Economic Consequences of Childhood Exposure to Urban Environmental Toxins*

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Abstract

During the late nineteenth century, half of all municipalities installed lead water pipes, exposing millions of people to harmful levels of lead consumption. This paper explores the long-term, and intergenerational, effects of waterborne lead exposure on men's labor market outcomes using linked samples drawn from the full count censuses. For identification, we leverage variation in lead pipe adoption across cities and differences in the chemical properties of a town's water supply, which interact to influence the extent of lead leaching. Results show adult men with higher levels of waterborne lead exposure as children have lower incomes, worse occupations, and lower levels of completed education compared to adult men who had lower levels of waterborne lead exposure as children. Men who are exposed to higher levels of waterborne lead have a significantly decreased probability of improving their income rank relative to their fathers, which is consistent with lead exposure behaving like a negative place-based shock that constrains upward mobility.

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1 Introduction

People around the world have experienced consequential levels of lead exposure throughout much of the nineteenth and twentieth centuries. Lead exposure has come through a variety of sources including occupational exposure, lead contaminated drinking water, fuel emissions, lead-based paint, and contaminated soil. The medical and epidemiological evidence is now explicitly clear that lead is harmful at any level of exposure, and can adversely affect an individual's health, especially when exposed to lead as a child (Bellinger et al., 1992; Borja-Aburto et al., 1999; Hu et al., 2006; Needleman, 2004). For young children, these adverse health effects have resulted in worse birth outcomes, impaired cognition, and higher rates of mortality (Dave and Yang, 2022; Aizer et al., 2018; Clay et al., 2014). Among adolescents, this has led to lower test scores, behavior problems, and lower levels of educational attainment (Hollingsworth et al., 2022; Aizer and Currie, 2019; Grönqvist et al., 2020).

We know less about the detrimental effects of lead in later adulthood, particularly how it affects outcomes in the labor market.[1] Prior work focusing on educational attainment has imputed earnings losses based on returns to education (Grönqvist et al., 2020; Hollingsworth et al., 2022). Our paper uses individual-level US census data linked from 1900 to 1940 to directly estimate the impact of childhood exposure to lead-contaminated water on long-run labor market outcomes, including income and occupational choices. Additionally, we consider the impacts of lead exposure on educational attainment, spatial mobility, and intergenerational income mobility.

In the late nineteenth and early twentieth century, the dominant form of lead exposure for children in the US was waterborne lead. Over this period, many towns constructed water infrastructure systems that included lead service pipes which connected main water lines to individual residences and businesses.[2] Lead leached from these lead pipes

[1]Among later adult outcomes, Hollingsworth and Rudik (2021) and Lee et al. (2022) both find negative effects of lead exposure for mortality and cognition among the elderly.

[2]Experts and government officials now recognize that the use of lead as material in water infrastructure

and was introduced into drinking water, representing substantial exposure to this environmental toxin.

Our empirical strategy leverages variation in the intensity of waterborne lead exposure due to the pipe material (lead vs. non lead) used and the chemical properties of the local water supply. More corrosive water increases the amount of lead leached from lead pipes, which exposes individuals to higher levels of waterborne lead. Our approach builds on a rich literature that exploits similar differences in water source chemistry to identify the causal impacts of lead. Troesken (2008) and Clay et al. (2014) leverage variation in waterborne lead exposure to show a strong link between lead exposure and elevated infant mortality. Ferrie et al. (2012) and Lee et al. (2022) both find a negative relationship between lead exposure and cognition measured at different stages of life. Work in contemporary settings exploits changes in chemistry from changes in municipal water sources and find worse birth outcomes, education score, and lower housing prices (Dave and Yang, 2022; Zheng, 2021; Christensen et al., 2023).

The causal interpretation of the relationship between waterborne lead exposure and long-run adult labor market outcomes, including intergenerational income mobility, relies on the central assumption that variation in water chemistry is plausibly exogenous to the outcomes of interest. Critical for identification purposes, the chemistry of the local water source was exogenously determined by local geology and was not a consideration when towns chose whether or not to use lead service pipes. This helps alleviate the selection concerns where lead pipe adoption was more likely among larger and wealthier towns (Clay et al., 2014; Feigenbaum and Muller, 2016). In our preferred empirical specifications, we exploit differences in pH and hardness across towns and we show that towns with and without lead pipes have similar water chemistry.

For our analysis, we build an individual-level dataset from the full count population censuses in 1900 and 1940 (Ruggles et al., 2021), where we link men between the two

systems significantly increases exposure to the toxin. Amendments to the 1986 Safe Drinking Water Act prohibit the use of lead as a material in public water systems and residential plumbing.

decades, and combine this with town-level information on the type of service pipes and local water chemistry. We construct our linked samples using young men between the ages of 0 and 20 in 1900 linked to their census record in 1940 (Abramitzky et al., 2020). The full count censuses in each decade identify a limited number of towns. We apply the detailed town information from Berkes et al. (2023) to increase the number of towns that can be identified in the full count censuses. Due to the challenges of linking women across decades, primarily due to name changes that occur with marriage, we focus only on men. Similar to prior literature, we digitize town water system information from Baker (1897), and water chemistry information for the US Geological Survey in 1952 (Lohr and Love, 1954).

Findings show a strong negative relationship between childhood waterborne lead exposure and long-run labor market outcomes. Individuals exposed to a higher intensity of waterborne lead, driven by corrosive water, experienced 4 – 5% lower wage and salary incomes in 1940 compared to individuals exposed to lead pipes and less corrosive water conditions. These same individuals do not experience a difference in their probability of being in the labor force, but they do have significantly lower levels of completed education and lower occupational prestige scores. Evidence suggests that individuals with more childhood waterborne lead exposure are sorted into occupations with lower median earnings.

We use family information within the 1900 census to consider whether lead exposure affects intergenerational mobility. Our measures of intergenerational mobility focus on changes in the income rank of sons relative to their fathers. Results reveal a sharp negative relationship between lead exposure and the likelihood of the son having an improved income rank relative to their father. Consistent with other literature showing that higher socio-economic status can mitigate the negative impacts of lead exposure (Ferrie et al., 2015; Grönqvist et al., 2020; Hollingsworth et al., 2022), heterogeneity analysis shows that young men whose fathers were in the upper part of the income distribution did not experience lower rates of economic mobility. The results demonstrate how local shocks, like lead exposure, can behave like a negative place-based shock that constrains upward mobility.

This paper contributes to three literatures. First, this paper complements the literature on lead exposure among adolescents and adults. Our findings reinforce the educational attainment results in Grönqvist et al. (2020) while sharpening our understanding of the impacts on earnings, by directly estimating the effects on income. Our paper is also the first to examine occupational sorting, where we find that lead exposure, and subsequent education decisions, induced young men to sort into lower paying occupations.

Second, our paper builds on the existing work that assesses the impact of lead exposure in historic contexts (Troesken, 2008; Clay et al., 2014; Feigenbaum and Muller, 2016). Most of the prior work relies on comparisons of town-level outcomes over time, whereas our paper takes advantage of the availability of individual-level data.[3] In this way, we complement recent work that uses granular data to evaluate the impact of the introduction of water systems in the early twentieth century (Beach et al., 2016; Beach, 2022; Coury et al., 2022).

Finally, we add to the literature on intergenerational mobility. Our paper builds on a growing literature that considers how policies and other local shocks contributed to changing intergenerational mobility over time and across locations (Olivetti and Paserman, 2015; Tan, 2023; Ward, 2022). Our findings are consistent with lead exposure behaving like a local shock that produced local differences in intergenerational mobility. This highlights the potential role of infrastructure in shaping patterns of mobility and relates to recent work on the importance of place for explaining differences in economic mobility (Chetty et al., 2014; Chetty and Hendren, 2018).

[3] For exceptions that use linked individual-level data see, Ferrie et al. (2012) and Lee et al. (2022).

2 Pathways Linking Lead and Adult Outcomes

It is now well known that lead is highly toxic to humans, and absorption interferes with the body's normal processes (Bradbury and Deane, 1993; Needleman, 2004).[4] Exposure to lead starts as early as *in utero*, when a mother's lead levels can affect fetuses, as lead can cross the placenta and be absorbed by the fetus (Needleman, 2004; Manton et al., 2003). Exposure and absorption of lead continue throughout life as breast milk contains lead leached from the mother's bones (Gulson et al., 1998), and the toxin is directly ingested via lead-contaminated substances.

For this paper, there are two salient characteristics of how lead impacts individuals. First, lead affects children differently than it does adults. Children absorb lead five times more efficiently than adults (Hammond, 1982; Bellinger, 2004) and children have immature central nervous systems that are more vulnerable to lead poisoning than mature adults (Needleman, 2004). For this reason, we focus on a sample of individuals who were exposed to lead-contaminated drinking water between the ages of 0 - 20.

The second salient characteristic is that the body does not expel lead quickly. Repeated exposure to the toxin accumulates in an individual's bones, which can impact the level of lead in their blood years later (Troesken, 2006; Ferrie et al., 2015). Therefore, we would expect childhood exposure to the toxin may have both immediate and lasting impacts. Prior literature has documented the lasting impacts of childhood exposure to lead, this is summarized in Grönqvist et al. (2020).

2.1 Lead Exposure in the Nineteenth Century

In the late nineteenth century, a common form of lead exposure was from ingesting lead-polluted water (Troesken, 2006).[5] As the population began to grow and urbanization

[4] For a summary of the medical literature see Needleman (2004).

[5] In the late twentieth century, common forms of lead exposure shifted to be from the inhalation of dust and fumes containing lead, and the ingestion of lead-tainted paint.

occurred in the latter half of the nineteenth century, towns began to implement organized water infrastructure systems. Lead was a common choice of material to use for water pipes because it was durable and cost-effective in the long run, with lead pipes typically lasting twice as long as iron or steel pipes (Troesken, 2008). Pipes that connected main water lines to individual residences, commonly known as service pipes, were often made of lead.[6] Water that runs through lead pipes leaches lead from the pipe into the water, causing town inhabitants to drink lead-polluted water.

Two properties of water, pH, and alkalinity interact to influence the amount of lead that can be leached into the water running through lead pipes.[7] Figure 1 depicts the relationship between the amount of lead in water, caused by running through a lead pipe, and the pH and alkalinity of the water.[8] The more acidic the water (i.e. the lower the pH), the more lead is leached into the water. If the water is more acidic, the amount of lead leaching into the water also depends on the alkalinity of the water. Below a pH of 7.3, lower levels of alkalinity indicate more lead is leached into the water from a lead pipe.

Engineers and health officials in the nineteenth century encouraged the use of lead plumbing, not understanding how much lead leaches into the water via lead service pipes and the risks of low-level lead exposure (Troesken, 2006; Committee on Service Pipes, 1917; Journal of the American Medical Association, 1942).[9] The scientific community at the time focused on the effects of very high levels of lead exposure, due mainly to occupational exposure. A common engineering principle at the time, known as the Doctrine of Protective Power, informed engineers and public health officials that lead pipes were safe to use if the water supply was not corrosive (Troesken, 2006). While this advice was correct, it was not followed. Many city officials and water supply companies ignored the portion of the Doctrine of Protective Power that considered the chemical properties of the

[6] In addition to lead service pipes, lead solder was also commonly used to join segments of piping.

[7] The diameter and length of pipe can also influence how much lead was leached into drinking water (Schock, 1990). However, this information is not available for the sample used in this paper.

[8] This figure is based on Schock (1990) and Clay et al. (2014).

[9] One notable exception was Swann (1892), who postulated that lead leaching from lead plumbing was a problem, but he did not have robust scientific evidence to prove it.

water supply, and universally assumed lead pipes were safe to use everywhere (Troesken, 2006).[10] It was commonly argued that a protective coating quickly formed within a lead pipe, removing the risk of lead leaching into water (Adams, 1852; Lindsay, 1859). While a protective coating can form, it can take decades to do so and may not completely mitigate the risk of lead leaching into the water (Troesken, 2006; Ferrie et al., 2012).

Contemporaneous evidence demonstrates that lead was indeed being leached into drinking water in the late nineteenth century, at what is now considered dangerous levels. In 1900, the Massachusetts State Board of Health calculated the lead content in water for twenty-two towns in Massachusetts. For the ordinary use of water, the average lead content was 51 times the current EPA threshold.[11] If water was allowed to stand in the pipes for a few hours, the average lead content was 114 times the current EPA threshold.

2.2 Pathways Linking Lead Exposure and Long-Run Labor Market Outcomes

There are three main pathways linking lead exposure and long-run labor market outcomes. The fist pathway through which lead may impact long-run labor market outcomes, is lead's negative impact on cognition and intelligence. Decreased cognitive functioning and intelligence may influence one's earning power and occupation. There is a large body of literature documenting that lead exposure, even at very low doses, decreases test scores, cognitive functioning and intelligence (Needleman and Gatsonis, 1990; Canfield et al., 2003; Dorsey et al., 2006; Stewart and Schwartz, 2007; Ferrie et al., 2012; Aizer et al., 2018). While much of this evidence is based on present day data and blood lead levels, Ferrie et al. (2012), use data on WWII U.S. Army enlistees, to show that enlistees exposed to more waterborne lead, measured by using the type of water pipes and

[10] Clay et al. (2014) also notes an article from *Engineering News* in 1916, stating that concerns over lead pipes were inflated. Similarly, several articles from the *Journal of the American Medical Association* in the 1940s argue lead pipes were safe for consumers.

[11] The current EPA threshold for lead in drinking water is 15 parts per billion. Some researchers are calling on the EPA and the CDC to reduce this threshold even more, see Bellinger (2008).

the pH of the water an enlistee was exposed to, had lower scores on the Army General Classification Test, a proxy for intelligence. In a similar spirit, Ferrie et al. (2015), shows that WWII draftees were less likely to be assigned to the Army Air Corps, where the most intelligent and disciplined recruits were assigned, with increased exposure to waterborne lead.

Second, lead exposure negatively impacts one's health, leading to a variety of conditions such as anemia, kidney failure, renal failure, nerve disorders, irregular red blood cells, hypertension and decreased fertility (Needleman, 2004; Clay et al., 2014; Borja-Aburto et al., 1999). Being in worse health impacts an individual's ability to work full time, the type of occupation they can get and their performance. Being in worse health as a child may also influence an individual's ability to attend school, as they may not physically be able to go to school every day and may drop out of school sooner than they otherwise would have.

Third, lead exposure may influence long term labor market outcomes by increasing the likelihood of behavior and conduct problems. In a meta-analysis by Marcus et al. (2010), a review of 19 studies shows increased exposure to lead is associated with conduct disorder, oppositional defiant disorder, aggressive and violent behavior, and delinquent, antisocial and criminal behavior.[12] Lead exposure is also strongly associated with Attention Deficit/Hyperactivity Disorder (ADHD) in children and adolescents.[13] Neuroanatomical findings support the association between lead exposure and behavior and conduct problems (Cecil et al., 2008). Using whole brain MRI scans, childhood blood lead levels are found to be linked to a loss of gray matter in the brain. The loss of brain matter occurs specifically in the anterior cingulate cortex (ACC), which is associated with mood regulation, executive functioning, and decision-making. These neuroanatomical findings were more pronounced for males than for females, suggesting heterogeneous impacts by

[12] More recent studies, such as Reyes (2015) have also shown a strong causal link between lead exposure and delinquent behavior.

[13] Goodlad et al. (2013) provides a meta-analysis of this relationship, synthesizing 33 studies on this topic.

sex (Cecil et al., 2008).

One consequence of the behavior and conduct problems caused by lead has been an increase in crime. Using variation in exposure to lead via lead polluted water and leaded gasoline several papers have found increased lead exposure is linked to increases in criminal behavior (Reyes, 2007, 2015; Feigenbaum and Muller, 2016).[14] In particular, Feigenbaum and Muller (2016) look at exposure to waterborne lead and find cities' use of lead service pipes increased homicide rates in the early twentieth century.

This paper identifies the reduced form impact of exposure to waterborne lead on adult labor market outcomes; it does not identify the importance, or weight given, to each pathway. Focusing on exposure to waterborne lead, rather than contemporary diagnoses of lead poisoning, incorporates the fact that the scientific community now knows that even extremely low levels of lead can have adverse effects on individuals (Bellinger et al., 1992).

3 Data, Sample Selection, and Summary Statistics

Our data construction process focuses on measuring labor market outcomes in adulthood and lead water pipe exposure during childhood. We construct an individual-level linked dataset spanning from 1900 to 1940 from the full population censuses. Higher rates of mobility in the first half of the twentieth century imply we cannot infer lead exposure based on the place of residence in 1940, but instead need to determine an individual's place of residence during childhood. To do this, we build on two recent advancements that increase access to the person-level full population censuses between 1900 and 1940. First, we follow young men, between the ages of 0 - 20, in 1900 into adulthood in 1940 using linked crosswalks developed by Abramitzky et al. (2020). Second, we assign lead exposure using location information in the 1900 census. Location information in publicly

[14]Looking specifically at blood lead levels, Needleman et al. (2002), found lead levels were four times higher among convicted juvenile offenders than among other high school students not convicted of a crime.

available samples was limited to larger cities, but recent work by Berkes et al. (2023) significantly expanded location availability in the individual-level data. We apply their location crosswalks to our linked sample, resulting in specific place assignments for over 90% of our dataset. We measure labor market outcomes in 1940. Our primary outcomes of interest are total wage and salary income, occupation and total years of education.

Taken together, these two advancements allow us to assign lead exposure to young men based on their place of residence in 1900 and then evaluate the long-term effects of this lead exposure in later adulthood. In order to mitigate mismeasurement concerns, we *exclude* anyone captured in the following conditions: 1) birthplace does not match their state of residence in 1900 2) recorded year of birth differs significantly from a birth year inferred from their reported age 3) relationship to the household head in 1900 is not a child 4) the individual lives in a rural household in 1900.

We combine this individual-level census data with information on the type of pipes used in an individual's town water infrastructure and the chemical properties of the water supply. Town water system information was recorded in *The Manual of American Water-Works* Baker (1897). The manual reports service pipe information for all major cities and many smaller locations, as well as the year of system construction. We categorize lead towns as those locations reporting any use of lead service pipes. Town water chemistry information was published by the United States Geological Survey in "The Industrial Utility of Public Water Supplies in the United States, 1952" (1954). From this report, we record the pH and hardness of the historical water sources for each available town.

Finally, we restrict our sample to six northeastern states and focus exclusively on the places within those states that report water system pipe information and were constructed after 1840. This results in a final sample of roughly 200,000 adult men in 1940 drawn from 116 places where we observe water system pipe information in 1900. Figure 3 plots the location of each town in our dataset with water system information from Baker (1897). The figure distinguishes towns by whether they used any lead for the town service pipes.

Table 1 illustrates the characteristics of the matched men in the sample within the set of observed towns with service pipe information. Panel A reports characteristics from childhood in 1900, panel B reports outcomes of interest in 1940, and panel C reports features related to intergenerational mobility which we will discuss in section 5. The average age in 1900 is 8, and the average family size is 6 people. There are very few non-white individuals in the sample, and 92% live in a household with a male head. These same individuals in 1940 have an average wage and salary income of $1,880 USD, and 31% have completed high school.[15]

Our fundamental empirical comparisons are between individuals exposed to lead through their water systems to individuals whose water system did not expose them to lead leaching. This comparison raises concerns regarding selection into the types of cities that chose to incorporate lead pipes into their water systems. Section 2 highlights that health concerns did not influence the adoption of lead pipes. Both Clay et al. (2014) and Feigenbaum and Muller (2016) show that population and wealth were the predominant factors contributing to lead adoption.

Table 2 presents town-level summary statistics aggregated from the 1900 individual-level census for the sample of 116 towns with water system information. Columns 1 and 2 present the means and standard deviations of each measure split by lead and non-lead status. Column 3 reports the unconditional differences in means with the standard errors reported in brackets. The results reveal the strong population differences highlighted in prior work, along with differences in industrial composition as well. The results indicate that lead towns were significantly larger, had higher shares of manufacturing and retail employment, and had a smaller fraction of the population employed in farming.

Column 4 reports conditional differences between lead and non-lead cities. The column introduces state fixed effects, decile town population fixed effects, and decade fixed effects for the year of construction. The fixed effects restrict the comparisons to towns

[15]The 1940 census top-coded incomes above $5,000 and we exclude those individuals from any specifications that rely on income.

of similar size making construction decisions along similar time horizons. Figure 2 illustrates the variation in construction timing by the type of water system. The differences in column 4 suggest only the share of the population employed in farming remains significant following the inclusion of the fixed effects. Column 5 repeats the same conditional comparison for the 76 towns where we observe chemistry information. Within this sample of towns, we no longer observe statistically significant differences in demographic or economic conditions between lead and non-lead towns.

4 Persistence of Lead into Adulthood

4.1 Estimating Equation

Our empirical approach and predictions are motivated by three facts that emerge from the history of lead pipe adoption, as outlined in Section 2, and how lead is transmitted under different water chemistry conditions as illustrated in Figure 1. First, we expect individuals exposed to waterborne lead during childhood to face worse long-run economic outcomes on average than individuals not exposed to waterborne lead. Second, individuals exposed to lead pipes with *more* acidic water (i.e lower pH) should have worse average long-run outcomes than those exposed to lead pipes with less acidic water (i.e. higher pH) because lead leaching is worse in acidic conditions. Finally, variation in alkalinity *within* low pH water can additionally affect lead leaching. We expect that individuals living in cities with both more acidic water (low pH) and low hardness, which is highly correlated with alkalinity, would experience worse long-run outcomes than individuals living with lead pipes and less corrosive water chemical environments.

We test these three predictions by estimating the following equation:

$$y_{it} = \beta_1 lead_t + \beta_2 Corrosive_t + \beta_3 (lead_t \times Corrosive_t) + X'\delta_i + \tau_t + \rho_t + \psi_s + \epsilon_{it} \qquad (1)$$

where y_{it} is the outcome of interest for individual i who lived in town t in 1900. A town's lead status, $lead_t$, equals 1 if the town's service pipes included lead. We include a binary measure of water chemistry, $Corrosive_t$, which equals one if the town's water chemistry contributed to higher levels of lead leaching into the water supply. We include a vector of individual-level controls taken in 1900, including race, immigrant status, parent's immigrant status, sex of the household head, metropolitan status, and age.[16] Each element of X enters the model as a separate fixed effect. The specification includes the town-level controls as discussed in section 3. These include town population decile fixed effects, τ_t, year of construction decade fixed effects, ρ_t, and state fixed effects, ψ_s. Standard errors are clustered by town $\times$ 5-year age bins, to allow for correlations between similarly aged individuals within the same towns in 1900. From our predictions, we expect both β_1 and β_3 to be associated with worse outcomes.

Figure 4 illustrates the town-level variation in water chemistry, pH and hardness, and the vertical and horizontal lines help distinguish the thresholds used to define our chemistry interactions. We define more corrosive water as the intersection of low pH and low hardness, this includes all individuals in towns in the lower left corner of Figure 4. The interaction of these two conditions is more corrosive than low pH on its own and we would expect negative impacts of lead to affect individuals from these towns more than under less corrosive chemical conditions. Appendix figures A1 and A2 show maps of lead service pipe status and water corrosiveness measures by location.

4.2 Lead and Adult Outcomes

Table 3 presents results from estimating equation 1, where the outcomes of interest are wage and salary income and labor force participation. These two outcomes allow us to evaluate the impact of lead exposure on the intensive and extensive margins of the labor market. Each outcome is presented in a separate panel and each column presents

[16]See Table 1 for more information about each variable.

a slight variation of equation 1. Column 1 presents results from a specification with a single binary lead exposure treatment over the full sample of individuals and includes the complete set of covariates and fixed effects described above. In panel a, the resulting coefficient of interest indicates that childhood lead exposure is associated with large, negative differences in wage and salary income, but panel b shows no differences in extensive margin labor force participation. Column 2 focuses on individuals drawn from the set of towns with chemistry data and finds a smaller negative relationship between wage and salary income and childhood lead exposure.

Columns 3 and 4 introduce the chemical property interactions from the fully specified equation 1. The chemistry interaction in column 3 isolates locations with more acidic water (low pH), where we expect elevated lead exposure. The two coefficients of interest align with the first two predictions above. Lead exposure on its own is associated with slightly lower wages, with more detrimental wage differences being concentrated among individuals that grew up in towns with lead service pipes and more acidic water supplies. Column 4 provides an initial test of the third prediction, that the combination of highly acidic water and low hardness should have worse effects on adult outcomes. The specification replaces the low pH interaction term, with a binary term that equals one if the town has low pH *and* has a hardness below 40. The coefficients of interest support this prediction, with individuals growing up in more corrosive lead environments earning roughly 5 percent less than individuals that grew up in towns with lead pipes with less corrosive conditions.

The results in columns 2 – 4 are suggestive of lead exposure having a strong negative effect on wage and salary earnings, with no impact on labor force participation. Given the conditional balance in town characteristics for this sample in Table 2 and the historic narrative supporting positive selection by towns into adopting lead pipes, we believe these estimates are identifying a causal negative impact of lead exposure. Column 5 adds additional support for this claim by restricting the specification to only evaluate the effect of highly corrosive water conditions on wage and salary earnings for individuals that lived in towns with lead water systems. The results indicate that adult wage and salary earnings for individuals that grew up in lead towns with more corrosive water are 4 percent lower on average than earnings for individuals that grew up in lead towns with less corrosive water.

Earnings differences of 4 – 6% are larger in magnitude than those associated with other public health interventions, like reducing typhoid (Beach et al., 2016), but are in line with historic benefits from developing public health programs (Hoehn-Velasco, 2021) and contemporary estimates of the imputed wage effects of lead exposure in Sweden (Grönqvist et al., 2020).

Table 4 provides some insight into the channels that could explain these results. The top panel introduces completed years of education as the outcome of interest and repeats the prior five specification table structure. The results suggest that lead exposure during childhood is associated with lower completed years of education. The point estimate in column (2), which features a binary lead treatment and is restricted to the sample of cities with chemistry data, suggests that childhood lead exposure is associated with 0.293 fewer years of education. Similar to the earlier patterns, these effects are largely driven by childhood residents of lead cities with worse chemical environments. The results indicate that individuals that grew up in a particularly corrosive environment faced reduced education levels of over 1/3 of a year.

These reductions in educational attainment coincided with the rapid secular rise in education levels, as high school attendance and completion rates grew considerably over this period (Goldin, 1998). Given the high returns to education during this period, a large fraction of the income result is likely explained by lower educational attainment (Goldin and Katz, 1999; Feigenbaum and Tan, 2020; Clay et al., 2021). Table 4 panel B switches the focus to occupation and introduces the occupational income score from IPUMS. The coefficient patterns that result from using occupational income scores mirror the earlier results using wage and salary income, however, the magnitudes are slightly lower. This likely reflects the fact that these scores are determined based on median earnings within each occupation, which compresses the variation relative to wage and salary income. The panels suggest that lead exposure contributed to both lower levels of educational attainment and lower median salary occupations.

Table 5 partitions the continuous measure of educational attainment into three binary measures based on attainment cutoffs relevant to the era. The top panel focuses on the first major inflection point in educational attainment, the decision to stop schooling after middle school (grade 8). Over 86% of the sample completed middle school, but only 48% went on to pursue any additional education. The results in panel a suggest that lead exposure contributed to many young men stopping schooling and not continuing into high school. It similarly lowered the likelihood of completing high school (panel b) and attempting any post-secondary education (panel c). Given the overall increases in high school completion rates during this era and the transition to more educational requirements, these sharp declines in attainment around key education thresholds likely contributed to lower earnings and occupational quality (Goldin, 1998).

Figure 5 directly explores differences in occupational sorting by estimating the effect of lead exposure on whether an individual's occupation was in one of the ten single-digit occupational categories in the census. Each point estimate in the figure is from a separate regression of the chemistry interacted specification that exploits low pH (column 3 from prior models). The ten occupational categories are sorted from the lowest average income to the highest average income, which helps illuminate a pattern where men facing higher levels of lead exposure were more likely to be working in lower paying occupations like laborers and operatives and were less likely to be working in professional occupations. Many of these white collar positions included educational requirements, making them inaccessible to the young men that did not complete high school, and included relatively high wage premiums (Goldin and Katz, 1995).

5 Lead and Intergenerational Mobility

Education and occupation are two key channels that influence intergenerational mobility Parman (2011); Long and Ferrie (2013); Olivetti and Paserman (2015); Tan (2023); Ward (2022). Section 4 documents that lead exposure is associated with lower earnings, reduced educational attainment, and increased likelihood of sorting into lower paying occupations, all of which could affect upward mobility. In this section, we evaluate whether lead exposure altered the intergenerational mobility between fathers and sons and whether the initial income rank of fathers enhances or suppresses these effects.

5.1 Measuring Intergenerational Mobility

In order to measure intergenerational mobility, we use the household information in 1900 from our main sample to identify the fathers of our sample of young men. Income information was unavailable prior to the 1940 census. To determine income ranks for fathers in 1900, we follow the approach in Abramitzky et al. (2021) and Collins and Wanamaker (2022) of imputing income ranks for each individual using the father's occupation, race, age, state of residence, and which IPUMS metropolitan category they reside in. We use these characteristics to predict an individual's income in 1900 and rank the incomes from 0 (lowest) to 100 (highest). Similar to prior work that has applied this approach, the specific values of predicted incomes are less important than their rank order. We determine the rank order of sons based on their reported wage and salary income in 1940.

Panel C of Table 1 shows overall summary statistics for the sample of father-son linked individuals between 1900 and 1940. Within this sample, roughly 39.5% of children had improved their income rank relative to their fathers and the average change in ranking between fathers and sons was a decline of 9.3 places, indicating that the average father's rank exceeds their son's within this sample.

5.2 Estimation and Results

We estimate the effect of lead exposure on intergenerational mobility by modifying estimating equation 1 to include additional covariates for the linked father.

$$y_{ift} = \beta_1 lead_t + \beta_2 Corrosive_t + \beta_3(lead_t \times Corrosive_t) + X'\delta_i + \tau_t + \rho_t + \psi_s + Z'\mu_f + \epsilon_{ift} \quad (2)$$

We focus on two mobility related outcomes of interest, y_{ift}, between son i and father f. The first is the difference between the ranks (son rank minus father average rank) and the second is an indicator for whether the son's rank improved relative to the father's. Table 6 reports results replicating the earlier five column structure. The coefficient estimates across both outcome panels suggest that lead exposure is associated with less intergenerational mobility. The pattern of coefficients within the table mirrors the general pattern among the earlier adult outcomes, where the negative consequences of lead exposure are higher for individuals that grew up with more corrosive water chemistry conditions.[17]

The results are consistent with lead exposure behaving like a negative place-based shock that constrains upward mobility. This type of place-based shock relates to recent work documenting the regional differences in historic mobility Tan (2023) and the significant role that places play in shaping contemporary estimates of intergenerational mobility (Chetty et al., 2014; Chetty and Hendren, 2018).

Contemporary work examining the consequences of lead exposure finds that family socioeconomic status can exacerbate the negative consequences of lead Grönqvist et al. (2020); Zheng (2021). A fundamental challenge in evaluating the moderating role of socioeconomic status is separating lead exposure from other risk factors facing economically disadvantaged households. Historic, town-level exposure helps alleviate these concerns

[17] Our results are robust to adjustments to correct for mismeasurement concerns raised by Ward (2021). In Table A1 we add an additional link to the household head by leveraging the robust family tree links from Price et al. (2021). These include considerably more individual links between 1900 and 1910 to increase our observations of the permanent income of the household head. We repeat the rank predictions for fathers in 1910 and we use the average of the two income ranks to approximate the father's *permanent* income rank.

because lead exposure did not vary along neighborhoods or by racial groups, which gives us the ability to evaluate the effects of lead by different measures of socioeconomic status.

Figure 6 presents results from a series of specifications that estimate the effect of lead exposure for residents of towns within the chemistry sample. The first estimate reports the coefficient from column 3 of Table 6, providing the baseline estimate of the relationship between lead exposure and economic mobility. The subsequent estimates report the same coefficient, but restrict the sample to different quartiles of the father's income rank, where the first quartile estimates the relationship between lead and mobility within the lowest 25% of average income ranks.

Both figures reveal a consistent pattern, where the sharpest negative relationship between lead exposure and economic mobility occurs in the bottom two quartiles, with weaker differences among the top two quartiles. This is consistent with higher socioeconomic status households being able to mitigate these effects.

Given these clear differences by father's income quartile, we return to the adult outcomes from section 4 and estimate equation 2, but replace measures of economic mobility with wage and salary income, years of completed education, and the IPUMS occupational score. Figure 7 presents the estimated coefficients, where the first estimate is for the full sample and subsequent estimates are for each income rank quartile. Taken together, the three figures show slight differences by socioeconomic status, where the largest differences in income and occupation are concentrated among the lower part of the distribution. Similar to the mobility results, we consistently find no statistical differences in wages, education, or occupational score among children with fathers among the top 50% of the income distribution.

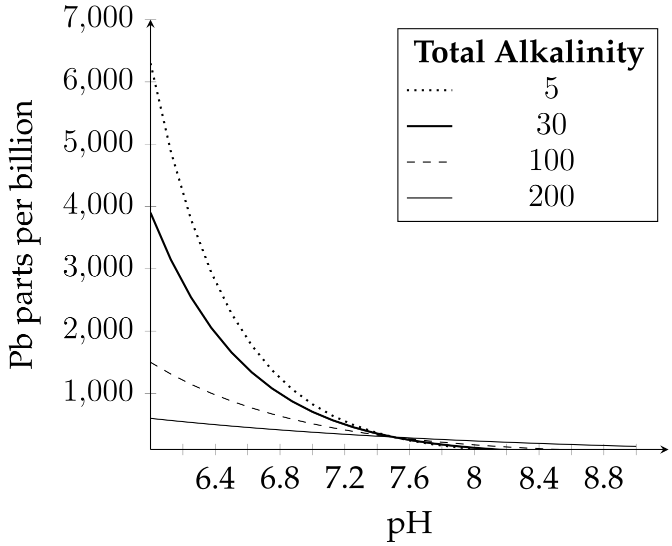
6 Conclusion

Municipal decisions in the late nineteenth and early twentieth century exposed millions of people to harmful levels of lead exposure. Unfortunately, the negative consequences of lead water pipe exposure are still a pressing issue today. The Environmental Protection Agency estimates that there are six - ten million active lead service lines in the United States (Environmental Protection Agency, 2021). In response, the Biden Administration recently approved legislation with the goal of replacing all lead pipes over the next decade (The White House, 2022).

This paper provides empirical evidence that lead service pipes had detrimental effects on exposed individuals into adulthood. This resulted in lower earnings, worse occupations, fewer years of education, and less intergenerational mobility. Earnings differences of 4–6% in 1940 correspond to differences of \$1,600–\$2,100 per person today. Given the historic prevalence of exposure, these differences aggregate to large negative economic impacts.

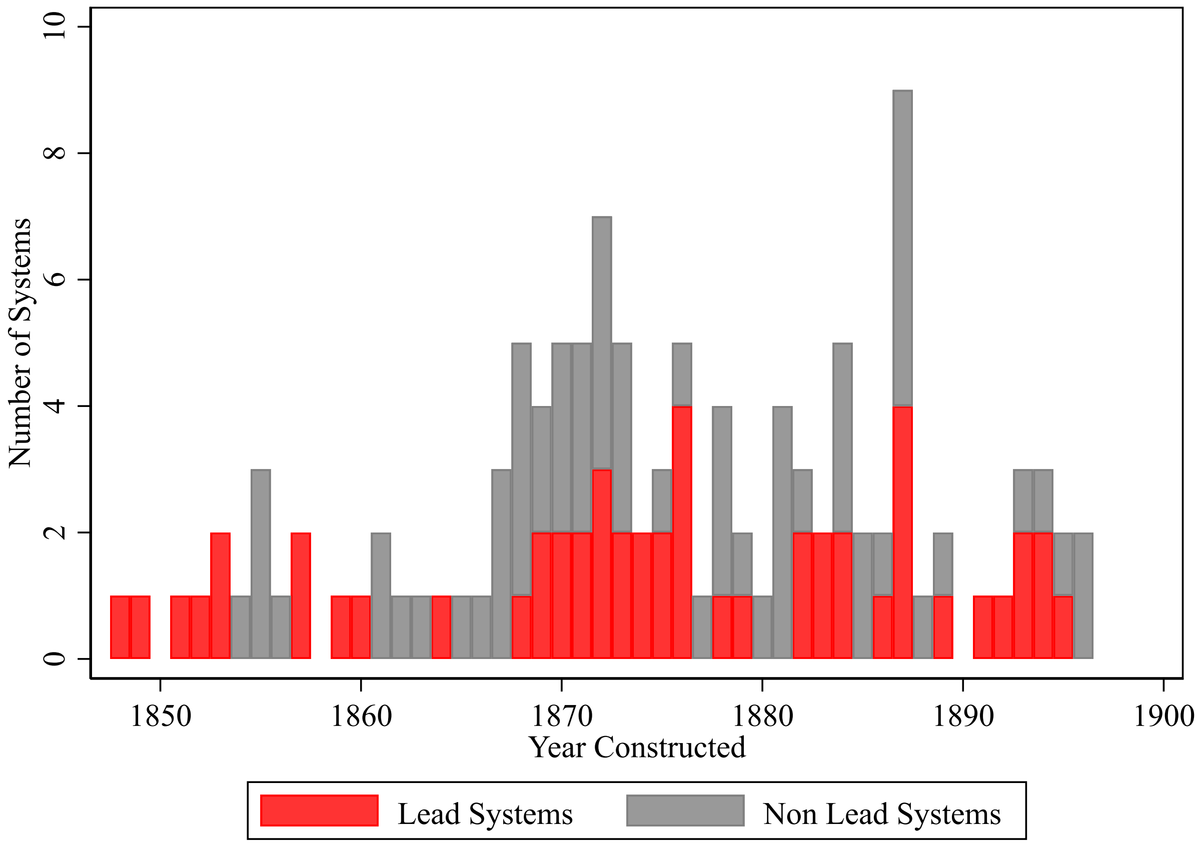
7 Figures

Figure 1: Lead Absorption by pH and Alkalinity of Water



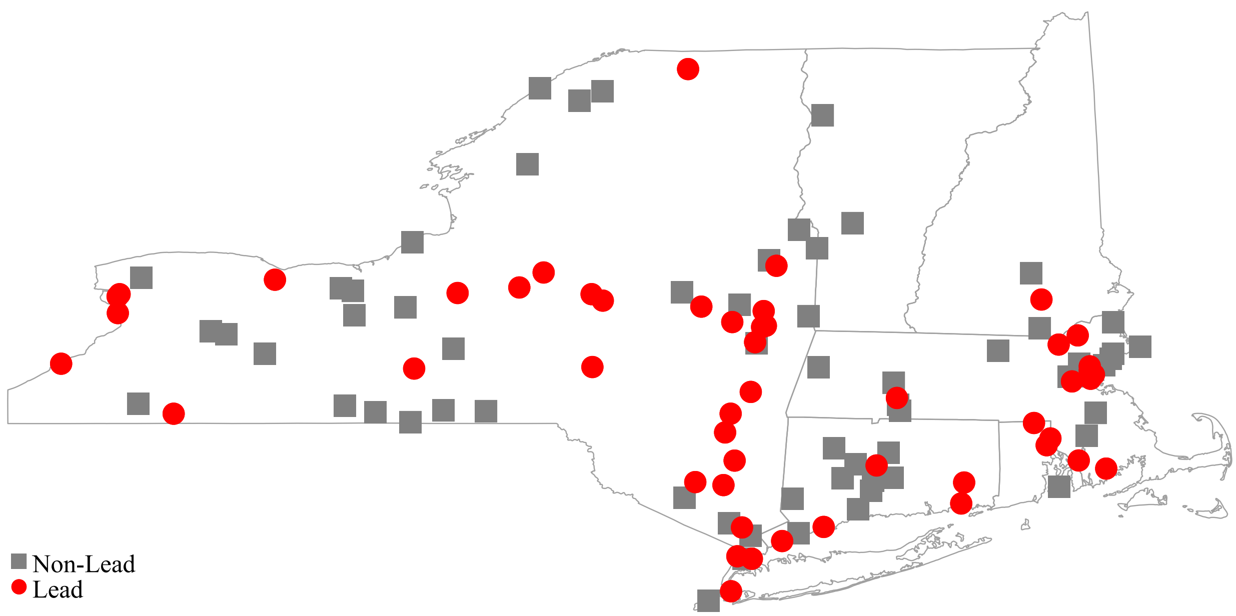
Notes: The figure depicts the relationship between lead in water (parts per billion) and the pH and Alkalinity of the water. The figure is based on Schock (1990) and Clay et al. (2014).

Figure 2: Water System Construction



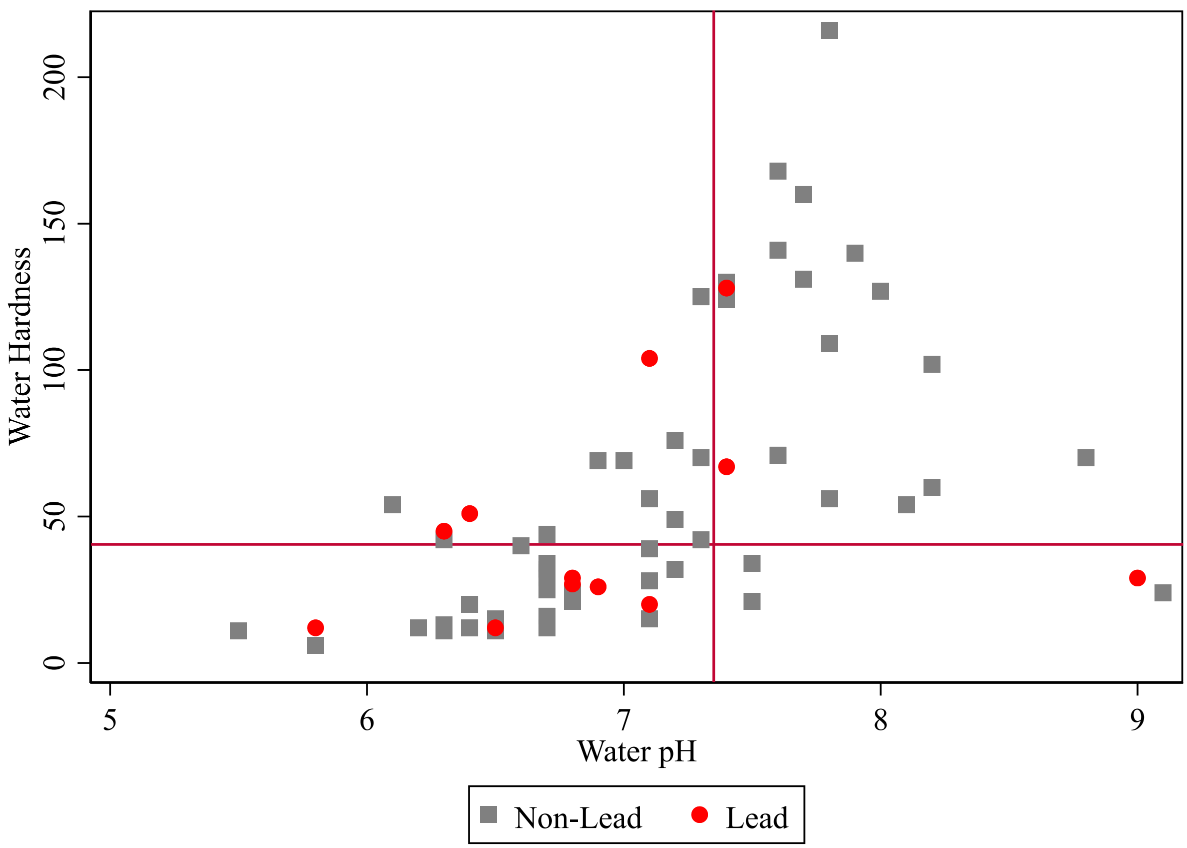
Notes: The figure plots the construction dates for water systems from Baker (1897).

Figure 3: Map of Lead Service Pipe Status by Location



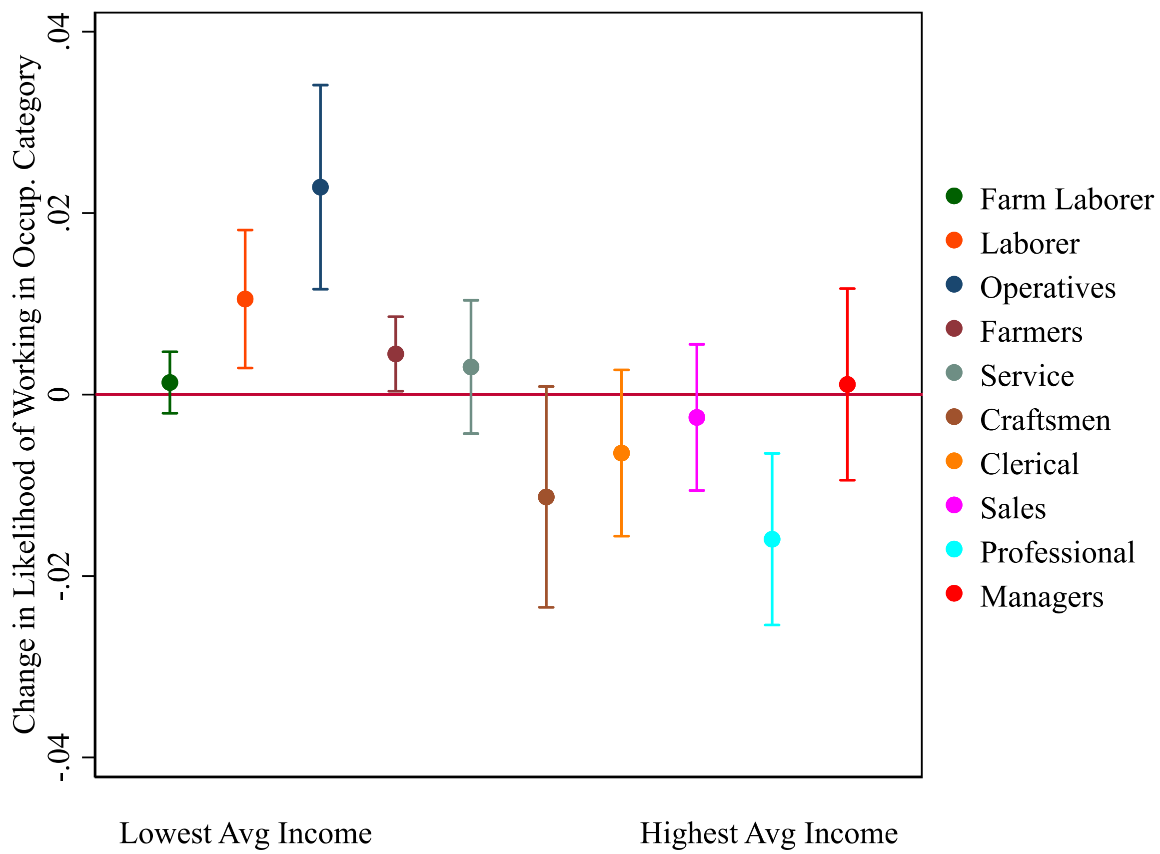
Notes: The figure plots the location of each town in the linked sample with water system information from Baker (1897). The figure distinguishes towns by whether they used any lead (red) or no lead (grey) for the town service pipes.

Figure 4: Water Hardness and Water pH Levels by Lead and Non-Lead Pipe Status



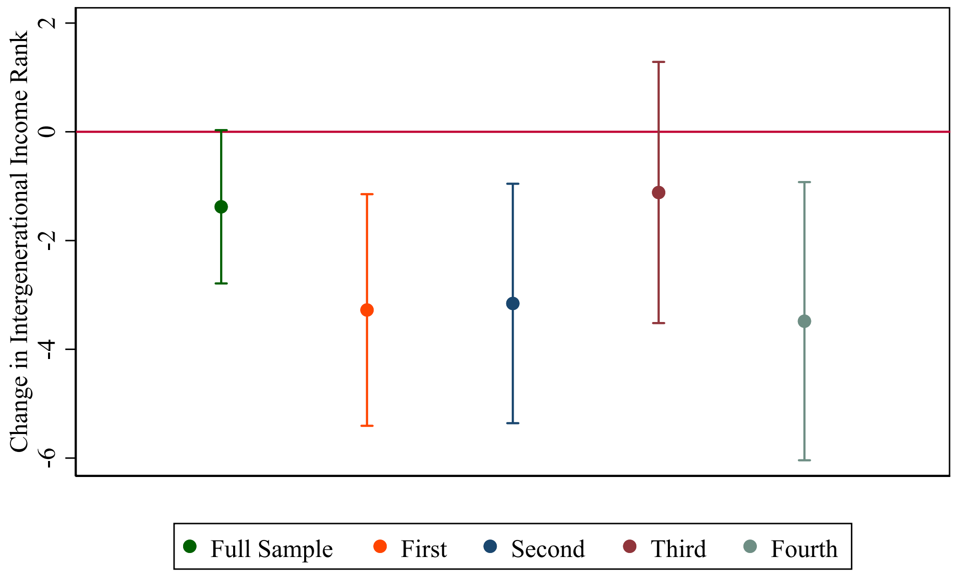
Notes:

Figure 5: Lead and Occupational Differences

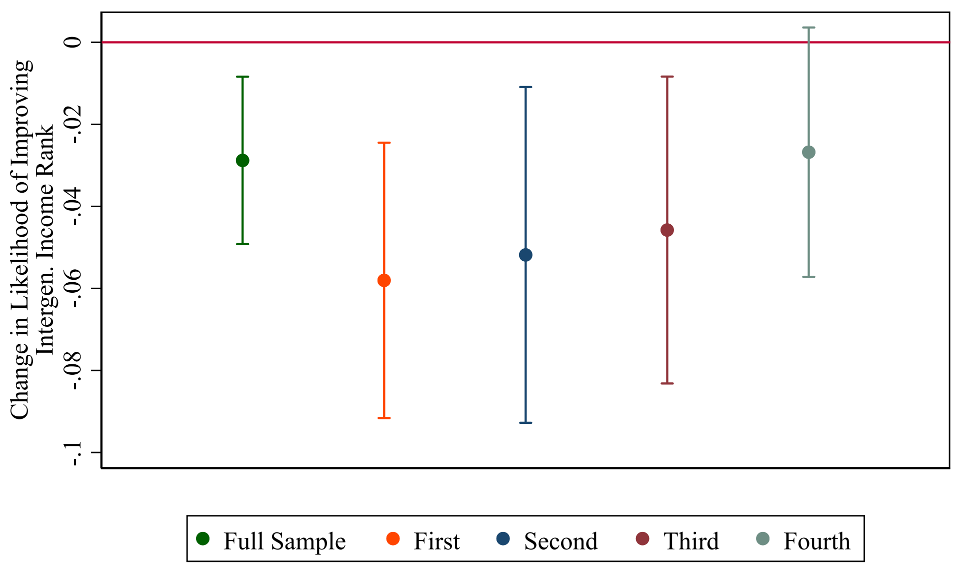


Notes:

Figure 6: Lead and Intergenerational Mobility by Father's Income Quartile



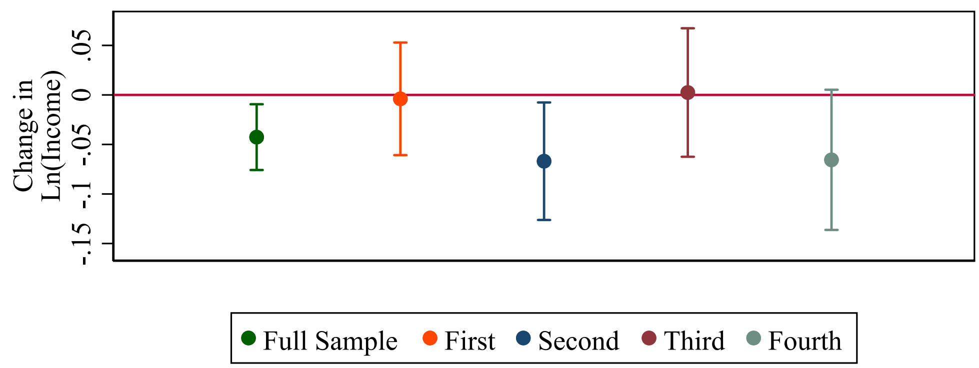
(a) Lead and Change in Intergenerational Mobility Ranking



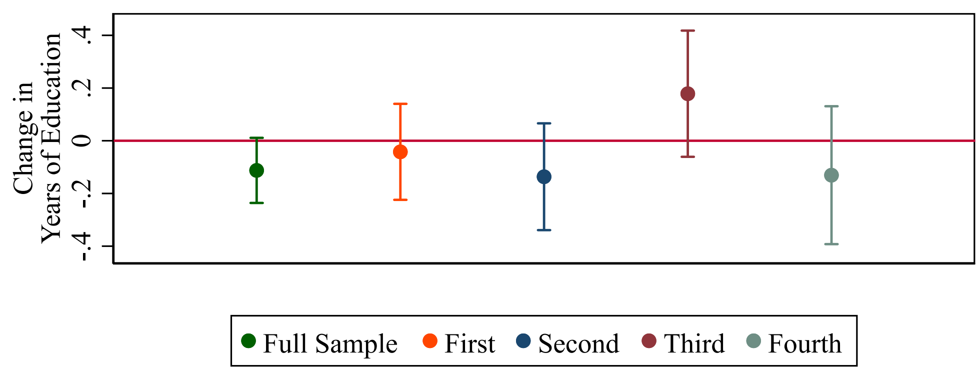
(b) Lead and Change in the Likelihood of Improving Intergenerational Mobility Ranking

Notes:

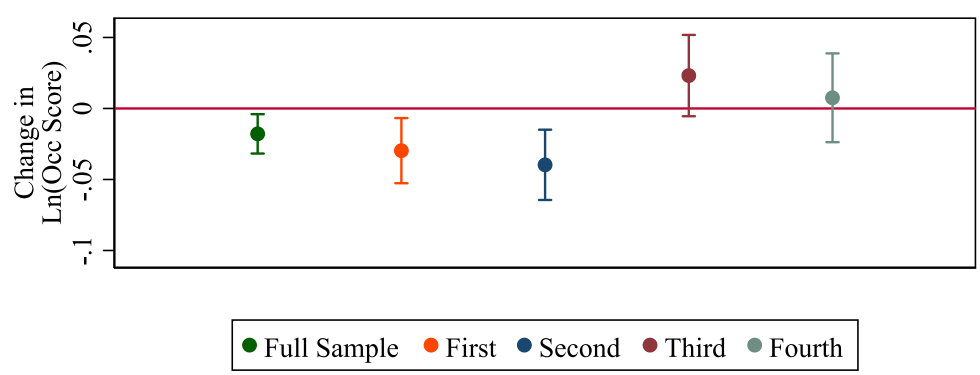
Figure 7: Lead and Adult Outcomes by Father's Income Quartile



(a) Lead and Change in Wage and Salary Income



(b) Lead and Change in Years of Education



(c) Lead and Change in Occupation Score

Notes:

8 Tables

Table 1: Individual Summary Statistics

	(1) Mean	(2) SD	(3) Min	(4) Max	(5) Count
Panel A: 1900 Census					
Age	8.108	5.689	0	20	200,816
Non-White	0.006	0.078	0	1	200,816
Family Size	6.025	2.164	1	53	200,816
Immigrant	0.002	0.043	0	1	200,816
Father Immigrant	0.033	0.178	0	1	200,816
Not in Metro	0.130	0.336	0	1	200,816
In Central City	0.661	0.473	0	1	200,816
Male Head of HH	0.925	0.263	0	1	200,816
Panel B: 1940 Census					
Wage and Salary Income	1880.418	1211.831	1	5,000	151,049
Occupational Prestige Score	30.122	10.450	3	80	186,919
Not in Labor Force	0.081	0.273	0	1	199,428
Completed Years of Education	10.787	3.114	0	21	195,536
Stopped with Middle School	0.487	0.500	0	1	195,536
Completed High School	0.313	0.464	0	1	195,536
Any Post-Secondary Education	0.145	0.352	0	1	195,536
Panel C: Intergenerational Mobility					
Improved Income Rank	0.395	0.489	0	1	116,308
Change in Income Rank	-9.367	33.239	-99	93	116,308
Son Rank 1940	55.012	27.474	1	100	116,308
Father Rank 1900	64.807	22.887	2	100	154,285

Notes: Significance levels are denoted by * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 2: Differences in Town Characteristics by Lead Status in 1900

	(1)	(2)	(3)	(4)	(5)
	Non-Lead	Lead	Difference: Lead - Non Lead		
Chemistry Data (0/1)	0.62	0.69	0.07	-0.02	0.00
	(0.49)	(0.47)	[0.09]	[0.08]	[.]
pH	6.93	7.10	0.17	-0.03	-0.03
	(0.55)	(0.85)	[0.17]	[0.15]	[0.15]
Hardness	53.52	51.11	-2.41	-10.26	-10.26
	(50.24)	(43.41)	[10.74]	[10.26]	[10.26]
Population (in 000s)	23.10	73.63	50.53**	4.21	-0.50
	(22.45)	(180.69)	[25.19]	[11.41]	[7.36]
Pct. Female	51.46	51.33	-0.13	0.24	0.24
	(3.26)	(1.96)	[0.49]	[0.65]	[0.48]
Pct. Married	45.59	44.82	-0.77	-0.38	-1.17
	(4.57)	(3.25)	[0.73]	[0.94]	[0.84]
Pct. Non-White	1.27	1.23	-0.04	-0.20	-0.09
	(1.91)	(1.20)	[0.29]	[0.37]	[0.35]
Pct. Urban	85.47	89.36	3.88	0.90	-1.25
	(19.35)	(16.04)	[3.29]	[3.06]	[2.39]
Pct. Employed	33.04	32.64	-0.39	-0.59	0.69
	(4.19)	(4.02)	[0.77]	[1.04]	[1.04]
Pct. in Group Quarters	3.65	3.01	-0.64	-1.10	-0.93
	(3.31)	(2.63)	[0.55]	[0.67]	[1.02]
Pct. Emp in Manuf	29.49	34.31	4.82*	5.55	3.95
	(15.32)	(15.95)	[2.93]	[3.81]	[4.95]
Pct. Emp in Retail	12.25	13.65	1.40**	0.60	0.19
	(3.00)	(4.04)	[0.67]	[0.79]	[1.08]
Pct. Emp in Service	23.74	22.62	-1.12	-2.14	-0.98
	(9.71)	(7.02)	[1.56]	[2.14]	[2.16]
Pct. Emp in Mining	0.68	0.33	-0.35	-0.48	-0.06
	(3.64)	(1.01)	[0.48]	[0.66]	[0.09]
Pct. Emp in Farming	11.75	7.07	-4.68**	-3.47*	-1.79
	(12.43)	(8.41)	[1.94]	[1.99]	[1.55]
Observations	64	52	116	116	76
Incl. Controls			No	Yes	Yes
Town Sample			Full	Full	Chemistry

Notes: This table reports on baseline differences in town characteristics. Columns 1–2 present mean and standard deviations by lead status. Column 3 reports differences unconditional differences, column 4 reports differences conditional on town controls, column 5 reports differences for the subset of towns with water chemistry information conditional on town controls. Significance levels are denoted by * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 3: Lead and Labor Market Outcomes

	(1)	(2)	(3)	(4)	(5)
Sample Towns	All		Chemistry		Lead Only
Panel A: Ln(Wage and Salary Income)					
Lead	-0.078***	-0.064***	-0.028	-0.031**	
	(0.009)	(0.011)	(0.018)	(0.014)	
Low pH			0.014		
			(0.013)		
Lead × Low pH			-0.045**		
			(0.018)		
More Corrosive				0.021*	-0.041***
				(0.012)	(0.015)
Lead × More Corrosive				-0.052***	
				(0.016)	
Observations	151,442	106,400	106,400	106,400	71,337
Panel B: Labor Force Participation					
Lead	0.001	0.001	0.004	0.002	
	(0.002)	(0.002)	(0.005)	(0.004)	
Low pH			0.000		
			(0.004)		
Lead × Low pH			-0.003		
			(0.005)		
More Corrosive				-0.003	-0.005
				(0.003)	(0.004)
Lead × More Corrosive				-0.000	
				(0.004)	
Observations	199,016	139,571	139,571	139,571	93,710

Notes: Significance levels are denoted by * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 4: Lead and Adult Outcomes

	(1)	(2)	(3)	(4)	(5)
Sample Towns	All		Chemistry		Lead Only
Panel A: Years of Completed Education					
Lead	-0.305***	-0.293***	-0.169***	-0.113**	
	(0.033)	(0.040)	(0.064)	(0.051)	
Low pH			-0.010		
			(0.046)		
Lead × Low pH			-0.157**		
			(0.068)		
More Corrosive				-0.050	-0.419***
				(0.048)	(0.061)
Lead × More Corrosive				-0.277***	
				(0.063)	
Observations	195,129	136,656	136,656	136,656	91,824
Panel B: Occupational Prestige Score					
Lead	-0.013***	-0.010***	0.004	-0.002	
	(0.003)	(0.004)	(0.007)	(0.005)	
Low pH			0.003		
			(0.005)		
Lead × Low pH			-0.018**		
			(0.007)		
More Corrosive				0.003	-0.015***
				(0.005)	(0.005)
Lead × More Corrosive				-0.012**	
				(0.006)	
Observations	186,533	130,926	130,926	130,926	87,852

Notes: Significance levels are denoted by * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 5: Educational Thresholds

	(1)	(2)	(3)	(4)	(5)
Sample Towns	All	Chemistry			Lead Only
Panel A: Stopped at Middle School					
Lead	0.051***	0.059***	0.038***	0.033***	
	(0.006)	(0.007)	(0.010)	(0.008)	
Low pH			0.001		
			(0.007)		
Lead × Low pH			0.026**		
			(0.010)		
More Corrosive				0.000	0.048***
				(0.008)	(0.010)
Lead × More Corrosive				0.039***	
				(0.010)	
Observations	195,129	136,656	136,656	136,656	91,824
Panel B: Complete High School					
Lead	-0.033***	-0.029***	-0.013	-0.003	
	(0.005)	(0.006)	(0.009)	(0.008)	
Low pH			-0.000		
			(0.007)		
Lead × Low pH			-0.020**		
			(0.010)		
More Corrosive				-0.008	-0.060***
				(0.007)	(0.009)
Lead × More Corrosive				-0.041***	
				(0.009)	
Observations	195,129	136,656	136,656	136,656	91,824
Panel C: Any Post-Secondary Education					
Lead	-0.017***	-0.016***	-0.007	-0.005	
	(0.003)	(0.004)	(0.007)	(0.005)	
Low pH			0.006		
			(0.005)		
Lead × Low pH			-0.011		
			(0.007)		
More Corrosive				-0.002	-0.024***
				(0.005)	(0.006)
Lead × More Corrosive				-0.017***	
				(0.006)	
Observations	195,129	136,656	136,656	136,656	91,824

Notes: Significance levels are denoted by * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 6: Lead and Intergenerational Mobility

	(1)	(2)	(3)	(4)	(5)
Sample Towns	All		Chemistry		Lead Only
Panel A: Intergenerational Income Rank					
Lead	-2.019***	-1.547***	-0.441	-0.544	
	(0.399)	(0.452)	(0.816)	(0.656)	
Low pH			0.743		
			(0.629)		
Lead $\times$ Low pH			-1.379		
			(0.856)		
More Corrosive				0.115	-1.393*
				(0.551)	(0.710)
Lead $\times$ More Corrosive				-1.562**	
				(0.727)	
Observations	116,307	81,720	81,720	81,720	54,975
Panel B: Improved Income Rank					
Lead	-0.022***	-0.014**	0.009	0.003	
	(0.006)	(0.007)	(0.012)	(0.009)	
Low pH			0.014		
			(0.009)		
Lead $\times$ Low pH			-0.029**		
			(0.012)		
More Corrosive				0.008	-0.014
				(0.008)	(0.010)
Lead $\times$ More Corrosive				-0.027**	
				(0.011)	
Observations	116,307	81,720	81,720	81,720	54,975

Notes: Significance levels are denoted by * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

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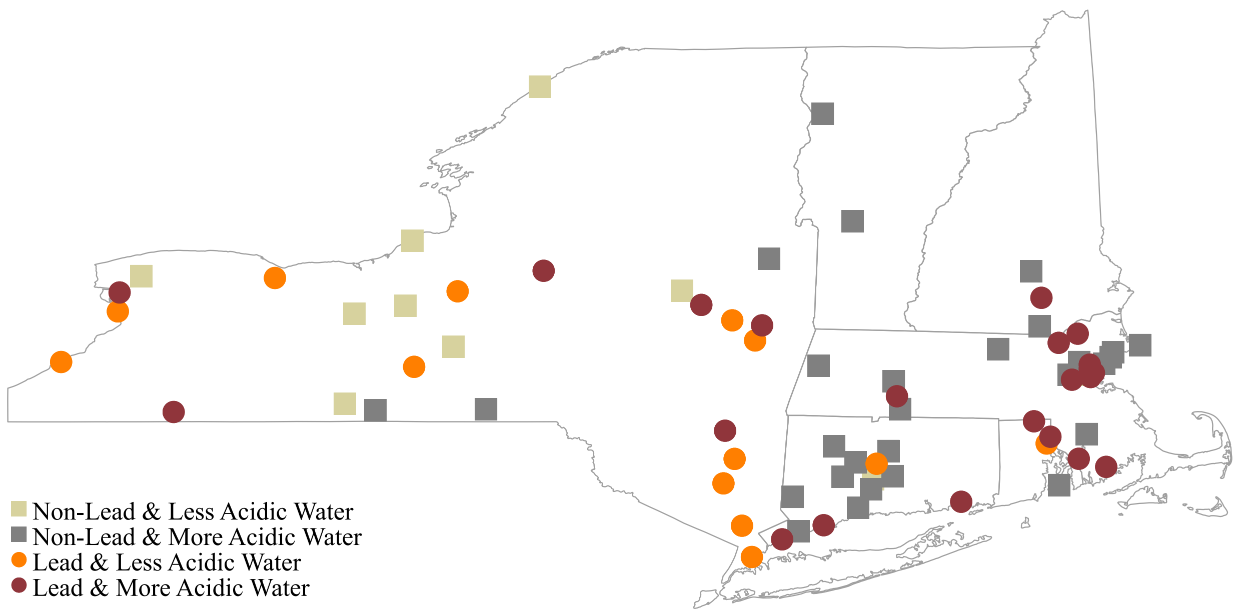
Appendix

to

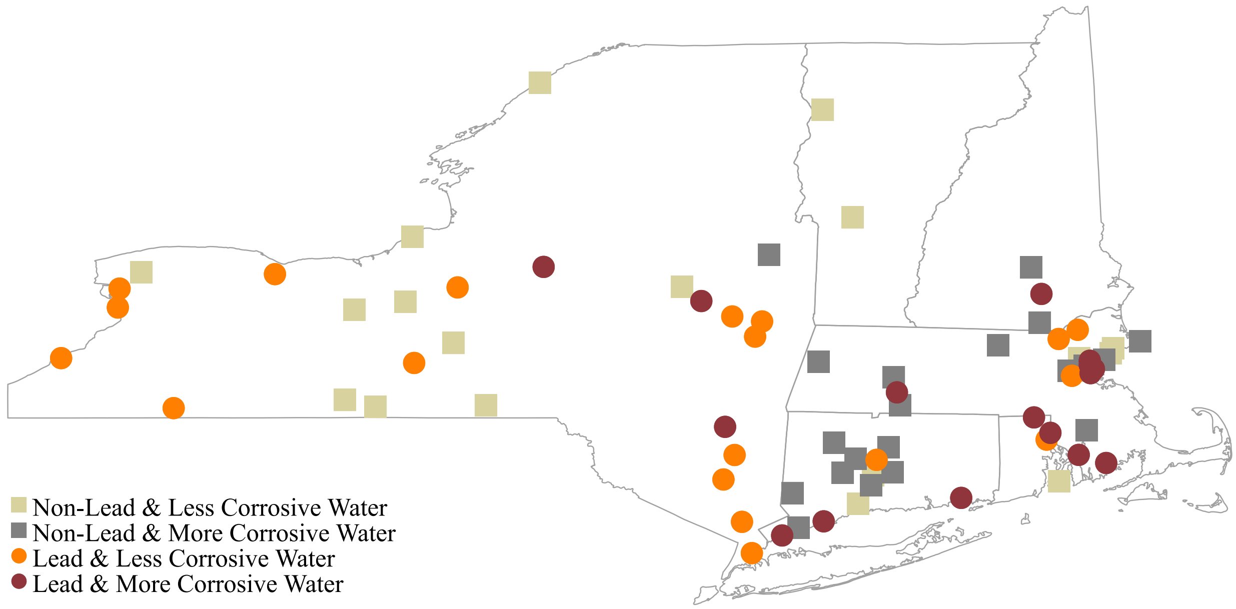
"Economic Consequences of Childhood Exposure to Urban Environmental Toxins"

Figure A1: Map of Lead Service Pipe Status and Water pH by Location



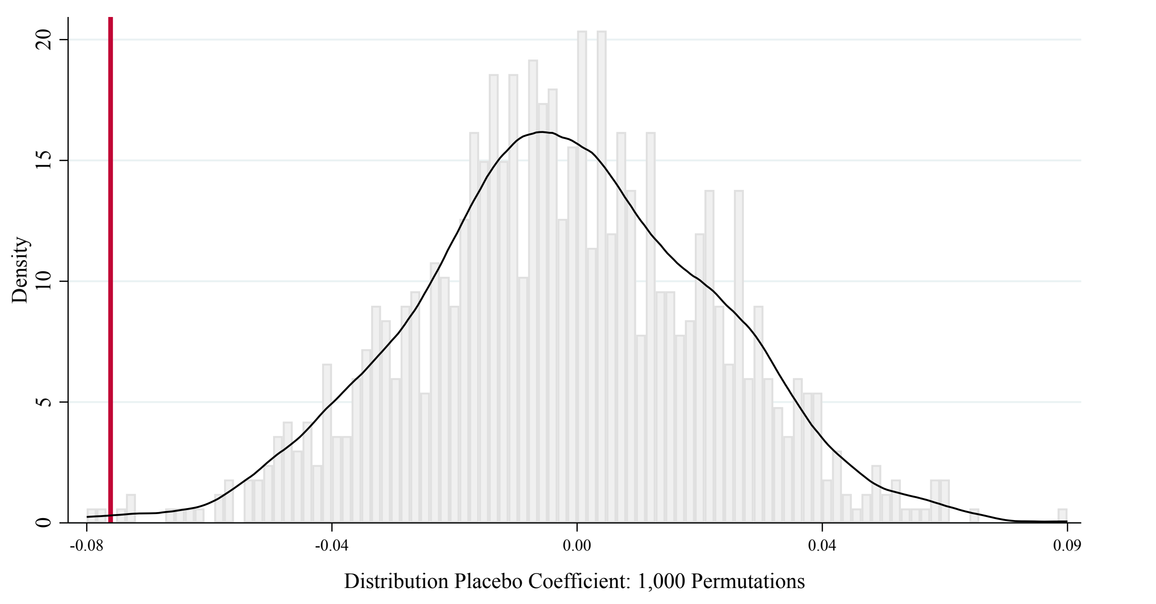
Notes:

Figure A2: Map of Lead Service Pipe Status and Water Corrosiveness Location



Notes: =

Figure A3: Randomized Inference Test



Notes: The figure depicts the distribution of results from estimating an effect of lead status where lead status was randomized at the city level and repeated 1,000 times. The vertical line represents the estimated effect from the true lead status.

Table A1: Lead and Intergenerational Mobility using Average Father's Rank from 1900 & 1910

	(1)	(2)	(3)	(4)	(5)
Sample Towns	All		Chemistry		Lead Only
Panel A: Intergenerational Income Rank					
Lead	-1.842***	-1.132*	0.064	0.370	
	(0.538)	(0.618)	(1.074)	(0.874)	
Low pH			1.561*		
			(0.819)		
Lead × Low pH			-1.449		
			(1.139)		
More Corrosive				0.945	-1.597*
				(0.744)	(0.960)
Lead × More Corrosive				-2.359**	
				(0.962)	
Observations	49,293	35,117	35,117	35,117	23,848
Panel B: Improved Income Rank					
Lead	-0.024***	-0.016	0.001	0.001	
	(0.009)	(0.010)	(0.018)	(0.014)	
Low pH			0.033**		
			(0.013)		
Lead × Low pH			-0.020		
			(0.018)		
More Corrosive				0.018	-0.021
				(0.012)	(0.015)
Lead × More Corrosive				-0.027*	
				(0.016)	
Observations	49,293	35,117	35,117	35,117	23,848

Notes: Significance levels are denoted by * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.