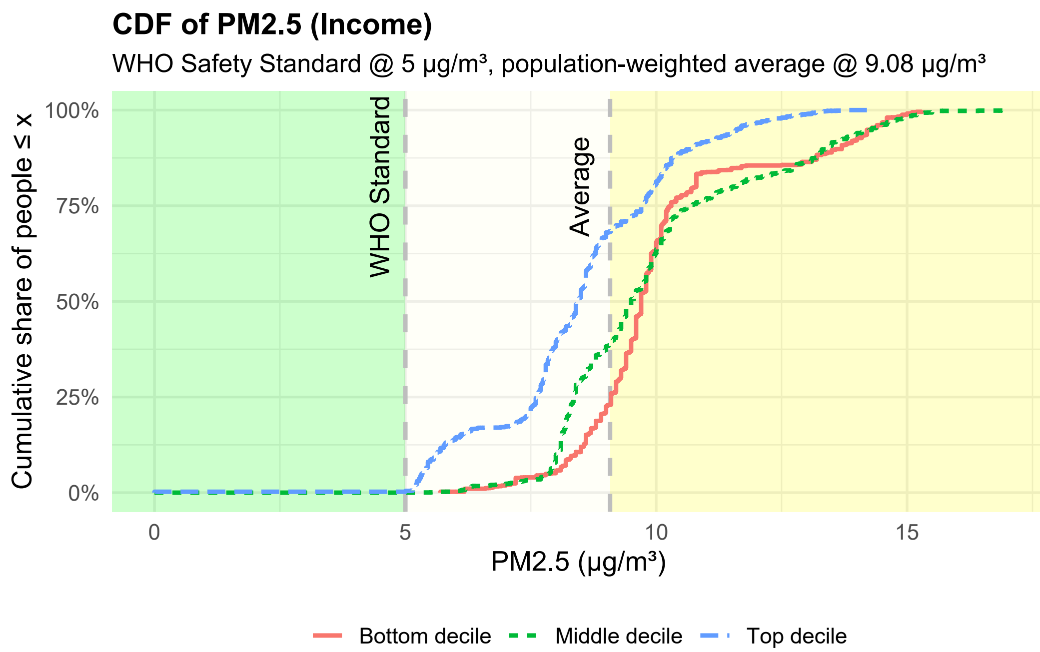
Figure A1: Map of Cities Included in the Analysis

Notes: The map highlights the 39 large U.S. cities for which we consistently assemble (i) digitized HOLC Residential Security Maps (1930s) and (ii) digitized 2024 municipal zoning maps.

B Additional Tables



(a) By Racial Share



(b) By Income Decile

Figure A2: Cumulative Distribution of Pollution Exposure

Notes: The figure plots polygon-level cumulative distribution functions (CDFs) of mean annual $PM_{2.5}$ exposure (average over 2021–2023) assigned to HOLC–zoning intersection polygons in the 39-city sample. Panel A compares polygons with a non-Hispanic White majority (share > 50%) to polygons with a minority majority. Panel B compares polygons in the lowest income decile to all other polygons, using polygon-level median household income from the 2024 Census ACS. In both panels, the disadvantaged-group distribution is shifted to the right, indicating higher $PM_{2.5}$ exposure at most points of the distribution.

Table B1: Impact of Historical Development on the Contemporary Land Use

	Business	Commercial	Industrial	Residential
	(1)	(2)	(3)	(4)
Grade A	0.001	-0.074^{***}	-0.063^{***}	0.203^{***}
	(0.002)	(0.017)	(0.009)	(0.024)
Grade B	0.002	-0.069^{***}	-0.057^{***}	0.165^{***}
	(0.002)	(0.011)	(0.009)	(0.020)
Grade C	0.006	-0.035^{***}	-0.038^{***}	0.106^{***}
	(0.005)	(0.009)	(0.009)	(0.011)
Nuisance Mentioned	0.000	0.002	−0.003	−0.016
	(0.001)	(0.008)	(0.009)	(0.026)
Pollution Mentioned	−0.004	−0.008	0.029^{***}	−0.029
	(0.003)	(0.09)	(0.006)	(0.017)
Race Mentioned	−0.003	0.004	−0.003	0.000
	(0.002)	(0.012)	(0.006)	(0.000)
Manuf. #	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Manuf. Output (1935 $)	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Building #	0.000	0.000^{*}	0.000^{**}	0.000^{**}
	(0.000)	(0.000)	(0.000)	(0.000)
Building Footprint (m^2)	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Dis. Freeway (km)	0.002	0.001	0.003^{*}	0.004
	(0.002)	(0.001)	(0.001)	(0.002)
City FE	Yes	Yes	Yes	Yes
Demographics	Yes	Yes	Yes	Yes
Observations	299,908	299,908	299,908	299,908

Notes: The unit of observation is a HOLC–zoning intersection polygon in the full HOLC–zoning sample. Each column reports an OLS regression for an indicator of the polygon's contemporary zoning category shown in the column header. Regressors include HOLC grade indicators (with Grade D omitted) and the historical covariates shown in the table. All specifications include city fixed effects and contemporary demographic controls. City-level clustered standard errors are in parentheses. P-values are from city-clustered wild bootstrap inference with 10,000 replications. Significance stars reflect these bootstrap p-values.
***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

Table B2: Regression Results: OLS vs 2SLS

	Annual $PM_{2.5}$ Level					
	OLS	OLS	2SLS	2SLS	2SLS	2SLS
	(1)	(2)	(3)	(4)	(5)	(6)
Multi-family Zoned	−0.146	0.067	1.626*	0.925***	1.523***	0.941***
	(0.217)	(0.033)	(0.881)	(0.222)	(0.428)	(0.236)
Mean $PM_{2.5}$	9.06	9.06	9.06	9.06	9.06	9.06
City FE	No	Yes	No	Yes	No	Yes
Demographics	No	Yes	No	Yes	No	Yes
Historical Nuisances	No	Yes	No	Yes	No	Yes
Historical Built Environment	No	Yes	No	Yes	No	Yes
Historical Road Network	No	Yes	No	Yes	No	Yes
Kleibergen-Paap rk Wald F			11.2	33.0	56.6	94.5
Cragg-Donald F			3,733	1,700	13,529	5,034
Observations	263,734	216,946	263,734	216,946	263,734	216,946
Instrument			A, B, C	A, B, C	Grades	Grades

Notes: The unit of observation is a HOLC–zoning intersection polygon in the residential-only sample. The dependent variable is polygon-level mean annual $PM_{2.5}$ (2021–2023 average), in $\mu g/m^3$. "Multi-family zoned" equals one if the polygon's 2024 zoning permits multi-family residential structures by-right. Columns (1)–(2) report OLS; Columns (3)–(6) report 2SLS. Columns (3)–(4) use HOLC grade indicators as instruments; Columns (5)–(6) use a linear HOLC grade score as the instrument. All specifications use analytical weights equal to the polygon's area. City fixed effects and the control sets shown in the table are included as indicated. Kleibergen–Paap rk Wald F and Cragg–Donald F are reported for instrument strength. City-level clustered standard errors are in parentheses. P-values are from city-clustered wild bootstrap inference with 10,000 replications. Significance stars reflect these bootstrap p-values.
***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

Table B3: Multi-Family Zoning and $PM_{2.5}$

	Annual $PM_{2.5}$ Level				
	(1)	(2)	(3)	(4)	(5)
Multi-Family Zoned	1.938***	1.450***	1.418***	1.189***	1.168***
	(0.506)	(0.375)	(0.486)	(0.349)	(0.358)
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	17.9	72.8	75.3	56.0	54.0
Cragg-Donald F	8,241	8,525	5,874	4,777	4,503
Observations	263,734	232,312	216,946	216,946	216,946
Instrument	Grades	Grades	Grades	Grades	Grades

Notes: The unit of observation is a HOLC–zoning intersection polygon in the residential-only sample. The dependent variable is polygon-level mean annual $PM_{2.5}$ (2021–2023 average), in $\mu g/m^3$. "Multi-family zoned" equals one if the polygon's 2024 zoning permits multi-family residential structures by-right. All columns report 2SLS estimates using a linear HOLC grade score as the instrument. All specifications use analytical weights equal to the polygon's total population. City fixed effects and the control sets shown in the table are included as indicated. Kleibergen–Paap rk Wald F and Cragg–Donald F are reported for instrument strength. City-level clustered standard errors are in parentheses. P-values are from city-clustered wild bootstrap inference with 10,000 replications. Significance stars reflect these bootstrap p-values.

***Significant at the 1 percent level.

**Significant at the 5 percent level.

*Significant at the 10 percent level.

Table B4: Multi-Family Zoning and $PM_{2.5}$ – Marginal HOLC Areas

	Annual $PM_{2.5}$ Level				
	(1)	(2)	(3)	(4)	(5)
Multi-Family Zoned	2.051***	1.634***	1.565***	1.471***	1.443***
	(0.517)	(0.463)	(0.613)	(0.376)	(0.382)
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	20.1	60.0	48.9	37.4	36.1
Cragg-Donald F	4,858	5,134	3,871	3,054	2,853
Observations	244,659	214,786	205,770	205,770	205,770
Sample	B, C, D	B, C, D	B, C, D	B, C, D	B, C, D
Instrument	Grades	Grades	Grades	Grades	Grades

Notes: The unit of observation is a HOLC–zoning intersection polygon in the residential-only sample. The dependent variable is polygon-level mean annual $PM_{2.5}$ (2021–2023 average), in $\mu g/m^3$. Sample restricts to polygons in HOLC Grade B, C, or D areas. "Multi-family zoned" equals one if the polygon's 2024 zoning permits multi-family residential structures by-right. All columns report 2SLS estimates using a linear HOLC grade score as the instrument. All specifications use analytical weights equal to the polygon's total population. City fixed effects and the control sets shown in the table are included as indicated. Kleibergen–Paap rk Wald F and Cragg–Donald F are reported for instrument strength. City-level clustered standard errors are in parentheses. P-values are from city-clustered wild bootstrap inference with 10,000 replications. Significance stars reflect these bootstrap p-values.
***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

Table B5: Effect of Multi-Family Zoning on PM2.5 – Marginal HOLC Areas

	Annual $PM_{2.5}$ Level				
	(1)	(2)	(3)	(4)	(5)
Multi-Family Zoned	2.076***	1.544***	1.431**	1.142***	1.095**
	(0.604)	(0.441)	(0.599)	(0.387)	(0.400)
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	31.7	33.1	24.2	18.2	17.6
Cragg-Donald F	2,599	2,593	1,972	1,639	1,537
Observations	244,659	214,786	205,770	205,770	205,770
Sample	B, C, D	B, C, D	B, C, D	B, C, D	B, C, D
Instruments	B, C	B, C	B, C	B, C	B, C

Notes: The unit of observation is a HOLC–zoning intersection polygon in the residential-only sample. The dependent variable is polygon-level mean annual $PM_{2.5}$ (2021–2023 average), in $\mu g/m^3$. Sample restricts to polygons in HOLC Grade B, C, or D areas. "Multi-family zoned" equals one if the polygon's 2024 zoning permits multi-family residential structures by-right. All columns report 2SLS estimates using HOLC Grade B and Grade C indicators as instruments. All specifications use analytical weights equal to the polygon's total population. City fixed effects and the control sets shown in the table are included as indicated. Kleibergen–Paap rk Wald F and Cragg–Donald F are reported for instrument strength. City-level clustered standard errors are in parentheses. P-values are from city-clustered wild bootstrap inference with 10,000 replications. Significance stars reflect these bootstrap p-values.
***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

Table B6: Effect of Multi-Family Zoning on PM2.5 – Marginal HOLC Areas

	Annual $PM_{2.5}$ Level				
	(1)	(2)	(3)	(4)	(5)
Multi-Family Zoned	2.165***	2.925***	2.837***	3.908***	4.027***
	(1.100)	(1.263)	(1.309)	(1.533)	(1.597)
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	9.9	14.6	7.1	6.5	6.0
Cragg-Donald F	3,048	1,597	950	417	372
Observations	191,499	166,184	161,910	161,910	161,910
Sample	C, D	C, D	C, D	C, D	C, D
Instrument	Grade D	Grade D	Grade D	Grade D	Grade D

Notes: The unit of observation is a HOLC–zoning intersection polygon in the residential-only sample. The dependent variable is polygon-level mean annual $PM_{2.5}$ (2021–2023 average), in $\mu g/m^3$. Sample restricts to polygons in HOLC Grade C or D areas. "Multi-family zoned" equals one if the polygon's 2024 zoning permits multi-family residential structures by-right. All columns report 2SLS estimates using a Grade D indicator as the instrument. All specifications use analytical weights equal to the polygon's total population. City fixed effects and the control sets shown in the table are included as indicated. Kleibergen–Paap rk Wald F and Cragg–Donald F are reported for instrument strength. City-level clustered standard errors are in parentheses. P-values are from weak-IV-robust wild-bootstrap Anderson–Rubin inference with 10,000 replications. Significance stars reflect these bootstrap p-values.

***Significant at the 1 percent level.

**Significant at the 5 percent level.

*Significant at the 10 percent level.