Economic Consequences of Childhood Exposure to Urban Environmental Toxins

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Childhood lead exposure causes well-documented damage to cognition, health, and mortality. Whether, and how, these harms translate into lasting labor market penalties is less clear. We estimate the consequences of childhood lead exposure on adult labor market outcomes by linking 6.2 million men, ages 20–50, from the 1940 full-count U.S. Census to their earliest childhood census record across 971 towns. Identification comes from the interaction of municipal pipe materials with geologically determined water chemistry that causes corrosion, leading to elevated lead leaching. Comparing across pipe types, men who were ages 0 to 10 in pure lead pipe towns with corrosive water earned 4.7% lower wages, worked 0.67 fewer weeks per year, and were 1.1 percentage points more likely to be unemployed than men in non-lead towns. The more tightly identified comparison exploits chemistry variation within pipe type: comparing across pure lead towns, men in high leaching risk water environments earned 3.6% less than those in low leaching risk environments, while the same chemistry variation has no differential effect on outcomes in towns without lead pipes. The wage penalty operates through both occupational sorting into lower-paying jobs and reduced earnings within the same detailed occupation. Lead exposure reduces childhood school attendance but does not affect self-reported completed years of education. Elevated lead exposure also compresses the relationship between childhood socioeconomic status and adult earnings. These findings demonstrate that childhood waterborne lead exposure imposes substantial, persistent economic costs, with implications for cost-benefit analyses of environmental contamination and ongoing infrastructure remediation.

Lead Exposure | Labor Markets | Occupational Sorting

Significance Statement

Millions of American children were exposed to lead through municipal water pipes in the late nineteenth and early twentieth centuries, and aging lead infrastructure remains in service today. While lead's effects on health, cognition, and mortality are well established, its broader labor market consequences are less understood. We link 6.2 million men from the 1940 Census to their childhood towns and exploit geologically determined water chemistry that affects lead leaching only in towns with lead pipes. Men exposed as children earned lower wages, faced higher unemployment, and worked in lower-paying occupations decades into adulthood. Higher parental socioeconomic status did not protect them. Accounting for these labor market costs reveals larger returns to lead remediation than health effects alone capture.

Introduction

Lead exposure is one of the most significant environmental health threats in American history. Millions of children were exposed through municipal water systems, leaded gasoline, lead-based paint, and contaminated soil throughout the twentieth century (1). Policy efforts to reduce exposure, including the phaseout of leaded gasoline, lead paint bans, and lead service line replacement, have generated a large literature documenting consequences of childhood lead exposure for cognition, behavior, health, birth outcomes, juvenile delinquency, educational attainment, and mortality (2–12). However, the economic burden of childhood exposure carried by affected cohorts across their adult working years, and the margins along which it falls, have not been fully established. How childhood lead exposure reshapes workers' careers across multiple dimensions of the labor market, whether the damage extends beyond what educational attainment captures, and whether childhood family resources can offset the harm are questions that require individual-level data linking adult wages, employment, and detailed occupations with childhood lead exposure and family socioeconomic status.

This paper uses a historical setting where exposed cohorts can be observed well into their working lives. During the late nineteenth and early twentieth centuries, American towns varied widely in the pipe materials used for municipal water delivery (13). Historical infrastructure records classify towns as using lead, a mixture of lead and other materials, or non-lead piping based on the materials reported in use at the time. Towns that adopted lead pipes tended to be larger and more industrial, a pattern of selection on observables documented in prior work (11, 13–15). The amount of lead leached from pipes into drinking water depended on local water chemistry, particularly pH and mineral content, which are determined by regional geology and stable over time (15–17). This interaction between pipe material and water chemistry creates a natural experiment: even among towns with the same pipe infrastructure, childhood lead exposure varied based on geologically determined water chemistry rather than municipal decisions or household choices. We link approximately 6.2 million men observed in the 1940 Census (ages 20–50) back to their

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childhood town of residence at ages 0–10, when developing nervous systems are most vulnerable to lead's effects (18–22). Combining these linked records with newly digitized data on historical pipe materials and water chemistry, we extend this established empirical framework from its prior focus on infant mortality and cognition to labor market outcomes measured at the individual level.

Comparing across pipe types, men who grew up in lead pipe towns with corrosive water earned 4.7% lower wages as adults, worked 0.67 fewer weeks per year, and were 1.1 percentage points more likely to be unemployed than men who grew up in non-lead pipe towns with similarly corrosive water. The earnings penalty reflects both where men work and how much they earn conditional on occupation: men from lead pipe towns were 2 percentage points more likely to work in below-median-wage occupations, and even within the same detailed occupation they earned 2.6% less than men from non-lead pipe towns, suggesting that lead exposure affected valued worker attributes beyond its effect on occupational sorting. Men from lead pipe towns show lower rates of childhood school attendance but no differences in self-reported years of completed education as adults.

The more tightly identified comparison exploits chemistry variation within pipe type. Among men who grew up in lead pipe towns, those in high leaching risk water environments earned 3.6% less than those in low leaching risk environments, while men in non-lead pipe towns show no differential outcomes across the same chemistry variation. This within-pipe-type contrast also reveals that corrosive water chemistry compresses the relationship between childhood socioeconomic status and adult earnings, reducing earnings for sons of middle- and upper-quartile fathers while having little effect on sons from the lowest quartile. Higher parental socioeconomic status did not shield children from the labor market harm caused by lead exposure.

This study contributes to the literature on lead exposure and economic outcomes in three ways. First, individual-level microdata allow us to examine the earnings penalty along two margins: occupational sorting and within-occupation wage losses, an analysis not possible with the town-level comparisons used in most historical studies of waterborne lead (13, 14, 23). By looking at multiple dimensions of individuals' labor market outcomes, these findings provide a measure of the costs exposed cohorts carry into adulthood. Second, our historical setting allows for a test of whether higher parental socioeconomic status can buffer children from environmental harm. Because the health risks of lead pipes were unknown during this period (24), families within a given town did not selectively avoid exposure, so heterogeneity by family background among households with comparable connection to municipal water largely reflects differences in the capacity to buffer against a common exposure rather than differences in exposure itself. The within-pipe-type chemistry contrast, which compares otherwise similar towns that differ only in geologically determined water chemistry, provides the tightest test of this buffering question. Finally, we contribute to the conversation on the impacts of lead exposure on educational attainment. We find that the earnings penalty is not accompanied by differences in self-reported years of completed education when individuals are adults, but is accompanied by a reduced likelihood of being in school as a child. Self-reported schooling in Census data is subject to heaping at grade-level milestones, and the institutional context of the High School Movement likely pushed children through grades regardless of cognitive capacity (25, 26). In our context, the earnings penalty appears to operate through channels that self-reported educational attainment may not capture, highlighting the value of directly observing labor market outcomes where possible.

Results

Geographic Variation in Waterborne Lead Exposure. As American cities expanded during the late nineteenth century, lead emerged as a preferred material for water service pipes due to its durability and malleability, with lead pipes typically lasting twice as long as iron or steel alternatives (13). Nineteenth-century engineers and health officials actively encouraged lead plumbing, lacking understanding of low-level lead exposure risks (24, 27, 28). Engineers argued that protective mineral coatings would quickly form within pipes and eliminate leaching risks (29, 30), though such coatings actually required decades to develop and provided incomplete protection (15, 24). The result was wide variation in pipe adoption across towns (Figure 1): of the 971 towns in our sample, 229 (23%) used lead pipes, 281 (29%) used a mixture of lead and other materials, and 461 (48%) used no lead piping. Together, these towns contained municipal water systems serving roughly 35% of the US population in 1900. After conditioning on categorical fixed effects for region, population, industry composition, metropolitan status, and other town-level attributes, towns with different pipe types are similar on a wide range of 1900 Census characteristics (SI Appendix, Table 3).

Water chemistry determines the extent to which lead leaches from pipes into drinking water, a property known as "plumbosolvency" (16, 31, 32). Low pH combined with low mineral content produces corrosive conditions that substantially increase lead dissolution. In less corrosive environments, the protective mineral scales that engineers had predicted do eventually form on pipe interiors, reducing but not eliminating lead leaching. We classify each town as High or Low Leaching Risk based on historical measurements of pH and water hardness, and cross this with the three pipe material types to yield six exposure cells (SI Appendix, Table 1). The highest-exposure group, Pure Lead × High Leaching Risk, contains 55 towns. All estimates compare outcomes across these six cells, with Non-Lead × High Leaching Risk as the omitted category. This structure yields two types of comparisons: across pipe types within the same chemistry environment (e.g., Pure Lead vs. Non-Lead towns, both with High Leaching Risk water), and within pipe type across chemistry environments (e.g., Pure Lead towns with High vs. Low Leaching Risk water). The second comparison is more tightly identified because it holds town-type characteristics fixed and isolates the effect of geologically determined water chemistry on lead dissolution. Complete details on data sources, variable construction, and the retrospective linking methodology are provided in the SI Appendix.

Employment and Earnings Impacts. Figure 2 presents estimates of the effect of childhood waterborne lead exposure on adult labor market outcomes. Each panel plots coefficients for the five treatment cells relative to the

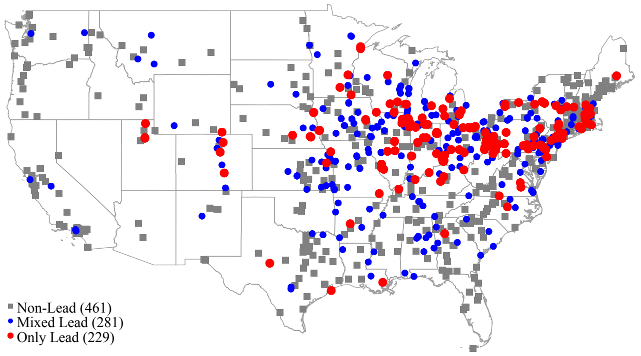


Fig. 1. Geographic distribution of the 971 towns in our analytical sample by water pipe material type. Towns are classified based on infrastructure records from *The Manual of American Water-Works* (1889–1897).

omitted category, Non-Lead towns in High Leaching Risk water environments (equation 1). All specifications absorb categorical fixed effects for the town-level attributes described in SI Appendix Section 3, as well as individual characteristics including age, race, household head's sex, occupation, and marital status, parental immigration status, homeownership, urban status, and group quarters status. Inverse probability weights account for differential selection into the linked sample, and standard errors are clustered at the pipe district level. Full regression results and variable definitions are provided in SI Appendix, Table 5 and Section 3.

Panel (A) of Figure 2 shows that men who grew up in Pure Lead × High Leaching Risk towns earned 4.7% lower wage and salary income than men from Non-Lead × High Leaching Risk towns ($p < 0.01$), conditional on positive earnings in the prior year. Panel (B) shows this same group of men worked 0.67 fewer weeks in the prior year ($p < 0.01$). Panel (C) shows they were 1.1 percentage points more likely to be unemployed at the time of enumeration ($p < 0.01$), a 13.4% increase relative to the 8.2% unemployment rate in Non-Lead towns. We find no effect on labor force participation.

The within-pipe-type comparison provides a more tightly identified estimate. Among men who grew up in Pure Lead towns, those in High Leaching Risk water environments earned 3.6% less than those in Low Leaching Risk environments ($p < 0.05$), worked nearly a full week less per year ($p < 0.01$), and were 1.1 percentage points more likely to be unemployed ($p < 0.01$) (SI Appendix, Table 5, Panel B). The same chemistry variation produces no differential effect on any outcome in Non-Lead towns, confirming that water chemistry affects labor market outcomes only in the presence of lead infrastructure. We do not find statistically significant effects for Mixed Lead towns in either comparison, consistent with lower average exposure from partial lead pipe coverage.

Occupational Sorting and Within-Occupation Wages. To better understand the earnings penalty, we examine two margins along which lead exposure could affect labor market outcomes: the types of occupations men hold and their earnings within those occupations. We classify occupations into two tiers based on occupation-level median earnings in 1940 and estimate whether lead exposure shifts the probability of working in a below-median occupation. Panel (A) of Figure 3 shows that men from Pure Lead × High Leaching Risk towns were 2.0 percentage points more

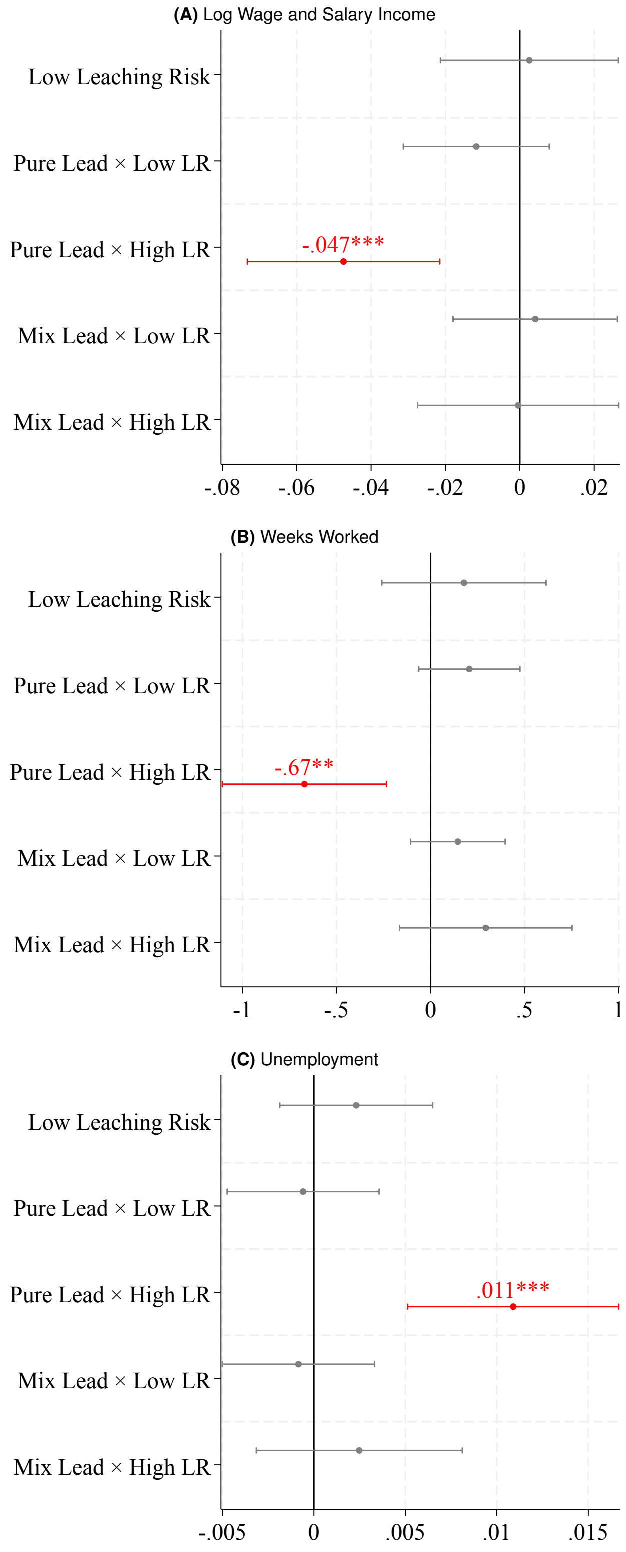
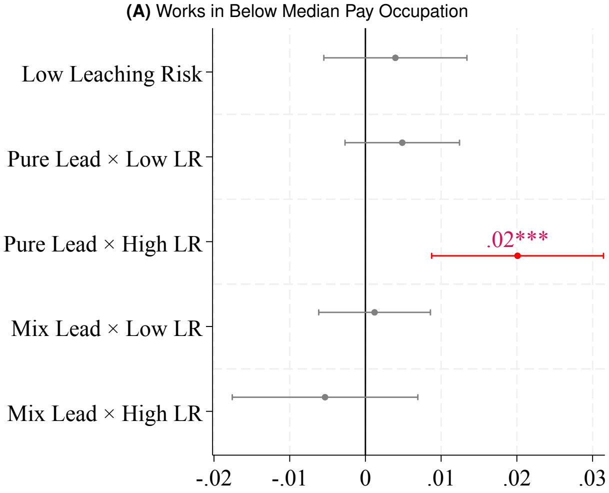


Fig. 2. Impact of childhood waterborne lead exposure on adult labor market outcomes. Each panel shows coefficient estimates and 90% confidence intervals from the primary IPW-weighted specification. The omitted category is Non-Lead pipes in High Leaching Risk environments. Pure Lead × High LR indicates towns with lead pipes and high lead leaching risk water chemistry; Pure Lead × Low LR indicates lead pipe towns with low leaching risk environments. Mixed Lead categories indicate towns using a combination of lead and other pipe materials. Standard errors clustered at the pipe district level. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

likely to work in lower-tier occupations than men from Non-Lead × High Leaching Risk towns ($p < 0.01$). Consistent with the earnings results, the within-pipe-type chemistry contrast is significant for Pure Lead towns and near zero for Non-Lead towns, and we find no significant effects of Mixed Lead pipe exposure on occupational sorting.


(A) Works in Below Median Pay Occupation

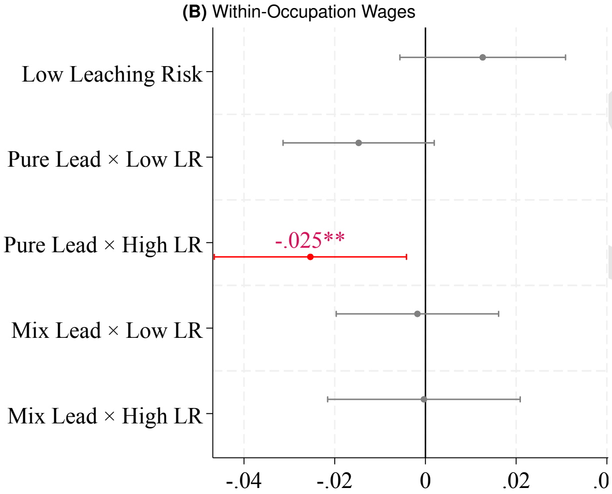

(B) Within-Occupation Wages

Fig. 3. Impact of childhood waterborne lead exposure on occupational sorting and within-occupation wages. In Panel (A), the dependent variable is an indicator for working in a lower-tier occupation, defined as below the occupation-level median earnings in 1940. Panel (B) augments equation (1) with 223 detailed occupation code fixed effects. Both panels show coefficient estimates and 90% confidence intervals from the primary IPW-weighted specification. The omitted category is Non-Lead pipes in High Leaching Risk water environments. Standard errors clustered at the pipe district level. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

A key advantage of our individual-level microdata over town-level aggregates is the ability to examine wage differences within occupation categories. Panel (B) augments equation (1) with fixed effects for 223 detailed 1950-basis occupation codes, comparing earnings among men in the same occupation. Men from Pure Lead × High Leaching Risk towns earned 2.6% less than men from Non-Lead × High Leaching Risk towns working in the same detailed occupation ($p < 0.05$). The within-occupation penalty is larger in High Leaching Risk environments than Low Leaching Risk environments, and the Non-Lead chemistry contrast remains near zero, confirming that the penalty operates through the chemistry channel. Because occupational placement is itself affected by lead exposure, the within-occupation estimate should be interpreted as descriptive: it indicates that the earnings penalty is not fully accounted for by the types of jobs men hold, but does not isolate a distinct causal channel. The finding is consistent with evidence that childhood lead exposure affects workplace-relevant skills and behaviors (15, 33, 34), though we cannot directly observe these pathways in the historical Census data.

Education. Despite the well-documented effects of lead on cognition and academic performance, we find no statistically significant effect of waterborne lead exposure on self-reported years of completed schooling in 1940 (SI Appendix, Figure 10, Panel (B)). We do find that children in Pure Lead × High Leaching Risk towns were less likely to be attending school at ages 6–10 ($p = 0.065$) (SI Appendix, Figure 10, Panel (A)). Self-reported schooling in Census data is subject to heaping at grade-level milestones, which may obscure real differences in attainment, and the null result does not rule out differences in the quality of learning during the same reported years of schooling.

Can Household Resources Buffer Against Lead Exposure? A central finding in the contemporary lead literature is that disadvantaged children bear a disproportionate burden of lead exposure. Today, African American and low-income children are two to three times as likely to have elevated blood lead levels (6), lead service lines are disproportionately located in lower-income communities (35, 36), and the long-run effects of childhood lead exposure on adult outcomes are larger for children from low-income households (8). These disparities reflect two interacting forces: disadvantaged families face greater exposure, and they may have fewer resources to buffer the developmental consequences of whatever exposure occurs. In modern settings, these forces are difficult to separate because exposure and household resources are strongly correlated.

Our historical setting offers an opportunity to isolate the buffering question. Lead service pipes were concentrated in large and relatively wealthy American cities (13, 14, 23), and because the health risks were not understood (24), entire city populations consumed water delivered through the same infrastructure with no avoidance behavior. Unlike the contemporary pattern, where wealthier families can reduce exposure through residential choices and home remediation (6), selective avoidance in our setting is unlikely. Heterogeneity we observe by household socioeconomic status among households with comparable connection to municipal water therefore largely reflects differences in the capacity to buffer against a common exposure rather than differences in exposure itself.

We examine heterogeneity by childhood socioeconomic status, proxied by father's predicted income quartile rank when the individual was ages 0–10 (measurement details in SI Appendix, Section 5.4). Race and immigrant background are natural additional dimensions suggested by the contemporary literature. However, nonwhite men are nearly absent from lead-pipe cities in our linked sample, with fewer than 3% of men in Pure Lead × High Leaching Risk towns being nonwhite, leaving insufficient variation to estimate differential effects by race (SI Appendix, Section 6.2). We find no differential effect by immigrant parentage, consistent with the historical exposure pattern in which all residents of a lead-pipe city faced similar waterborne lead regardless of national origin.

Figure 4 displays earnings by father's income quartile for Pure Lead and Non-Lead towns, estimated using across-town variation with the same town-level controls as the main specification. Mixed Lead results are reported in the SI Appendix. All coefficients are measured relative to a single baseline group (Non-Lead × High Leaching Risk × Q1), so both levels and gradients are directly comparable across town types (SI Appendix, Section 5.4). Because lead-pipe cities were wealthier and more industrial, the composition of father's income quartiles differs across town types: Q1 fathers account for 17% of the Non-Lead × High Leaching Risk population but only 5% of the Pure Lead × High Leaching Risk population. Comparing gradients across town types in Panels (A) and (B) must be interpreted with this compositional difference in mind. Panel (C) avoids this concern by comparing within Pure Lead towns across chemistry environments, where the Q1 share is similar (5–6% in both leaching risk groups).

Panel (A) shows that in High Leaching Risk environments, the two pipe types start at comparable Q1 earnings levels, confirming that the baseline is similar after conditioning on town characteristics. The Non-Lead gradient rises steeply: Q4 sons earn 10% more than Q1 sons ($p < 0.01$). The Pure Lead gradient is compressed: Q2 and Q3 sons show no earnings advantage over Q1, and Q4 sons earn only 4% more ($p < 0.05$). Panel (B) shows that in Low Leaching Risk environments, both pipe types display upward-sloping gradients of similar magnitude, confirming that lead infrastructure alone does not compress the SES gradient. The compression is specific to environments where chemistry promotes lead dissolution.

Panel (C) isolates the chemistry effect within Pure Lead towns by comparing High versus Low Leaching Risk environments at each quartile. Corrosive water chemistry reduces earnings at Q2 (-4%, $p < 0.01$), Q3 (-5%, $p < 0.01$), and Q4 (-3%, $p < 0.01$), with a small and insignificant effect at Q1. The Non-Lead chemistry contrast is near zero at every quartile (SI Appendix, Figure 9), confirming that water chemistry affects earnings only in the presence of lead pipes. Higher parental socioeconomic status did not shield children from the labor market harm caused by lead exposure in corrosive water environments: Q2, Q3, and Q4 sons all face significant earnings penalties while Q1 sons do not.

Discussion

Our findings establish that childhood waterborne lead exposure caused lasting labor market penalties. Men from lead pipe towns with corrosive water earned less, worked fewer weeks, and faced higher unemployment, with the within-pipe-type chemistry contrast confirming that these effects are driven by lead leaching rather than other correlates of urban infrastructure. The penalty operates along multiple margins of the labor market and is not offset by higher parental socioeconomic status.

Mechanisms Underlying Labor Market Penalties. The labor market penalties we document are not accompanied by differences in self-reported years of completed education, despite evidence from this same historical period that lead exposure reduced cognitive test scores (15). The birth cohorts in our sample (1890–1920) attended school during

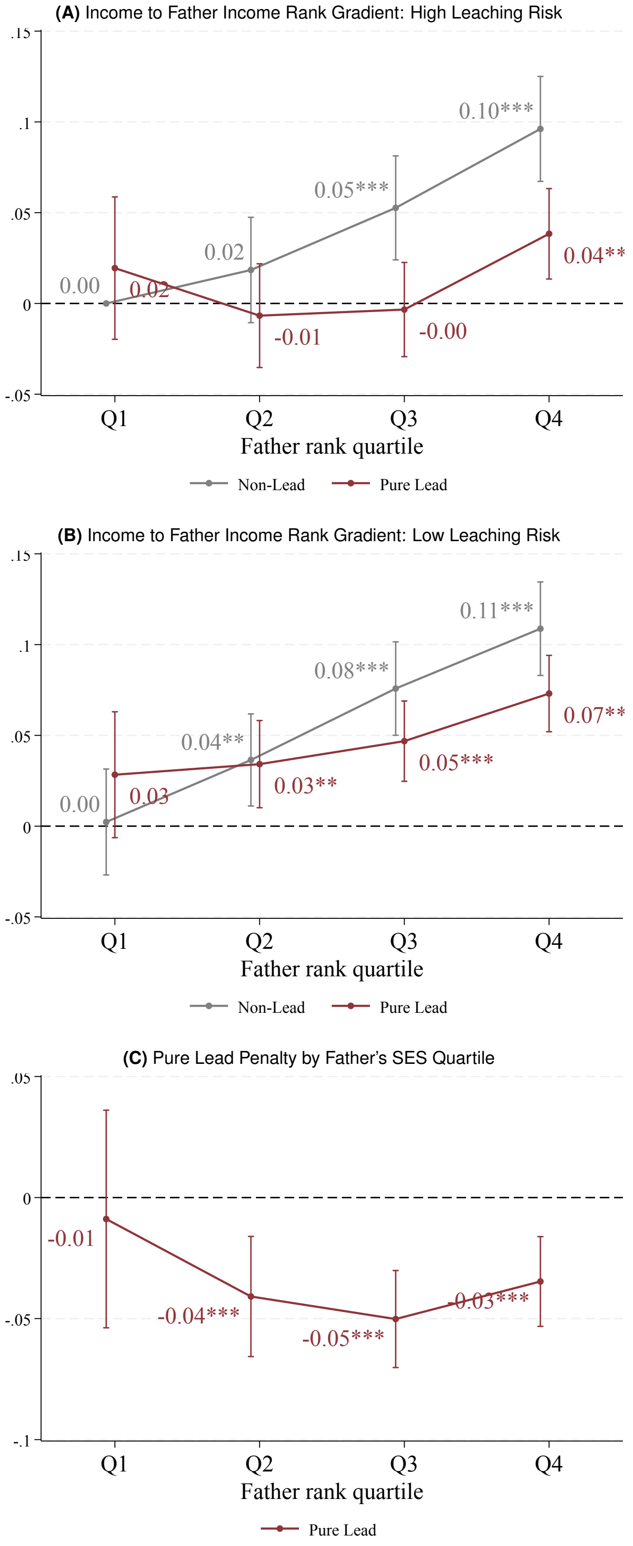


Fig. 4. Earnings by father's income quartile and pipe type. All coefficients are relative to Non-Lead × High LR × Q1, estimated using across-town variation with town-level controls and IPW weights. Panel (A): High Leaching Risk environments. Panel (B): Low Leaching Risk environments. Panel (C): Within-pipe-type chemistry contrast for Pure Lead towns (High LR minus Low LR at each quartile); Non-Lead placebo near zero at all quartiles (see SI Appendix). 90% confidence intervals. Standard errors clustered at the pipe district level. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

the High School Movement, a period in which secondary schooling expanded rapidly, driven by local institutional investment, compulsory attendance laws, and community wealth (25, 26). In this institutional environment, modest cognitive disadvantages attributable to lead exposure may not have translated into differences in reported attainment, particularly given that self-reported schooling in Census data is subject to heaping at grade-level milestones. The finding that lead-exposed men earn less even within the same detailed occupation is consistent with a broader literature linking childhood lead exposure to reduced cognitive functioning (11, 15, 20, 37), as well as behavioral and conduct problems that persist into adulthood (3, 33, 34). These capacities shape workplace performance and career progression in ways that Census data cannot directly observe, but that are consistent with the pattern of results we find.

Magnitude of Effects and Comparison to Prior Research. Our estimates are conservative for several reasons. First, our analysis captures only waterborne lead exposure. Men in our sample may also have been exposed through lead-based paint and occupational contact, meaning total lead exposure likely exceeded what our infrastructure-based measure reflects. Second, our intent-to-treat design assigns exposure based on town-level infrastructure and water chemistry rather than individual blood lead levels. Actual exposure varied within towns due to differences in water consumption, duration of residence, and household plumbing, so our estimates average across the exposure spectrum within treated towns. Third, any remaining endogeneity in pipe-type adoption is likely to bias our estimates toward zero. Because larger and more economically developed cities were more likely to adopt lead pipes, children raised in those cities would plausibly have experienced better labor market outcomes even in the absence of lead exposure, so simple comparisons across pipe types tend to attenuate the estimated negative effects of lead.

Our paper complements two recent papers exploring the relationship between earnings and lead exposure using modern policy variation. Reductions in airborne lead exposure for in-utero children from the U.S. Clean Air Act increased adult earnings by 3.5% (9). In Sweden, the phaseout of leaded gasoline increased earnings by an estimated 4%, though this is imputed from changes in educational attainment rather than directly observed wages (8). Our estimates are broadly comparable in magnitude to these other studies despite measuring a different exposure source (waterborne vs. airborne) in a different context, and despite the conservative features of our intent-to-treat design.

Heterogeneous Effects and the Compression of Socioeconomic Advantages. The compression of the intergenerational earnings gradient in lead-exposed towns speaks to a broader question about whether family resources can protect children from environmental harm. Our cleanest evidence is the within-pipe-type chemistry contrast (Figure 4, Panel C), which holds pipe material fixed and compares towns that differ only in geologically determined water chemistry: corrosive chemistry in Pure Lead towns reduces earnings for Q2, Q3, and Q4 sons, while the same chemistry variation has no effect in Non-Lead towns. Across-pipe-type comparisons at each quartile (Panels A and B) are broadly consistent but rely on our covariates fully absorbing cross-town compositional differences, which residual within-quartile variation in father's occupation mix suggests they do not fully do. One interpretation of the pattern is that lead exposure reduces the returns to the human capital investments that higher-SES families typically make in their children (38, 39): if lead impairs the cognitive and behavioral capacities needed to benefit from better schools, stronger networks, and greater parental investment, then the advantages these resources confer are diminished. We interpret the Q1 null with caution: both differential mortality selection prior to the 1940 observation (12) and unobserved within-town differences in actual lead exposure could contribute. Neither channel is directly testable in our data. The broader pattern of results — lead reduces earnings without reducing reported educational attainment — is consistent with the interpretation that the harm operates through capacities that family resources cannot easily replace.

Limitations. Several limitations warrant consideration. First, we cannot directly observe individual cognitive ability, behavioral outcomes, or other valued worker attributes in the Census data. The within-occupation wage penalty is consistent with lead-induced reductions in these capacities, but we cannot distinguish this from other sources of within-occupation earnings variation such as firm quality, work intensity, or chronic health conditions caused by lead exposure itself. Second, we observe each individual in a town at ages 0–10 but do not know the duration or precise timing of their exposure. The medical literature indicates that in-utero and early childhood exposure produce the largest developmental effects, but we cannot isolate these critical windows from later childhood exposure. Third, our analysis focuses exclusively on men because women's labor market participation was limited in this period. The effects of lead exposure on women likely operate through other margins, including fertility, marriage, and household production, that we do not examine. Fourth, nonwhite men are nearly absent from lead-pipe cities in our linked sample, preventing us from examining racial heterogeneity in the effects of lead exposure. Given the prominent role of racial disparities in the modern lead literature (6), this remains an important question that our data cannot address. Fifth, while conditional differences in household head characteristics across pipe types are small after town-level controls (SI Appendix, Table 4), parents who chose to live in lead-pipe cities may have differed on dimensions we cannot observe. The within-pipe-type chemistry contrast mitigates this concern because it compares families within the same type of city, and water chemistry was geologically determined and not a factor in household location decisions. Sixth, our inverse probability weights account for mortality between an individual's first census observation and 1940, but the direction of any remaining mortality selection is ambiguous: if the most severely affected individuals died before observation, our estimates understate the true effect, but surviving individuals may also carry chronic health burdens that contribute to the labor market penalties we measure.

Implications for Policy and Future Research. These findings are relevant for ongoing efforts to evaluate the costs and benefits of lead remediation. Current cost-benefit analyses of lead service line replacement focus primarily on health outcomes and cognitive gains. Our results indicate that the economic costs of lead exposure extend to labor market outcomes measured decades after childhood exposure, including reduced earnings, higher unemployment, and occupational downgrading. Accounting for these labor market costs alongside health effects provides a more complete picture of the returns to lead remediation, consistent with other work documenting broad economic returns to investments in water and sanitary infrastructure (40). We estimate annual per-person earnings losses of $950 to $1,350 in 2026 dollars, combining the wage penalty and increased unemployment (see SI Appendix, Section 6.3 for details). Over the 30-year working life observed in our data, cumulative losses range from $28,500 to $40,500 per exposed individual. The EPA estimates a central cost of $4,700 per full lead service line replacement, with a range of $1,200 to $12,300 (36). The per-person earnings losses we estimate exceed even the high end of replacement costs by a factor of two to three, and these losses reflect only male earnings from a single exposure source, omitting health costs, mortality, and effects on women. The SES findings add a distributional dimension: lead exposure compresses the returns to family background, suggesting that cost-benefit frameworks focusing only on average treatment effects may miss important consequences for economic mobility. Future research should prioritize examining the effects of lead exposure on women, on racial and ethnic minorities where data permit, and on outcomes later in the life course including health, disability, and retirement security (1).

Materials and Methods

Data Sources. The empirical analysis combines three primary data sources. First, individual-level data from the 1940 U.S. Decennial Census provide information on adult labor market outcomes (41). Second, we use the full-count 1900, 1910, and 1920 U.S. Decennial Censuses with person identifiers (HistIDs) provided by IPUMS (41) and cross-decade linkages from the Census Tree (42, 43). Third, hand-digitized historical sources on municipal water infrastructure and chemistry come from *The Manual of American Water-Works*, which documents service pipe materials at the town level, and U.S. Geological Survey publications documenting historical measurements of pH and hardness (44, 45). Full details on data sources, digitization procedures, and linkage methodology and rates are provided in SI Appendix, Section 1.

Sample Construction. Our sample is males ages 20–50 in the 1940 Census who can be linked to their childhood census record and who can be linked to town-level water infrastructure and chemistry information. We restrict the analysis to men because women's labor market participation was limited in this period. We link each individual back to their childhood Census record when they were ages 0–10, so that each individual in the sample has an initial observation (in either 1900, 1910, or 1920) and a 1940 observation. These sampling criteria yield 6.2 million men from 971 unique towns spanning all regions of the United States.

Measuring Childhood Lead Exposure. We categorize towns into three pipe material groups based on infrastructure records: Pure Lead (lead reported as the pipe material in use), Mixed Lead (a combination of lead and other materials reported), and Non-Lead (no lead pipes reported). To determine lead leaching potential, we predict theoretical lead solubility using Schock's solubility curves, which describe lead concentration as a non-linear function of pH and alkalinity (16, 31, 32). Because alkalinity is not consistently available in historical water quality records, we follow prior literature in using water hardness as a proxy and implement a Generalized Additive Model (GAM) fitted to digitized data from Schock's solubility figure. Towns are classified as High or Low Leaching Risk environments based on predicted lead solubility, with the threshold set at the 75th percentile of predicted values across all towns. This classification creates six exposure categories from the cross-classification of pipe type and leaching environment. As a robustness check, we provide the main results for two alternative classifications of High and Low Leaching Risk environments, at the 50th percentile of predicted lead values and at pH cutoffs used in prior literature (11, 15), in SI Appendix Section 7. Full technical details on the predicted lead solubility model, including extrapolation strategies for extreme pH and hardness values, are provided in SI Appendix, Section 2.

We provide evidence in SI Appendix, Section 4, that conditional on the town-level fixed effects used in all specifications, remaining differences in pre-existing town characteristics across pipe types are small and statistically insignificant.

Outcome Variables. The primary outcome is wage and salary income in 1939, constructed from 1940 Census questions on annual earnings from wages and salaries (excluding self-employment income, business profits, investment income, and government transfers). We also examine weeks worked in the previous year, unemployment status, labor force participation, and occupational category. Occupations are classified using harmonized 1950 occupation codes provided by IPUMS. We create two broad occupational tiers by splitting all occupations at the median of average occupation-level earnings in 1940: lower-tier occupations include laborers, service workers, and lower-skilled operatives, while upper-tier occupations include professionals, managers, craftsmen, and skilled operatives. All monetary values are expressed in 1940 dollars. Additional details on variable construction and treatment of missing or top-coded values are provided in SI Appendix, Section 3.

Empirical Specification. We estimate the effect of childhood waterborne lead exposure on adult labor market outcomes using ordinary least squares regressions of the form:

$$\begin{aligned} Y_{ic} = {} & \beta_1 \mathrm{LowLR}_c + \beta_2 \mathrm{PureLead}_c \times \mathrm{LowLR}_c \\ & + \beta_3 \mathrm{PureLead}_c \times \mathrm{HighLR}_c + \beta_4 \mathrm{MixLead}_c \times \mathrm{LowLR}_c \\ & + \beta_5 \mathrm{MixLead}_c \times \mathrm{HighLR}_c + X_i'\gamma + Z_c'\theta + \alpha_r + \varepsilon_{ic} \qquad [1] \end{aligned}$$

where Y_{ic} is the outcome for individual i who grew up in town c. The omitted category is Non-Lead pipes in High Leaching Risk (High LR) environments. The coefficient β_3 captures the effect of Pure Lead pipes in High LR water, while β_1 measures the main effect of Low LR environments for Non-Lead towns. Individual controls (X_i) include age, race, household head's sex, occupation, and marital status, parental immigration status, homeownership, urban status, and group quarters status. Region fixed effects (α_r) control for time-invariant regional differences based on childhood location. Town-level controls (Z_c) are absorbed as categorical fixed effects for population, industry composition, metropolitan status, proximity to large cities, water system characteristics, and mining activity. Standard errors are clustered at the pipe district level, which groups towns sharing a common water system (824 clusters). Inverse probability weights are used to weight an individual back to their representation in their original census observation (46). Unweighted results are comparable and reported in SI Appendix 7.

For occupational sorting analysis, we estimate equation (1) separately for an indicator of lower-tier occupation. For within-occupation wage analysis, we augment equation (1) with 223 detailed occupation fixed effects, comparing earnings among workers in the same occupation. For heterogeneity analysis by childhood socioeconomic status, we interact equation (1) with the four father income quartiles. Complete variable definitions, regression specifications, and robustness checks are provided in SI Appendix, Sections 3, 5, and 7.

Validation of Research Design. To support the validity of our research design, we conduct several tests. First, we show that conditional on the town-level fixed effects used in all specifications, towns with different pipe materials are balanced on pre-exposure demographic and economic characteristics observed in the 1900 Census (SI Appendix, Table 3), and that household head characteristics are similarly balanced at the individual level (SI Appendix, Table 4). Second, we demonstrate that leaching risk is not systematically correlated with pipe type choice (SI Appendix, Figure 8). Third, we show that linkage rates from childhood to adulthood do not vary systematically with pipe type or leaching environment (SI Appendix, Figure 2). Finally, we conduct robustness checks including alternative chemistry cutoffs, state fixed effects, town-level leave-one-out estimates around the highest exposure group, and excluding modern pipe assignments (SI Appendix, Section 7).

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