Residential Zoning and Neighborhood Air Quality: Evidence from HOLC Boundaries*

Mingxuan Fan† Corbett A. Grainger‡ Siyuan Hu§

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Abstract

We examine whether contemporary land-use regulation is associated with disparities in air pollution exposure across neighborhoods in 37 major U.S. cities. Our contribution is to identify a durable institutional mechanism through which historical neighborhood classifications continue to shape the spatial distribution of environmental quality. Because zoning is endogenous to neighborhood amenities and historical development patterns, we instrument for present-day zoning using historical Home Owners' Loan Corporation (HOLC) neighborhood grades. To isolate the regulatory legacy of HOLC assessments from pre-existing urban geography, we control extensively for historical manufacturing activity, transportation networks, built-environment characteristics, and pollution-related nuisances documented in HOLC records. The first stage is strong and monotonic: historically lower-graded neighborhoods are substantially more likely to permit multi-family residential development today. Our preferred 2SLS estimates indicate that areas permitting multi-family housing experience approximately 1.1 $\mu g/m^3$ higher annual $PM_{2.5}$ exposure, equivalent to 13 percent of the sample mean. Mechanism evidence suggests that multi-family residential areas are systematically located closer to commercial and industrial land uses, consistent with a spatial configuration in which exclusionary zoning separates single-family neighborhoods from pollution-generating activities. These findings suggest that local land-use institutions not only shape housing markets and segregation but also govern the long-run allocation of environmental amenities and burdens across urban space.

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†Department of Real Estate, NUS Business School, National University of Singapore. Email: mfan@nus.edu.sg.

‡Corresponding Author. Department of Agricultural and Applied Economics, University of Wisconsin–Madison; CESifo. Email: corbett.grainger@wisc.edu.

§Department of Agricultural and Applied Economics, University of Wisconsin–Madison. Email: shu248@wisc.edu.

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 examines whether residential zoning contributes to environmental inequality. We focus on one prominent form of exclusionary land-use regulation: single-family zoning. While a large literature studies how zoning affects housing supply, segregation, and neighborhood composition, much less is known about whether zoning shapes residents' exposure to environmental hazards. This question is important because zoning governs not only where housing may be built, but also the spatial relationship between residential neighborhoods and pollution-generating activities.[1]

Our focus is not on the short-run effect of a marginal zoning change. Instead, we examine whether areas governed by different zoning regimes exhibit persistent differences in air pollution exposure. Multi-family residential areas may experience higher pollution exposure for several reasons, including greater proximity to commercial corridors, industrial activity, and transportation infrastructure. At the same time, zoning is highly endogenous: the same economic and political forces that influence land-use regulation—including neighborhood income, political influence, and historical development patterns—are also correlated with environmental quality. Identifying the relationship between zoning and pollution exposure therefore requires plausibly exogenous variation in contemporary zoning patterns.

To address this endogeneity, we use an instrumental variables strategy based on the historical

[1]Single-family zoning often operates alongside occupancy restrictions that limit the number of unrelated individuals who may share a dwelling. Such rules can further restrict residential density and reinforce sorting by income and household structure, even when the physical housing stock remains unchanged.

"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 neighborhood assessments influenced the long-run evolution of land-use regulation, but affect contemporary pollution exposure only through their impact on zoning and related land-use patterns. Recent evidence suggests that HOLC maps had limited direct effects on subsequent mortgage lending (Fishback et al., 2023, 2024). Our focus is instead on a distinct long-run channel: the role of HOLC assessments in shaping the evolution of local land-use regulation. In our setting, the identifying variation comes from discontinuities at HOLC boundaries, which generate persistent differences 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 37 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, HOLC grades strongly predict contemporary land use: historically higher-graded areas are more likely to remain residential and less likely to permit commercial or industrial activity. Second, within residential areas, lower HOLC grades predict both a higher probability of multi-family zoning and higher levels of $PM_{2.5}$ exposure. Third, our preferred 2SLS estimates indicate that areas permitting multi-family housing experience approximately 1.1 $\mu g/m^3$ higher annual $PM_{2.5}$ concentrations, equivalent to roughly 12 percent of the sample mean. Importantly, we interpret these estimates as long-run differences associated with alternative zoning regimes rather than treatment effects of a contemporaneous upzoning policy. Fourth, these relationships remain robust to extensive controls for contemporary demographics and historical features of the urban environment, including manufacturing activity, transportation infrastructure, built-environment characteristics, and pollution-related nuisances documented in HOLC records. Together, these findings suggest that zoning is an important institutional channel linking historical discrimination to contemporary environmental inequality.

We contribute to three distinct literatures. More broadly, we show how historical neighborhood assessments become embedded in durable land-use institutions that continue to shape urban environmental quality decades later. 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*, is central to 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 specific administrative pathway through which HOLC-era assessments remain related to modern welfare: durable local land-use rules. 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., Figure 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 these assessments. For example, appraisal forms routinely identified racial and ethnic composition as a detrimental influence, sometimes listing minority residents as *the* primary justification for assigning a lower grade. These records indicate that neighborhood demographics were not merely correlated with HOLC grades—they were often an explicit component of the evaluation itself.

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 distinction is important for our identification strategy because it suggests that HOLC boundaries need not operate primarily through subsequent mortgage lending. Instead, they may capture persistent institutional responses to neighborhood classification, including the evolution of local land-use regulation.

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., Figure 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 influenced the evolution and persistence of local zoning regimes that continue to shape land-use patterns 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 literature by examining whether HOLC-era neighborhood assessments are associated with contemporary zoning patterns and, through those patterns, differences in neighborhood air quality. More broadly, our framework emphasizes the role of long-run institutional persistence and spatial sorting in shaping contemporary environmental inequality.

This mechanism need not imply that planners explicitly copied HOLC maps into zoning ordinances. Rather, neighborhood assessments likely influenced political coalitions, investment patterns, and administrative expectations surrounding appropriate land uses. Because zoning ordinances exhibit substantial institutional persistence, early neighborhood classifications could become embedded in subsequent land-use decisions and survive long after the original HOLC maps ceased to have direct relevance.

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. Constructing a comparable zoning dataset at this scale required collecting parcel-level zoning maps city by city, parsing municipal ordinance text and development standards, and harmonizing thousands of locally defined zoning codes into a common classification framework. We use a commercial large language model (Gemini 2.5 Pro) to assist in interpreting ordinance text and mapping local zoning codes into common categories. All classifications were subsequently reviewed against city-specific ordinance language 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 37 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, to incorporate into diagnostic robustness exercises, and to test mechanisms related to proximity to commercial and industrial zoning

In addition to the HOLC grades themselves, we use the accompanying area-description sheets to construct measures of historical environmental conditions. For each graded area, we extract text from fields including "detrimental influences," "clarifying remarks," "infiltration of," "negro yes or no," and "foreign-born nationality." Using a text-classification procedure based on the same large language model, we create indicators for whether the descriptions explicitly mention: (i) major point pollution sources (e.g., industrial plants, coal yards, or railroads); (ii) general nuisances (e.g., smoke, odors, or sewage); and (iii) minority or foreign-born residents as a justification for the assigned grade (Figure 1c). These indicators are merged to the analysis polygons and included as controls in our preferred specifications.

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, 2016). 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., Figure 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 B1 reports descriptive statistics for our analytical sample of 263,734 residential land polygons across the 37 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 $\mu g/m^3$). Most variation in $PM_{2.5}$ exposure occurs across cities rather than within cities, motivating our use of city fixed effects. Accordingly, identification in the main specifications comes from within-city differences in zoning and pollution exposure rather than comparisons across cleaner and dirtier cities. Figure A2 further illustrates these disparities.

Panel A2a shows that the pollution distribution in non-white-majority neighborhoods first-order stochastically dominates that in 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 urban geography. Grade D polygons historically contained substantially higher manufacturing, with an average 1935 manufacturing output of $6,117 per polygon compared to $738 in Grade A polygons (in 1935 U.S. dollars). Grade D polygons are also situated much closer to transportation networks than their Grade A counterparts. 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 conceptual framework is that HOLC neighborhood assessments influenced the evolution of local zoning institutions, which in turn shaped the spatial configuration of residential and commercial land uses and, ultimately, differences in pollution exposure. Because HOLC grades may also proxy for other dimensions of historical urban development, our specifications condition on extensive measures of historical manufacturing activity, transportation infrastructure, built intensity, and environmental nuisances.

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 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.

4.2 2SLS Specification

To address endogeneity, we instrument contemporary multi-family zoning with historical HOLC variation. Let $\mathbf{Z}_{ic}$ denote the HOLC instrument for polygon i in city c. In our preferred specification, $\mathbf{Z}_{ic}$ is a linear HOLC grade score coded from 0 for Grade D to 3 for Grade A. In alternative specifications, $\mathbf{Z}_{ic}$ is a vector of HOLC grade indicators, with Grade D omitted. We also report marginal-sample specifications that restrict comparisons to B/C/D neighborhoods.

The first stage is:

$$\text{MultiFamily}_{ic} = \alpha_0 + \mathbf{Z}'_{ic}\alpha_1 + X'_{ic}\alpha_2 + \delta_c + \mu_{ic}. \tag{2}$$

Here, α_1 captures the relationship between HOLC grades and the probability that a polygon permits multi-family housing by-right, and μ_{ic} is an unobserved first-stage error term.

We also report the corresponding reduced-form relationship:

$$\text{PM}_{2.5,ic} = \pi_0 + \mathbf{Z}'_{ic}\pi_1 + X'_{ic}\pi_2 + \delta_c + \eta_{ic}. \tag{3}$$

The reduced-form coefficient vector $\hat{\pi}_1$ shows whether the same HOLC variation that shifts contemporary zoning also predicts $\text{PM}_{2.5}$ exposure.

Using the predicted value $\widehat{\text{MultiFamily}}_{ic}$ from Equation (2), the second stage is:

$$\text{PM}_{2.5,ic} = \theta_0 + \theta_1\widehat{\text{MultiFamily}}_{ic} + X'_{ic}\theta_2 + \delta_c + \nu_{ic}. \tag{4}$$

The coefficient of interest, $\hat{\theta}_1$, admits a standard local average treatment effect interpretation. Because zoning co-evolves with land use, transportation infrastructure, and industrial activity, we interpret these estimates as characterizing differences in pollution exposure across areas governed by different zoning regimes rather than the effect of a marginal zoning reform in isolation. Accordingly, our estimates should not be interpreted as the effect of immediately rezoning a parcel from single-family to multi-family use. Rather, they characterize long-run exposure differences across places governed by different land-use regimes that have co-evolved with surrounding development patterns over many decades.

The identifying assumption is a conditional exclusion restriction: conditional on city fixed effects and the covariates in X_{ic}, HOLC variation affects contemporary $\text{PM}_{2.5}$ exposure only through its influence on subsequent land-use regulation. This interpretation is consistent with evidence that HOLC maps had limited direct effects on subsequent mortgage lending and capital allocation (Hillier, 2003b,a; Michney, 2022; Fishback et al., 2023, 2024). Rather than operating through credit markets alone, HOLC assessments may have influenced the evolution of local planning institutions and zoning practices. Our empirical strategy therefore focuses on this long-run institutional channel linking historical neighborhood classification to contemporary land-use regulation.

One concern is that HOLC variation may proxy for persistent neighborhood characteristics unrelated to zoning, including industrial geography, transportation infrastructure, or other dimensions of urban development. Our empirical strategy therefore conditions on unusually rich measures of historical manufacturing activity, transportation networks, built intensity, and environmental conditions documented in contemporaneous HOLC records. We do not argue that zoning is the sole determinant of environmental exposure. Instead, we view zoning as a durable institutional mechanism through which historical development patterns become codified and reproduced over time.

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 strategy follows the logic of Casey and Klemp (2021), who emphasize that historical instruments may affect contemporary outcomes through persistent local characteristics rather than the treatment of interest alone. By conditioning on detailed measures of historical development intensity, manufacturing activity, transportation access, and environmental conditions, we reduce the likelihood that HOLC variation proxies for long-standing industrial geography rather than the evolution of local zoning institutions (Imbens and Wooldridge, 2009).

4.3 Mechanism: Proximity to Pollution Sources

Why are areas permitting multi-family housing associated with higher $PM_{2.5}$ exposure? One possibility is that denser development generates additional congestion-related emissions (Carozzi and Roth, 2023). Our preferred explanation is spatial sorting. Historically, zoning has been used to separate land uses and populations across urban space (Monarrez and Schönholzer, 2023; Sahn, 2025; Shertzer et al., 2016). We hypothesize that multi-family residential zones are systematically located closer to commercial and industrial (CI) areas, effectively buffering single-family neighborhoods from pollution-generating activity. Consistent with related work (Shertzer et al., 2018; Zirogiannis et al., 2023), we test whether multi-family zoning is disproportionately concentrated near commercial and industrial land uses.

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

$$\text{ProxCI}_{ic} = \gamma_0 + \gamma_1 \text{ZoneType}_{ic} + \delta_c + \omega_{ic}, \tag{5}$$

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. If multi-family zones disproportionately border commercial and industrial uses, increases in residential density concentrated within existing multi-family districts may place additional residents in relatively high-exposure locations.

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 reported in the table notes. Table B2 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 significantly more likely to be zoned industrial today; the corresponding coefficient for residential zoning is negative but not statistically distinguishable from zero. 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 1 reports the first-stage and reduced-form relationships. The first-stage estimates show that HOLC grades 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 8.5 percentage points. Column (3) reveals a clear gradient across grades: relative to Grade D, Grade A, Grade B, and Grade C polygons are 26.5, 16.2, and 5.4 percentage points less likely to be zoned for multi-family use. Column (5) shows a similar ordering within the B/C/D sample, where Grade B and

Grade C polygons are 15.9 and 5.1 percentage points less likely than Grade D polygons to permit multi-family housing.

The reduced-form estimates move in parallel. A one-unit increase in the HOLC grade score reduces $PM_{2.5}$ exposure by 0.092 $\mu g/m^3$ (Column (2)). Relative to Grade D polygons, Grade A, Grade B, and Grade C polygons have lower $PM_{2.5}$ exposure by 0.232, 0.220, and 0.209 $\mu g/m^3$, respectively (Column (4)). The same pattern holds within the B/C/D sample: Grade B and Grade C polygons have 0.212 and 0.205 $\mu g/m^3$ lower exposure than Grade D polygons (Column (6)). These reduced-form patterns show that the historical variation shifting zoning also predicts pollution exposure in the same direction as the 2SLS estimates. The corresponding first-stage F-statistics comfortably exceed conventional weak-instrument thresholds in all baseline specifications.

Table 2 reports the population-weighted OLS and 2SLS estimates of θ_1 from Equation (4). 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 1.1 $\mu g/m^3$, roughly 12% of the sample mean.[2] This estimate is statistically significant, economically large, and substantially exceeds the corresponding OLS estimate, suggesting that conventional regressions understate differences in pollution exposure across zoning regimes. As discussed above, we interpret this coefficient as characterizing long-run exposure differences associated with alternative zoning configurations rather than the effect of a marginal zoning reform. Columns (3) and (4) show that the alternative residential-sample specification using HOLC grade indicators also produces positive estimates of 1.2 and 0.8 $\mu g/m^3$.

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

[2] Unreported area-weighted specifications produce comparable estimates. In otherwise identical fully controlled models, the estimated effect is 0.873 $\mu g/m^3$ using HOLC grade indicators and 0.933 $\mu g/m^3$ using the linear HOLC grade score; both are statistically significant under the same wild-bootstrap inference.

a similar order of magnitude as the gains from one of the most significant air-quality interventions in recent U.S. history. These comparisons suggest that the estimated exposure differences are economically meaningful and comparable in magnitude to pollution reductions achieved by major federal air-quality regulations.

We next examine robustness within the narrower "marginal" B/C/D sample and under alternative instrument definitions. Table 3 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 B3 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 1.0 to 2.1 $\mu g/m^3$. Appendix Table B4 adds a CI zone-adjacency control. The estimates remain broadly stable, suggesting that the estimated effect is unlikely to be driven by differential proximity to contemporary CI zoning, and the resulting deviations reflect both the added indicator and the smaller estimation sample. Because CI adjacency is a proxy for contemporary exogenous pollution sources and may itself be downstream of HOLC, we treat these specifications as a diagnostic robustness exercise rather than the preferred specification. These results indicate that the estimated relationship between zoning and pollution exposure remains large and stable even when attention is restricted to neighborhoods near the center of the historical HOLC grading distribution.

Finally, Table 4 examines the spatial sorting mechanism in Equation (5) 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 are consistent with a spatial-sorting mechanism in which multi-family residential areas are more likely to be located adjacent to commercial and industrial land uses. This pattern provides a plausible explanation for the higher pollution exposure observed in areas permitting multi-family housing(Shertzer et al., 2016, 2018).

6 Conclusion

This paper identifies land-use regulation as an important institutional channel linking historical housing discrimination to contemporary environmental inequality. Using 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.

Our results speak to the policy debate around zoning. As the United States faces a 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., forthcoming; Liao, 2026; Rollet, 2025), historical land-use regimes play an important role. Because historical land-use regimes systematically concentrated multi-family housing near commercial and industrial activity, policies that increase density primarily within existing multi-family districts could unintentionally concentrate additional population in relatively high-exposure locations (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 up-zoning of high-amenity single-family neighborhoods, density reforms may risk exacerbating inherited environmental inequalities. 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 influence a broader set of environmental and socioeconomic outcomes, including flood risk, access to green space, health, and intergenerational mobility (Weiwu, 2024). More generally, the findings suggest that persistent disparities in environmental exposure reflect not only market forces and residential sorting, but also durable local institutions that shape the allocation of environmental amenities and burdens across urban space. Reversing these disparities likely requires policy changes that address both current conditions and the historical roots of land-use rules.

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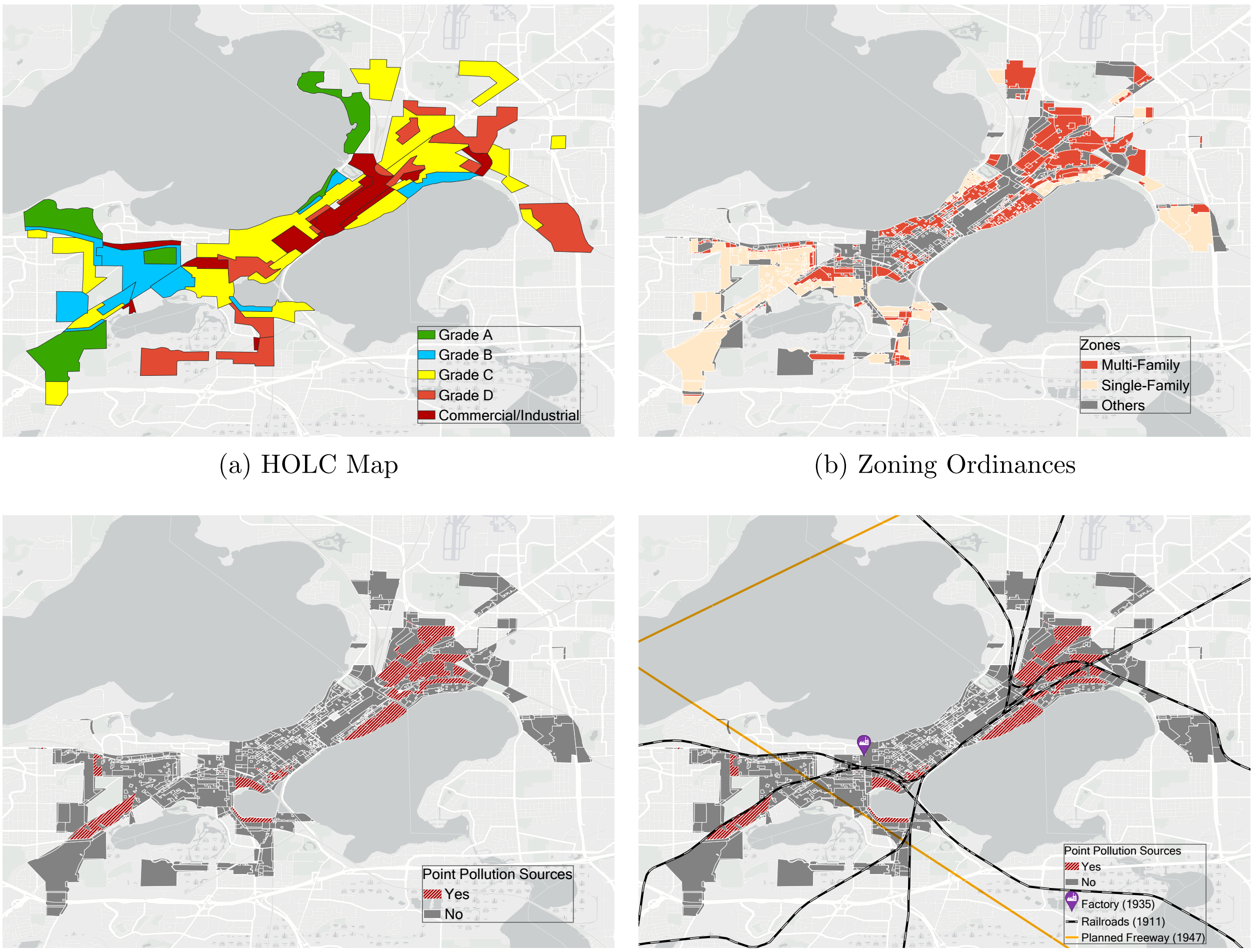
Exhibits

Figure 1: Maps of Madison, WI



(a) HOLC Map

(b) Zoning Ordinances

(c) HOLC Map Description

(d) Historic Controls

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.

Table 1: First-stage and Reduced-form Results

	MF Zoned (1)	$PM_{2.5}$ (2)	MF Zoned (3)	$PM_{2.5}$ (4)	MF Zoned (5)	$PM_{2.5}$ (6)
HOLC Grades	-0.085^{***}	-0.092^{***}				
	(0.011)	(0.030)				
Grade A			-0.265^{***}	-0.232^{***}		
			(0.028)	(0.096)		
Grade B			-0.162^{***}	-0.220^{***}	-0.159^{***}	-0.212^{***}
			(0.026)	(0.060)	(0.026)	(0.059)
Grade C			-0.054^{***}	-0.209^{**}	-0.051^{***}	-0.205^{**}
			(0.018)	(0.053)	(0.019)	(0.052)
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Demographics	Yes	Yes	Yes	Yes	Yes	Yes
Historical Nuisances	Yes	Yes	Yes	Yes	Yes	Yes
Historical Built Environment	Yes	Yes	Yes	Yes	Yes	Yes
Historical Road Network	Yes	Yes	Yes	Yes	Yes	Yes
Kleibergen-Paap rk Wald F	55.6		30.7		19.0	
Cragg-Donald F	4,679		1,647		1,581	
Hansen J			6.3		3.6	
Observations	216,946	216,946	216,946	216,946	205,770	205,770
Sample	All	All	All	All	B, C, D	B, C, D

Notes: The unit of observation is a HOLC–zoning intersection polygon in the residential-only sample. Odd-numbered columns report first-stage estimates where the dependent variable is an indicator for whether a polygon's 2024 zoning permits multi-family residential structures by-right. Even-numbered columns report reduced-form estimates where the dependent variable is polygon-level mean annual $PM_{2.5}$ (2021–2023 average), in $\mu g/m^3$. Columns (1)–(2) use a linear HOLC grade score as the HOLC variable. Columns (3)–(4) use HOLC grade indicators. Columns (5)–(6) restrict the sample to B/C/D polygons and use HOLC Grade B and Grade C indicators. 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 the corresponding first-stage specifications; 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 2: 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 (0.215)	0.041 (0.042)	1.171* (0.785)	0.823** (0.360)	1.938*** (0.506)	1.076*** (0.363)
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			25.5	30.7	17.9	55.6
Cragg-Donald F			3,986	1,647	8,241	4,679
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 3: 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***	1.388***
	(0.517)	(0.463)	(0.613)	(0.376)	(0.370)
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 4: Mechanism Results

	Commercial/Industrial		
	(1)	(2)	(3)
Residential-Single	-0.799^{*}		
	(0.582)		
Residential-Multi		0.461^{*}	
		(0.249)	
HOLC Grade A			-0.136^{***}
			(0.037)
HOLC Grade B			-0.091^{***}
			(0.028)
HOLC Grade C			-0.042^{**}
			(0.016)
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	1.9	8.7	
Cragg-Donald F	1,740	5,382	
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

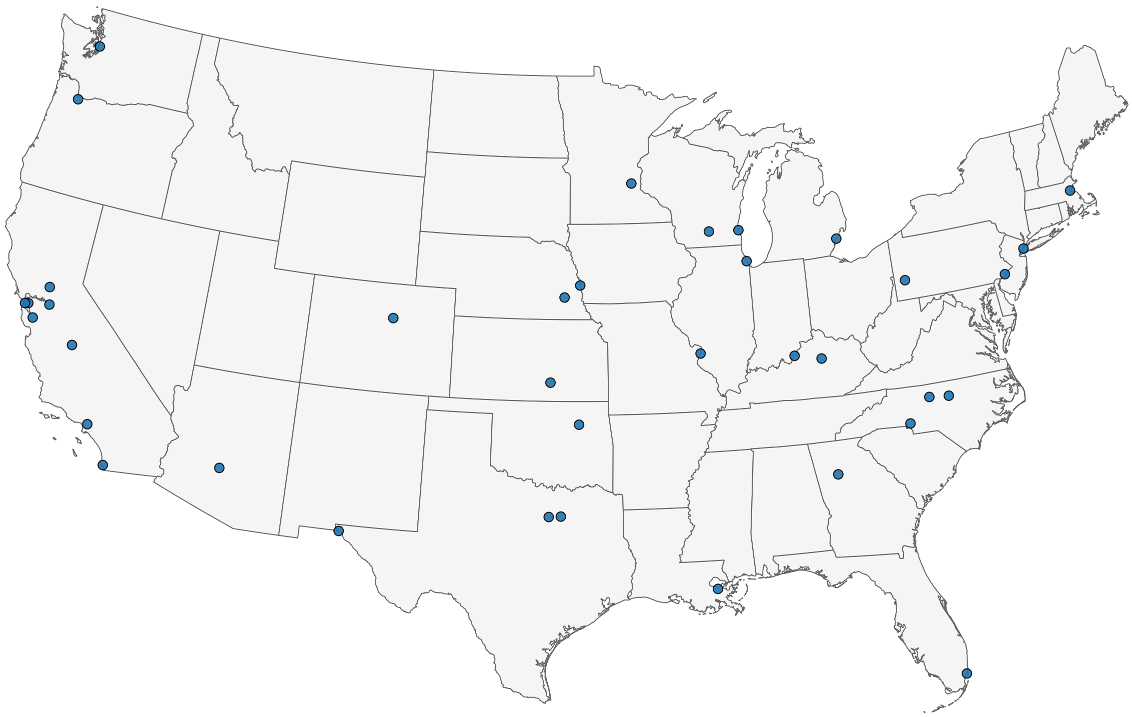
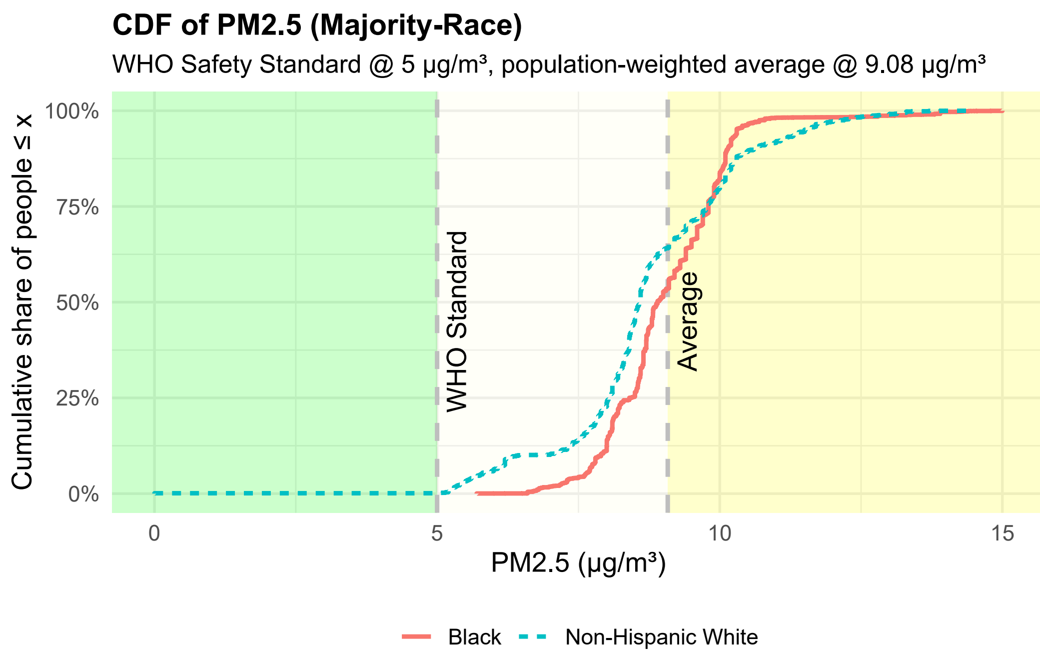
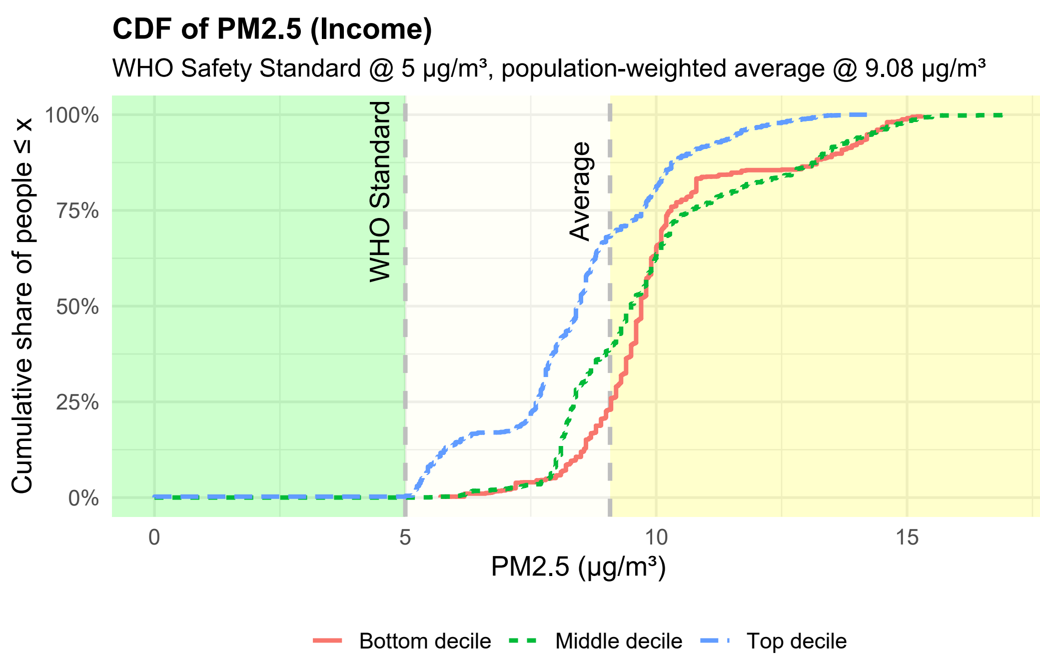


Figure A1: Map of Cities Included in the Analysis

Notes: The map highlights the 37 large U.S. cities for which we consistently assemble (i) digitized HOLC Residential Security Maps (1930s) and (ii) digitized 2024 municipal zoning maps.



(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 37-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.

B Additional Tables

Table B1: 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
Dist. Railroad (km)	1.92	1.44	1.35	1.23	1.10	1.13	0.91	1.07	1.13	1.18
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 the 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 $PM_{2.5}$ 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 37 cities in our analysis sample for which complete zoning and historical data are available.

Table B2: Historical Neighborhood Characteristics and Contemporary Land Use

	Business	Commercial	Industrial	Residential
	(1)	(2)	(3)	(4)
Grade A	0.001	−0.076***	−0.060***	0.199***
	(0.002)	(0.017)	(0.009)	(0.024)
Grade B	0.002	−0.070***	−0.056***	0.164***
	(0.002)	(0.011)	(0.009)	(0.020)
Grade C	0.006	−0.035***	−0.037***	0.105***
	(0.005)	(0.009)	(0.008)	(0.011)
Nuisance Mentioned	0.000	0.003	−0.005	−0.014
	(0.001)	(0.008)	(0.008)	(0.024)
Pollution Mentioned	−0.004	−0.007	0.026***	−0.026
	(0.003)	(0.009)	(0.006)	(0.019)
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	0.002	0.002*
	(0.002)	(0.001)	(0.001)	(0.001)
Dis. Railroad (km)	0.001	0.003**	0.007**	0.008
	(0.002)	(0.001)	(0.002)	(0.006)
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 populated 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 B3: Multi-Family Zoning and $PM_{2.5}$ – Marginal HOLC Areas

	Annual $PM_{2.5}$ Level				
	(1)	(2)	(3)	(4)	(5)
Multi-Family Zoned	2.076***	1.544***	1.431**	1.142***	1.038***
	(0.604)	(0.441)	(0.599)	(0.387)	(0.364)
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	19.0
Cragg-Donald F	2,599	2,593	1,972	1,639	1,581
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 B4: Multi-Family Zoning and $PM_{2.5}$ – C&I Zone Adjacency Specifications

	Annual $PM_{2.5}$ Level				
	OLS	2SLS	2SLS	2SLS	2SLS
	(1)	(2)	(3)	(4)	(5)
Multi-Family Zoned	0.055*	0.909***	1.242***	1.635***	1.216***
	(0.029)	(0.271)	(0.337)	(0.427)	(0.300)
Mean $PM_{2.5}$	9.06	9.06	9.06	9.06	9.06
City FE	Yes	Yes	Yes	Yes	Yes
Demographics	Yes	Yes	Yes	Yes	Yes
Historical Nuisances	Yes	Yes	Yes	Yes	Yes
Historical Built Environment	Yes	Yes	Yes	Yes	Yes
Historical Road Network	Yes	Yes	Yes	Yes	Yes
C&I Zone Adjacency	Yes	Yes	Yes	Yes	Yes
Kleibergen-Paap rk Wald F		12.6	24.6	16.9	8.8
Cragg-Donald F		1,208	3,337	2,030	1,124
Observations	187,671	187,671	187,671	178,342	178,342
Sample	All	All	All	B, C, D	B, C, D
Instruments		A, B, C	Grades	Grades	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 $\mu g/m^3$. "Multi-family zoned" equals one if the polygon's 2024 zoning permits multi-family residential structures by-right. All specifications include the C&I zone-adjacency control, city fixed effects, demographic controls, historical nuisance indicators, historical built-environment controls, and historical road-network controls. Columns (1)–(3) use the full residential-only sample. Columns (4)–(5) restrict the sample to polygons in HOLC Grade B, C, or D areas. Columns (2)–(3) and (4)–(5) report 2SLS estimates using the instruments shown in the table. All specifications use analytical weights equal to the polygon's total population. 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.