Toxic Truth: Lead Exposure and Fertility Choices

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Abstract

Evidence from the epidemiology literature suggests that exposure to lead impairs the reproductive system of both males and females, leading to lower fecundity (i.e. the physiological ability to have children). It is unclear, however, whether this would cause a decrease in fertility (i.e. the actual production of offspring). Households could take actions to avoid lead exposure and/or to remediate undesirable consequences of some exposure. In this study we examine the impact of lead on fertility in U.S. counties over the period 1978-1988, when airborne lead concentration decreased considerably. We leverage the implementation of Clean Air Act regulations and the 1944 Interstate Highway System Plan within a fixed-effect instrumental variable approach, and find two main results. First, exposure to airborne lead causes a reduction on the number of births and birth rates, indicating that avoidance and/or compensatory behavior might not fully offset the pathologic effects of lead. Second, such a reduction in fertility rates seems smaller for high-educated households (those with mothers with high school or higher education), suggesting that some actions may attenuate the potentially harmful effects of lead, and that the relationship between lead and fertility is not purely epidemiological.

Introduction

The latest evidence from epidemiology points out that exposure to lead impairs the reproductive system of both males and females, potentially reducing the fecundity of couples (e.g. Lancranjan et al. 1975, Wani, Ara, and Usmani 2015)[1]. For males, lead seems to undermine the reproductive function by reducing sperm count, volume, and density, or changing sperm motility and morphology (e.g. Hauser and Sokol 2008). For females, lead exposure is associated with delays in pubertal development, irregular menstruation, spontaneous abortions, subfertility, and in the extreme infertility (e.g. Mendola, Messer, and Rappazzo 2008). It is unclear, however, whether these potentially harmful effects of lead would cause a reduction in fertility. Indeed, households might make defensive investments: they may take actions to avoid exposure such as living in houses with no lead painting, and/or to mitigate the effects of exposure such as using assisted reproductive technologies. In this study we estimate the causal effect of exposure to airborne lead on fertility rates, and investigate whether avoidance and/or compensatory behavior may attenuate those undesirable consequences.

To examine the impact of exposure to lead on fertility rates, we use monthly county-level data derived from the birth and mortality records of the U.S. National Vital Statistics System, and from readings of the U.S. Environmental Protection Agency's network of airborne lead monitoring stations across the nation over the period 1978-1988. Identification in this setting is known to be challenging because of endogenous sorting related to household preferences for air quality (e.g. Chay and Greenstone 2003, 2005, Banzhaf and Walsh 2008), avoidance behavior (e.g. Neidell 2004, 2009, Moretti and Neidell 2011), and remediation investments (e.g. Deschenes, Greenstone, and Shapiro 2017). Thus, we use a fixed-effect instrumental variable approach, leveraging the implementation of federal Clean Air Act (CAA) regulations regarding the phase-out of lead in gasoline, and nonattainment designations associated with violations of the National Ambient Air Quality

[1] Again, *fecundity* is the physiological ability to have children and *fertility* is the actual production of offspring.

Standards (NAAQS) for particulate matter (PM).

The phase out of lead in gasoline had two important milestones: (i) starting in October 1979, refineries were required to produce a quarterly average of no more than 0.8 grams per gallon (gpg) among the *total gasoline output*; (ii) from July 1985 onwards, the standard was reduced to 0.5 grams per *leaded* gallon (gplg). Lead was eventually banned as a fuel additive in the U.S. beginning in 1996. In our analysis, those two milestones are interacted with an indicator for whether a county was planned to receive a highway from the 1944 Interstate Highway System Plan, which was designed primarily for military purposes. The impact of the phase out of lead in gasoline on airborne lead should be felt more strongly in counties with a higher probability of having a highway running through them. The two milestones and their interactions with the "1944 plan" provide us four instrumental variables. The last one comes from the compliance with the NAAQS for PM. Following the 1977 CAA Amendments, in 1978 EPA published a list of all nonattainment areas for the first time. The Amendments also required counties in violation with the PM standard to comply by January 1983. Because lead is measured as a portion of PM, our fifth instrument was defined to be a dummy variable indicating nonattainment status for PM in 1978 interacted with the period starting in January 1983.

We have two main findings. First, the IV estimates for the impact of lead exposure on number of births and fertility rates (number of births per 1000 females 16-39 years old) are negative and statistically significant. The OLS estimates are much smaller in magnitude, suggesting a positive bias potentially arising from endogenous sorting, avoidance behavior, and/or remediation. Indeed, households with higher preference for air quality may sort into cleaner areas to offer a better quality of life to their children, but concerns about the overall quality of their offspring might also make them more likely to favor quality over quantity of children. This broad picture is corroborated by estimates using another measure of lead exposure in more recent years. Leveraging lead concentration in soil as measured by the U.S. Geological Survey (USGS) in the late 2000s, which could reflect deposition of previous airborne lead, and the 1944 interstate highway instrument, we report qualitatively similar results in the 2000s.

Our second finding is more revealing in terms of the mechanisms behind the estimated reduction in fertility rates. If the relationship between lead exposure and fertility was purely epidemiological, then we would observe no differential causal effects based on mother's education. Nevertheless, when we split the sample into high education (mothers with high school or higher education) versus low education (mothers with less than high school), we find that the reduction in birth rates is stronger for low-educated households. This finding is consistent with more informed or wealthier households avoiding lead exposure and/or making investments to compensate for the potentially lower fecundity associated with some lead exposure. Avoidance and/or compensatory behavior require at least partial knowledge of the effects of lead exposure and of the changes in lead concentration over time. Because it is more likely that highly educated households were more informed than lower educated households, more educated individuals might have responded relatively more to the phase out of lead in gasoline and compliance with the NAAQS for PM. At the same time, education could be a proxy for income. Since engaging in defensive investments is costly, more educated families are more likely to have more resources to overcome (at least partially) the negative effect of lead. It is important to notice, however, that avoidance behavior should be more limited in this context. It may be relatively cheap to repaint or renovate a house built before 1978 – when the federal government banned consumer uses of lead-containing paint – to attenuate lead-paint hazards, but it might be much more expensive to avoid exposure to airborne lead because a household would have to live in a neighborhood with lower concentrations. That might be a reason why we observe some effects of airborne lead on fertility rates even for households with more educated mothers.

This study makes two main contributions to the literature. First, it provides the first causal estimates of the impact of exposure to airborne lead on fertility. The relationship between exposure to lead and fecundity/fertility is well established in the epidemiological literature, but the evidence is mostly observational and focused on case studies (e.g. Hauser and Sokol 2008, Mendola, Messer, and Rappazzo 2008, Wu and Chen 2011, and Wani, Ara, and Usmani 2015). Second, it presents evidence consistent with more informed households avoiding lead exposure and/or making remediating investments to compensate for the potential lower fecundity, suggesting that behavioral responses also play an important role in explaining the effects of pollution on fertility. Besides these key contributions, this study adds to a growing body of work investigating impacts of environmental insults on economic outcomes (e.g. Chay and Greenstone 2003, 2005, Currie and Neidell 2005, Currie and Walker 2011, Currie et al. 2014, Currie et al. 2015, and Schlenker and Walker 2016), in particular the causal effects of lead exposure on education (Aizer et al., forthcoming) and crime (Reyes 2007, 2015).

This paper is organized as follows. After this introduction, section 2 provides a conceptual framework highlighting the epidemiological and economic links between exposure to lead exposure and fertility. Section 3 discusses our empirical strategy, along with important background information behind our instrumental variables approach. Section 4 describes the data used in our analysis, and section 5 reports our results. Lastly, section 6 presents some concluding remarks.

2. Conceptual Framework

2.1. The Epidemiology of Lead Exposure and Fertility

Lead was identified as an abortifacient and a cause of male infertility and impotence during the days of the Roman Empire. However, it was the pioneering study of Lancranjan et al. (1975) that focused attention on the role that chemicals might play in male factor infertility. These investigators studied reproductive outcomes in men who worked on the production line and compared them to men working in the office of a battery plant in Eastern Europe. They reported a dose-related suppression of spermatogenesis, normal or decreased serum testosterone, and inappropriately normal urinary gonadotropins in the face of low testosterone levels in men with higher blood lead levels.

In recent decades, a growing body of evidence has emphasized the hazardous effects of high doses of lead exposure (see, for example, reviews by Needleman 2004, Patrick 2006, Flora, Gupta, and Tiwari 2012, and Wani, Ara, and Usmani 2015). The scientific community has also noticed that the toxicity of lower-dose lead exposure can cause some negative physical problems, which lack obvious clinical signs and thus are easily neglected. For example, a possible negative effect of the middle-low levels of lead exposure on the change in female hormone systems may lead to female infertility.

Some epidemiological human studies focusing mainly on semen quality, endocrine function, and birth rates in occupationally exposed subjects showed that exposure to concentrations of inorganic lead impaired the male reproductive function by reducing sperm count, volume, and density, or changing sperm motility and morphology (see, for example, reviews by Sallmen 2001, Sheiner et al. 2003, and Hauser and Sokol 2008). In women, a body of experimental evidence also indicates that lead at high doses is toxic to reproductive function (see, for example, reviews by Mendola, Messer, and Rappazzo 2008, and Wu and Chen 2011). Clinical reports, most of them from the first half of the twentieth century, describe an increased incidence in spontaneous abortion among female lead workers as well as in the wives of male lead workers. The evidence appears that women with elevated lead exposure from occupational settings are at increased risk of developing infertility compared with women with no such exposure. Recent epidemiological studies also found that reproductive impairments may develop in women even with low-to-moderate lead levels, including intrauterine growth retardation, preterm delivery, and spontaneous abortion.

To summarize the latest evidence, the reproductive system of both males and females is affected by lead (see, for example, review by Wani, Ara, and Usmani 2015). In males sperm count is reduced and other changes occur in the volume of sperm when blood lead levels exceed 40 μg/dL. Activities like motility and the general morphology of sperm are also affected at this level. The problems with the reproductivity of females due to lead exposure are more severe. Toxic levels of lead can lead to miscarriages, prematurity, low birth weight, and problems with development during childhood.

2.2. The Economics of Lead Exposure and Fertility

Following Becker (1960) and Becker and Lewis (1973), we consider households making fertility choices. Estimating the relationship between lead pollution and fertility is complicated for at least two reasons related to defensive investment. First, optimizing individuals may compensate for increases in pollution by reducing their exposure to protect their health (e.g. Neidell 2004, 2009, Moretti and Neidell 2011). Second, households may engage in activities to remediate the effects of pollution exposure (e.g. Deschenes, Greenstone, and Shapiro 2017).

To fix ideas on measuring and interpreting the effect of lead pollution on fertility, assume the following short-term fertility production function:

$$f = f(lead, avoid, remed, W, S) \tag{1}$$

where f is a measure of fertility, *lead* is airborne lead levels, *avoid* is avoidance behavior, and *remed* is remediation activities. W are other environmental factors that directly affect fertility, such as weather, allergens, and other pollutants. S are all other behavioral, socioeconomic, and genetic factors affecting fertility. We can rearrange the total derivative of the fertility production function (1) to give the following expression for the partial effect of ambient pollution on fertility:

$$\delta f/\delta lead = df/dlead - (\delta f/\delta avoid * \delta avoid/\delta lead) - (\delta f/\delta remed * \delta remed/\delta lead) \tag{2}$$

This expression is useful because it underscores that the partial derivative of fertility with respect to airborne lead pollution is equal to the sum of the total derivative, the product of the partial derivative of fertility with respect to avoidance behavior (assumed to have a negative sign) and the partial derivative of avoidance behavior with respect to pollution (assumed to have a positive sign), and the product of the partial derivative of fertility with respect to remediation (assumed to have a negative sign) and the partial derivative of remediation with respect to pollution (assumed to have a positive sign). In general, complete data on defensive behavior is unavailable, so most empirical investigations of pollution on fertility (e.g., REFS) reveal *df/dlead*, rather than *δf/δlead*. As equation (2) demonstrates, the total derivative is an underestimate of the desired partial derivative. Indeed, it is possible that virtually all of the response to a change in pollution comes through changes in defensive behavior and that there is little impact on fertility outcomes; in this case, an exclusive focus on the total derivative would lead to a substantial understatement of the fertility effect of pollution. The full impact therefore requires either estimation of each element of the second and third terms of equation (2), which is almost always infeasible, or isolating *δf/δlead* using instrumental variables that are orthogonal to avoidance and remediation behavior.

Instead of directly observing defensive investment to estimate *δf/δlead*, the strategy used in this paper is to use instruments that shift lead levels but are unrelated to both avoidance/remediation behavior and other unobserved determinants of fertility. As described in the introduction, we use the phase-out of lead in gasoline, the enforcement of the NAAQS for particulate matter, and their interactions with the 1944 interstate highway plan as instruments for lead levels to obtain estimates of *δf/δlead*. While it is likely that consumers might have had some information about the harmful effects of lead in gasoline even before the phase-out due to the labels "unleaded" versus "regular" in gas station pumps, it is unlikely they were informed about the amount of lead in the "regular" gasoline, which was the policy parameter that changed during the phase-out. Households might have had less information on the enforcement of NAAQS because only heavy emitter firms were dealing with the regulators; hence, lack of salience might have been an issue. In addition, it is highly unlikely that households would have a clear idea about the 1944 plan, which was developed primarily for military purposes. Therefore, we will be assuming that those instruments allow us to uncover *δf/δlead*.

Although defenses used both before and after pollution is ingested (i.e., averting and mitigating activities) are indistinguishable in such an instrumental variable analysis, from the point of view of policymaking the distinction between them is relevant. Therefore, we explore the heterogeneity of *δf/δlead* with respect to a proxy for household income –

mother's education. Fertilization treatments are generally expensive, so rich households might be able to remediate the effects of lead exposure more than poor households. That is, *abs[(δf/δlead)|rich] ≤ abs[(δf/δlead)|poor]*.

3. Empirical Strategy

3.1. Airborne Lead and Fertility

To estimate the causal effect of lead pollution on fertility, we adopt an instrument variable approach. The equation of interest is

$$Y_{cmy} = \alpha + \beta Lead_{cmy} + X'_{cmy}\gamma + \eta_c + \theta_m + \lambda_y + Z'_c\delta_y + \varepsilon_{cmy},$$

where Y_{cmy} is an outcome variable for county *c*, month *m*, and year *y*, *Lead* is lead pollution measured by EPA monitoring stations, *X* is a set of time-varying control variables, η_c is a set of county fixed effects, θ_m is a set month fixed effects to deal with the seasonal patterns of the variables of interest, λ_y is a set of year fixed effects, *Z* represents latitude and longitude, which are interacted with year fixed effects to control for unobservable economic and meteorological conditions known to vary over time, and ε is an error term.

Our coefficient of interest is β. Because we cannot control for all time-varying factors affecting the outcome variables and correlated with *Lead* such as preferences for air quality, it is likely that $\hat{\beta}_{OLS}$ is biased and inconsistent. In order to provide a causal interpretation for β, we proceed with an instrumental variable approach. We exploit the roll out of the Clean Air Act (CAA) regulations to define a number of instruments.

Among the CAA regulations pushed forward by EPA, the phasedown of lead in gasoline figured prominently[2]. Initially, EPA scheduled performance standards requiring refineries to decrease the average lead content of all gasoline – leaded and unleaded pooled – beginning in 1975. These standards were postponed until October 1979, when refineries

[2] This discussion was heavily drawn from Newell and Rogers (2003).

were required to produce a quarterly average of no more than 0.8 grams per gallon (gpg). The regulation set an average lead concentration among *total gasoline output* to deliberately provided refiners with the incentive to increase unleaded production. By the early 1980s gasoline lead levels had declined by about 80 percent (see Figure 1). Then, EPA decided to review and tighten the standards, and lead limits were recalculated as an average of lead in leaded gas only, as unleaded fuel was by then a well-established product. The new rules specifically limited the allowable content of lead in *leaded* gasoline to a quarterly average of 1.1 grams per leaded gallon (gplg). From 1983 to 1985 the EPA conducted an extensive cost-benefit analysis of a dramatic reduction in the lead standard to 0.1 gplg by 1988. As a result, in July 1985 the standard was reduced to 0.5 gplg, and beginning in 1986 the allowable content of lead in leaded gasoline was reduced to 0.1 gplg. Lead was eventually banned as a fuel additive in the U.S. beginning in 1996.

Based on the regulations described above, we define four instrumental variables: (i) a dummy variable for the period October 1979–June 1985, when the 0.8 gpg standards were in place, (ii) a dummy variable for the period starting in July 1985, when the standards were changed and tightened to 0.5 gplg, and interactions between (i) and (ii) and an indicator variable for whether a county would be run through by highways planned by the 1944 Interstate Highway System Map (see Figure 2).

Following Baum-Snow (2007) and Michaels (2008), we use the advent of the U.S. Interstate Highway System as a policy experiment. In 1941, President Roosevelt appointed a National Interregional Highway Committee. This committee was headed by the Commissioner of Public Roads, and appears to have been professional, rather than political (U.S. Department Transportation, Federal Highway Administration, 2002). The highways were designed to address three policy goals (Michaels, 2008). First, they intended to improve the connection between major metropolitan areas in the U.S. Second, they were planned to serve U.S. national defense. And finally, they were designed to connect with major routes in Canada and Mexico. As a consequence – but not an objective – many rural counties were also connected to the Interstate Highway System. Rural counties crossed by the highways were arguably exogenously affected.

Congress acted on these recommendations in the Federal-Aid Highway Act of 1944. In our analysis, we refer to the plan recommended by that committee as the "1944 plan" (again, see Figure 2). The construction of the Interstate Highway System began after funding was approved in 1956, and by 1975 the system was mostly complete, spanning over 40,000 miles. Political agents may have changed the highways routes in response to economic and demographic conditions in rural counties, contrary to the original planners' intent. That is the reason why we use the highway location from the original plan of routes proposed in 1944 in our analysis.

The last instrumental variable is related to the CAA regulations for criteria pollutants. The nation's first Federal efforts at controlling air pollution began in 1963 with passage of the CAA. Four amendments followed in 1967, 1970, 1977 and 1990. The 1967 Amendments directed the previous Department of Health, Education and Welfare to identify regional areas with common air masses throughout the nation [Air Quality Control Regions (AQCR's)]. By 1970, 57 AQCR's were named. Later that year, 34 additional areas were announced.

The 1970 Amendments authorized the Administrator of the newly created EPA to identify additional areas, but only at the States' initiative. As of January 1972, 247 AQCR's were listed. The 1977 Amendments gave the EPA the authority to designate areas nonattainment without a State's request. After EPA's initial designation of areas as attainment/unclassifiable or nonattainment in 1978, however, subsequent designations could be made only at a State's request. In that same year, EPA published, for the first time, a list of all nonattainment areas.

For all criteria pollutants, the CAA Amendments of 1977 required that each nonattainment area had to reach attainment "as expeditiously as practicable, but, in the case of national primary ambient air quality standards, not later than December 31,1982." Because lead is measured as a portion of total suspended particles (TSP), and particulate matter had been regulated since 1971, we define the fifth instrumental variable in our analysis to be a dummy variable indicating nonattainment status for TSP in 1978 interacted with the period starting in January 1983.

Given these five instrumental variables, our first stage equation is

$$
\begin{aligned}
Lead_{cmy} = \alpha &+ \pi_1 LeadPhaseDown\_0.8gpg_{my} \\
&+ \pi_2 LeadPhaseDown\_0.5gplg_{my} \\
&+ \pi_3 (LPD\_0.8gpg_{my} * HWPlan1944_c) \\
&+ \pi_4 (LPD_{0.5gplg_{my}} * HWPlan1944_c) \\
&+ \pi_5 (Attainment_{my} * CAANAS\_TSP1978_c) \\
&+ X'_{cmy}\gamma + \eta_c + \theta_m + \lambda_y + Z'_c\,\delta_y + \varepsilon_{cmy},
\end{aligned}
$$

where *LeadPhaseDown_0.8gpg* is a dummy variable for the period October 1979–June 1985, when refineries were required to produce a quarterly average of no more than 0.8 grams per gallon (gpg) among *total gasoline output*. *LeadPhaseDown_0.8gpg* is a dummy variable for the period starting in July 1985, when the standards were tightened to 0.5 gplg, and beginning in 1986 to 0.1 gplg. Again, gplg – grams per leaded gallon – refers to the new rules specifically limiting the allowable content of lead in *leaded* gasoline only. *HWPlan1944* is an indicator for whether a county would be run through by a highway as planned in the 1944 Interstate Highway System Map. The interactions with *HWPlan1944* are supposed to capture the intention-to-treat effect associated with potential exposure to lead in gasoline burned and emitted in highways. *Attainment* is an indicator for the period starting in January 1983, when counties out of attainment regarding TSP standards were supposed to comply with CAA regulations, as required by the 1977 Amendments. *CAANAS_TSP1978* is a dummy variable for whether a county was designated in nonattainment with the TSP standards, as published by EPA for the first time in 1978. *CAANAS* stands for *C*lean *A*ir *A*ct *N*on-*A*ttainment *S*tatus.

3.2. Soil Lead and Fertility

To supplement our analysis of airborne lead exposure on fertility during 1978-1988 we also study the effects of soil lead exposure on fertility in more recent years. As we have data on soil lead concentration only in single year for each county we estimate the following cross sectional model:

$$Y_c = \alpha + \beta SoilLead_c + X_c\ \gamma + \eta_s + \varepsilon_c,$$

where Y_c is the outcome of interest (fertility or mortality measures), *SoilLead*- lead in soil, X_c - various county level controls, such as climate, county specific demographic and macroeconomics characteristics, etc. η_s- state fixed effects. As before, we estimate this equation using instrumental variable strategy, using Federal-Aid Highway Act of 1944 as an instrument for *SoilLead*.

4. Data

4.1. Lead Data

Our lead pollution data were obtained by a FOIA request at EPA. We consider only monitors located in the city limits to better measure exposure to lead of city residents and not to focus on pollution measured near industrial facilities that might have few people living nearby.

The number of lead monitors varies over time. It gradually increases until 1979 then it remains relatively stable until 1986-1988, after that the number sharply declines. Lead measurements are available once every three months before 1978. After 1978 the lead measurements are available monthly. For these reasons we use 1978-1988 as a time period of our study.

We focus our attention on counties for which we have at least one lead monitor. To construct our lead measures we aggregate monitor’s readings to a county level, by taking the mean of all monitors in the county. As a result, we have an (unbalanced) panel of 302 counties observed monthly over 1978-1988.

There is a big decline in lead level during 1978-1988 as demonstrated in Figure 3. The average lead level in 1978 is 0.55 $\mu g/m^3$ vs 0.12 $\mu g/m^3$ in the 1988, the last year of our study.

Figure 4 plots the decline in lead levels over time for counties with the highway as planned in the 1944 Interstate Highway System Map and counties without the highway. The airborne lead level is initially higher in the counties with highway. During 1980 -1986 there is a gradually decline in lead, and after 1980 lead level is actually lower in the counties with highway.

Soil Lead data are from the U.S. Geological Survey (USGS) conducted in the late 2000s. Soils samples are collected from a depth of 0 to 5 cm. There are about 2100 counties in our analisys.

4.2. Fertility Data

Fertility outcomes data are from the Vital Statistics of the United States. These files contain detailed information on 100% of the births in most counties and 50% of the births in the remaining counties. The monthly birth counts are defined by county of residence.

To study the effect of lead on fertility and children's quality we focus on the following outcomes: birth counts and birth rate by county-by-month, and birth weight and gestation weeks. Birth rates are constructed by dividing births counts by population in that county[3]. We also construct these measures separately for mothers with high school education and

[3] Another way to construct birth rate would be divide birth counts by female population between 15 and 44 years of age.

mothers with more than high school education (more than12 year of schooling). Figure 1 shows the change in number of births over time. The number of births were relatively stable in 1978-1980. After 1980 the number of births is increasing reaching the peak of 817 in 1988.

Figure 5 plots the number of births over time in counties with highway plans of 1944 Interstate Highway System Map vs counties which were not suppose to get a highway based on the 1944 plan. There are fewer births in the counties without highway. That is not surprising, as these are smaller and more rural counties. The number of births is relatively constant in these counties, around 200 births per month, whereas the number of births has increased from 500 to more than 800 in counties with planned highway.

4.3. Other Controls

We use other controls in our analysis as well. Temperature and precipitation data are taken from PRISM Climate Data. We have average monthly temperature and precipitation. We also include county income and population which are taken from the Census.

4.4. Summary Statistics

Table 1 shows the summary statistics for the main variables used in our analysis. Panel A reports the means and standard deviations for the variable used in the panel data analysis of the effects of airborne lead on fertility over the period 1978-1988. Column 1 presents the summary statistics for all people in our sample of 302 counties over the period 1978-1988. Column 2 and 3 show the means and standard deviations for the first and the last year in our sample: 1978 and 1988. Average airborne lead is 0.30 with a standard deviation of 0.45. There has been a significant decline in the airborne lead over the study period. The leas level was on average 0.62 in 1978, and it has declined to 0.11 in 1988. The average birth rate per month per county is 11.42 birth per 1000 women. The average birth rate is higher among people with less than high school education than among individuals with high school or more: 11.42 vs 9.27 births per 1000 women. Birth rate was higher in 1978 than in 1988: 11.37 vs 10.36. Average number of births of birth per county per month is 604.11. Panel B presents the means and standard deviations for the main variables used in the cross sectional analysis. Average lead in soil is 21.11. Average annual birth rate is 67.84, and average infant mortality rate is 7.17.

5. Results

First, we present the results for airborne lead exposure effects on fertility using panel dataset of US counties over the period 1978-1988. Second, we show the results from the cross sectional analysis of the effect of lead in soil on fertility.

5.1. Effects of Airborne Lead on Fertility

In this section we report preliminary results regarding the effects of lead exposure on fertility choices. Table 2a and 2b show the effect of lead on fertility estimated using OLS and our IV approach.

Table 2a presents the results for the birth rates. Panel A shows the effects estimated by OLS, Panel B presents the estimates using our IV approach, and Panel C reports the first stage for the IV estimation. In column 1 we do not include any additional controls, in column 2 we control for county, month and yearXlatitude and yearXlongitude fixed effects as well as macroeconomic indicators, such as log of employment and log of per capita income. In column 3 we additionally control for climate characteristics (temperature, precipitation, and their squares), and, finally, in column 4 we include an extensive set of individual mother's and child's characteristics (mother's education, mothers' age, marital status, indicator for whether the birth was given at a hospital, dummy for whether the physician was present, dummy for twin births, etc).

Both OLS and IV estimated effects are negative and statistically significantly different from zero, suggesting that the decline in lead increases the number of births. Those effects do not change much when we include additional controls. Estimated coefficients in IV specifications are considerably larger than corresponding OLS estimates. For a one standard deviation decrease in lead (0.45) IV estimates imply an increase in the birth rate by around one (=2.311*0.45), which is a considerable effect given that the mean birth rate in our sample is around 11 and the standard deviation is around 4.

OLS estimates are much smaller, suggesting that they are biased towards zero. We conjecture that this might come from households with higher preference for air quality sorting into cleaner areas that offer a better quality of life to their children. At the same time, such households being more concerned about overall quality of their offspring in the quality-quantity tradeoff might prefer to have fewer children as well.

Table 2b presents the effect of lead on other measures of fertility: number of births, log of number of births, and log of birth rate. The estimated effects are again negative regardless of the measure used and similar in magnitudes.

Table 3 presents the results for the effect of lead on fertility across the two groups: low educated households (those with mothers with less than high school education) and educated households (those with mothers with high school education or more). Panel A presents the estimates using OLS, Panel B shows the estimates using out IV approach. OLS estimates are positive, but small and not statistically significant. IV estimates are negative, large in magnitude, and all but one are statistically significantly different from zero. Moreover, the estimated effect for the sample of households with less education (column 5) in much larger than the effect for more educated households (column 6). For a one standard deviation increase in lead (0.45), the birth rate among low educated families would decline by 1.45 (=0.45*3.233), whereas the effect for high educated families is smaller: 0.9 (=0.45*2.011). Columns 7 and 8 use another measure of fertility: log of birth rate, but the results show the similar pattern: low educated families are affected more by high lead concentrations than high educated families. Overall, these findings support the defensive expenditure conjecture and provide the evidence that the relationship between lead exposure and fertility is not purely epidemiological.

5.2. Effects of Soil Lead on Fertility

Table 4 shows the effect of lead in soil on birth rate measured in 2005 for different set of controls. Column 1 presents the estimated effect only controlling for state fixed effects to account for unobserved state specific variables, in column 2 we further include county specific climate variables, column 3 adds demographic controls, column 4 additionally controls for economics characteristics of the counties, in column 5 we add county-specific housing stock, and column 6 includes all previous controls and adds the county 's nonattainment status for other pollutants and share of democratic votes. The estimated effects are negative in statistically significant across all specifications. For a one standard deviation increase in lead (12.26), the fertility rate on average declines by 3.66 (=12.26*0.299), which is ¼ of the standard deviation of the birth rate in 2005. Table A4 in the appendix shows the results for other years as well: 2003, 2004, 2005, 2006 and 2007. The effects are similar in magnitudes.

Table 5 presents the differential effect of lead in soil for counties with a share of individuals with at least high school education higher than a median share (84.3). Columns 1 through 5 show the effects using the same structure as in table 4: from the less restrictive specification to the most restrictive one. Overall, we estimate a negative effect of lead on birth rate, but this negative effect gets smaller in counties with more high school graduates which parallels our finding that more educated households are affected less by lead pollution.

Table 6 presents the cross sectional results for the effect of soil lead on mortality in 2005. Overall, we estimate positive coefficients, suggesting that an increase in soil lead level is associated with higher mortality. Across different specifications, the estimated effects are of similar magnitudes, however, some are not statistically significantly different from zero. Table 6A in appendix presents the results the most restrictive specification (similar to the specification used in column 5 in Table 6) for other years: 2003-2007.

6. Concluding Remarks

Evidence from the epidemiology literature suggests that exposure to lead impairs the reproductive system of both males and females, and undermines brain development which may lead to lower IQ scores, poorer language function, poorer attention, and violent behavior. In this study we investigate these effects empirically over the period 1978-1988, when airborne lead concentration decreased considerably. We leverage the implementation of Clean Air Act regulations and the 1944 Interstate Highway System Plan within a fixed-effect instrumental variable approach, and find two main results. First, an exposure to lead seems to cause a reduction in the number of births and birth rates for a typical U.S. county. Second, we present suggestive evidence of households' engagement in defensive investment to counter the adverse effects of pollution on fertility, the estimated negative effect of lead on fertility being smaller for the families with more educated mothers.

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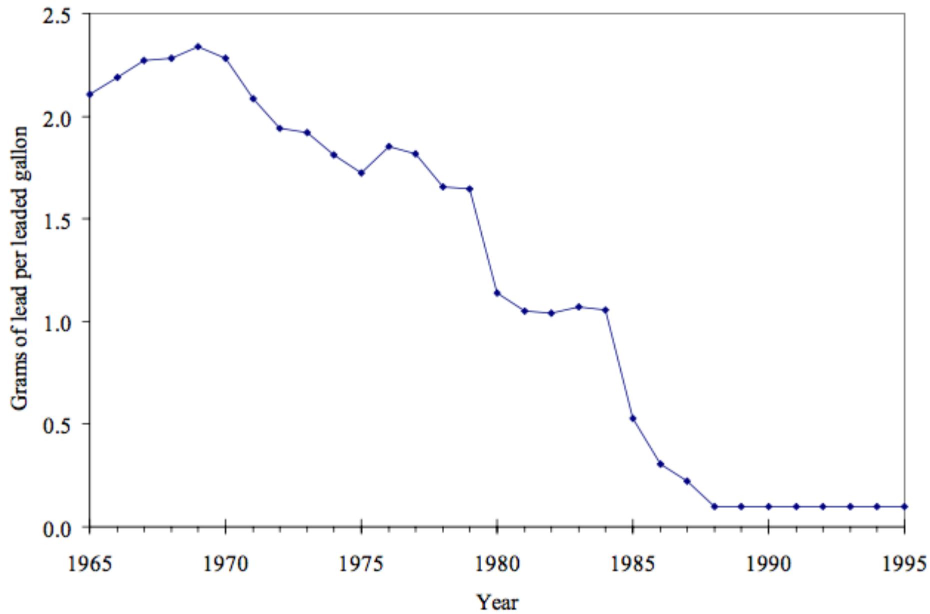
Figures and Tables

Figure 1. Lead Content in Leaded Gasoline (U.S. average)

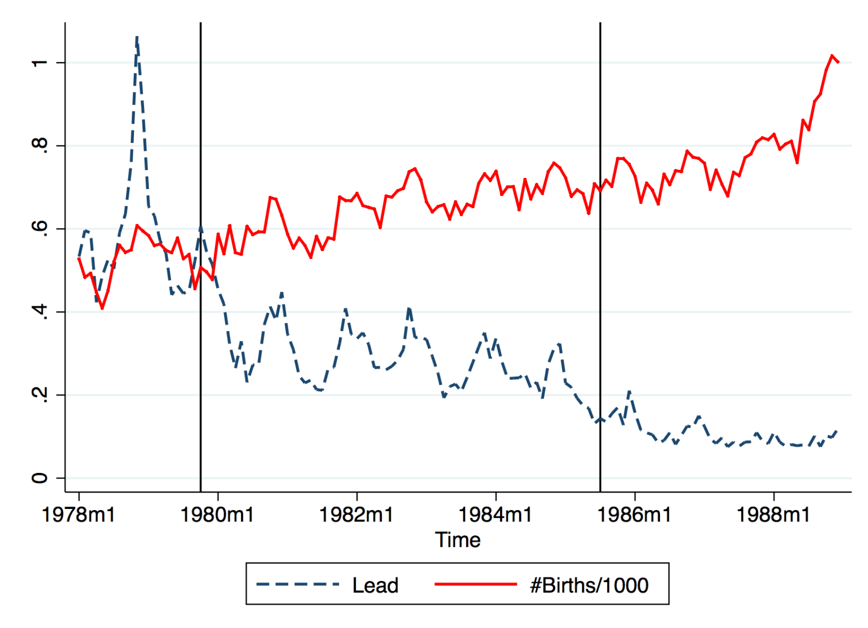


Source: Newell and Rogers (2003).

Figure 2. Routes of the Recommended Interregional Highway System – "1944 Plan"

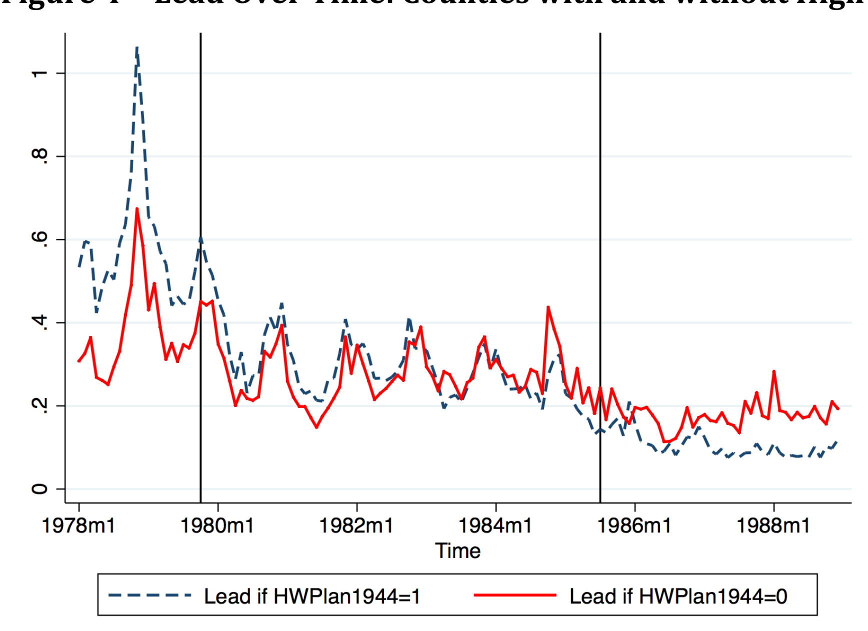
Source: Michaels (2008).

Figure 3: Lead and Number of Birth Over Time



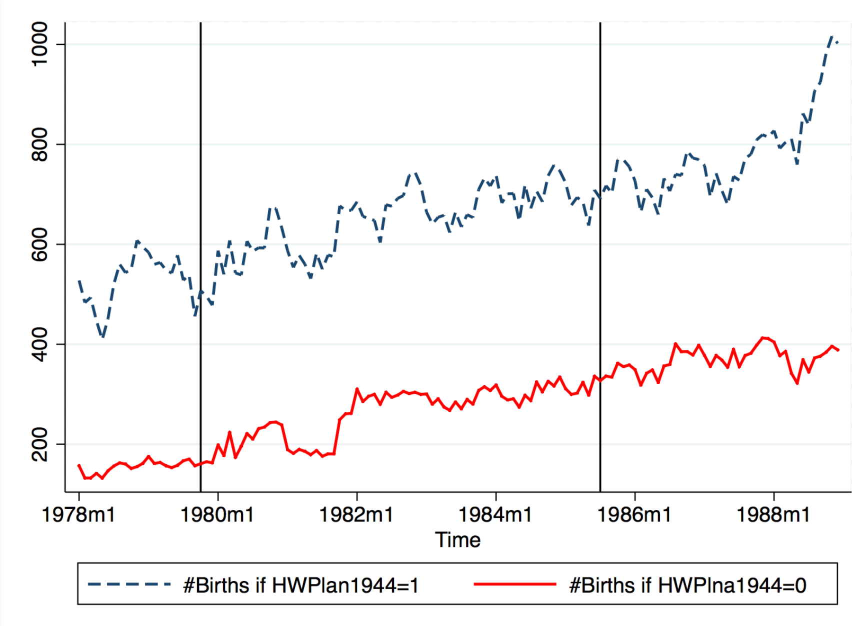
Notes: Figure shows lead levels and number of births/1000 over time during our study period 1978-1988. Two vertical lines show the time of the two policies we are using in our analysis: October 1979, when refineries were required to produce a quarterly average of no more than 0.8 grams per gallon (gpg) among total gasoline output and July 1985, when the standards were tightened to 0.5 gplg.

Figure 4 - Lead Over Time: Counties with and without Highway



Notes: Figure shows lead levels over time in counties with and without highway as planned in the 1944 Interstate Highway System Map during our study period 1978-1988. Two vertical lines show the time of the two other policies we are using in our analysis: October 1979, when refineries were required to produce a quarterly average of no more than 0.8 grams per gallon (gpg) among total gasoline output and July 1985, when the standards were tightened to 0.5 gplg.

Figure 5 - Number of Births Over Time: Counties with and without Highway



Notes: Figure shows number of births levels over time in counties with and without highway as planned in the 1944 Interstate Highway System Map during our study period 1978-1988. Two vertical lines show the time of the two other policies we are using in our analysis: October 1979, when refineries were required to produce a quarterly average of no more than 0.8 grams per gallon (gpg) among total gasoline output and July 1985, when the standards were tightened to 0.5 gplg.

Table 1: Summary Statistics

Variables	*1978-1988*	*1978*	*1988*
Lead	0.30	0.62	0.11
	(0.45)	(0.57)	(0.31)
Birth Rate	11.17	11.37	10.36
	(3.77)	(4.66)	(4.08)
Birth Rate HS drop	11.42	13.02	9.97
	(7.57)	(8.52)	(6.76)
Birth Rate HS+	9.27	9.29	8.64
	(4.49)	(5.33)	(4.51)
#Births	604.11	451.14	936.58
	(1164.70)	(804.52)	(1650.50)
#Births HS drop	86.59	76.16	158.06
	(207.00)	(168.54)	(463.72)
#Births HS+	322.37	250.64	564.57
	(510.32)	(351.78)	(965.39)
Annual Summary Statistics: 2005			
Lead in Soil	21.11		
	(12.26)		
Birth Rate 2005	67.84		
	(13.37)		
IMR 2005	7.17		
	(8.50)		

Notes: Top panel shows the mean and standard deviations in parentheses for our main variables used in the analysis for the whole time period 1978-1988 as well as for the first and the last year of study. Bottom panel presents the mean and standard deviations (in parentheses) for our cross sectional analyses using data for 2005.

Table 2a: Airborne Lead and Fertility

Panel A.	(1)	(2)	(3)	(4)
	Birth Rate	Birth Rate	Birth Rate	Birth Rate
VARIABLES	OLS	OLS	OLS	OLS
Lead	-0.559***	-0.137**	-0.168**	-0.169**
	(0.178)	(0.065)	(0.074)	(0.075)
Observations	24,700	24,700	24,700	24,700
R-squared	0.008	0.883	0.887	0.888
Panel B.	(5)	(6)	(7)	(8)
	Birth Rate	Birth Rate	Birth Rate	Birth Rate
VARIABLES	IV	IV	IV	IV
Lead	-2.821***	-2.611***	-2.554***	-2.311***
	(0.299)	(0.953)	(0.944)	(0.870)
Observations	24,700	24,700	24,700	24,700
R-squared	-0.121	-0.297	-0.229	-0.129
First Stage F	60.02	29.99	22.49	22.44
Panel C.	(9)	(10)	(11)	(12)
	Lead	Lead	Lead	Lead
VARIABLES	1st Stage IV	1st Stage IV	1st Stage IV	1st Stage IV
$Attainment$ X $CAANAS\_TSP_{1978}$	-0.039*	-0.072*	-0.072*	-0.082**
	(0.022)	(0.038)	(0.038)	(0.036)
$LPD_{0.8gpg}$ X $HWPlan1944$	0.078*	-0.083*	-0.083*	-0.085**
	(0.043)	(0.043)	(0.042)	(0.041)
$LPD_{0.5gplg}$ X $HWPlan1944$	0.012	-0.137**	-0.139**	-0.139**
	(0.029)	(0.063)	(0.063)	(0.066)
$LeadPhaseDown_{0.8gpg}$	-0.458***	0.006	-0.005	-0.003
	(0.069)	(0.040)	(0.040)	(0.037)
$LeadPhaseDown_{0.5gplg}$	-0.636***	-0.040	-0.047	-0.046
	(0.064)	(0.054)	(0.054)	(0.054)
First Stage F	60.02	29.99	22.49	22.44
Fixed Effects	No	Yes	Yes	Yes
Economic Variables	No	Yes	Yes	Yes
Climate Variables	No	No	Yes	Yes
Mother and Child Characteristics	No	No	No	Yes
Observations	24,700	24,700	24,700	24,700
R-squared	0.284	0.520	0.527	0.529

Notes: All dependent variables measured nine months in the future. Birth Rate is the number of children born divided by female population 16-39 age old. Table shows the results for OLS and IV using instruments discussed in the identification section. Fixed Effects are county, month and year by latitude and year by longitude fixed effects. Economic Variables are log of employment and log of per capita income. Climate variables are temperature and precipitation and their squares.

Mother and Child Characteristics are mother's education, mothers' age, marital status, indicator for whether the birth was given at a hospital, dummy for whether the physician was present, dummy for twin births, skin color of a child, dummy for previous dead child, dummy for previous child alive, controls for the start of prenatal care. Regressions are weighted by number of females 16-39 age old. Standard errors are clustered at the county level and are in parentheses. *, **, and *** indicate statistical significance at the 10, 5, and 1 percent levels.

Table 2b: Airborne Lead and Fertility

VARIABLES	(1) # Births OLS	(1) # Births IV	(2) Log (# Births) OLS	(2) Log (#Births) IV	(3) Log (Birth Rate) OLS	(3) Log (Birth Rate) IV
Lead	-181.64*	-1,184.5*	-0.014**	-0.250***	-0.015**	-0.171***
	(100.61)	(658.04)	(0.006)	(0.087)	(0.006)	(0.064)
Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Economic Variables	Yes	Yes	Yes	Yes	Yes	Yes
Climate Variables	Yes	Yes	Yes	Yes	Yes	Yes
Mother and Child Characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Observations	24,700	24,700	24,700	24,700	24,700	24,700
R-squared	0.990	-0.397	0.986	-0.059	0.833	-0.019
First Stage F		22.44		22.44		22.44

Notes: All dependent variables measured nine months in the future. #Births is the number of children born. Birth Rate is the number of children born divided by female population aged 16-39. Table shows the results for OLS and IV using instruments discussed in the identification section. Fixed Effects are county, month and year by latitude and year by longitude fixed effects. Economic Variables are log of employment and log of per capita income. Climate variables are temperature and precipitation and their squares. Mother and Child Characteristics are mother's education, mothers' age, marital status, indicator for whether the birth was given at a hospital, dummy for whether the physician was present, dummy for twin births, skin color of a child, dummy for previous dead child, dummy for previous child alive, controls for the start of prenatal care. Regressions are weighted by number of females 16-39 age old. Standard errors are clustered at the county level and are in parentheses. *, **, and *** indicate statistical significance at the 10, 5, and 1 percent levels.

Table 3: Airborne Lead and Fertility by Education

VARIABLES	(1) Birth Rate HS drop OLS	(2) Birth Rate HS+ OLS	(3) Log (Birth Rate) HS drop OLS	(4) Log (Birth Rate) HS+ OLS
Lead	0.106	0.023	0.125	0.101*
	(0.169)	(0.068)	(0.091)	(0.057)
Observations	24,700	24,700	24,700	24,700
R-squared	0.834	0.895	0.880	0.900

VARIABLES	(5) Birth Rate HS drop IV	(6) Birth Rate HS+ IV	(7) Log (Birth Rate) HS drop IV	(8) Log (Birth Rate) HS+ IV
Lead	-3.233**	-2.011*	-0.832***	-.7735748
	(1.256)	(1.135)	(0.322)	(.4996966)
Economics Vars	Yes	Yes	Yes	Yes
Climate Vars	Yes	Yes	Yes	Yes
Demographic Vars	Yes	Yes	Yes	Yes
Year, Month, County FEs	Yes	Yes	Yes	Yes
Observations	24,700	24,700	24,700	24,700
R-squared	-0.068	-0.059	-0.040	-0.033
First Stage F	18.43	23.31	18.43	23.31

Notes: Columns 1, 3 and 5, 7 present the results for people with less than high school education. Columns 2, 4 and 6, 8 report the results for people with completed high school or more. (more than 12 years of schooling). All dependent variables measured nine months in the future. Birth rate is number of births divided by female population aged 16-39. All specifications include controls for economics and climate variable, mother and child characteristics, as well as year, month, county, year by latitude, year by longitude fixed effects. Regressions are weighted by female population age 16-39. Standard errors are clustered at the county level and are in parentheses. *, **, and *** indicate statistical significance at the 10, 5, and 1 percent levels.

Table 4: Lead in Soil and Fertility

VARIABLES	(1) Birth Rate IV	(2) Birth Rate IV	(3) Birth Rate IV	(4) Birth Rate IV	(5) Birth Rate IV	(5) Birth Rate IV
Soil Lead	-0.151	-0.239***	-0.273***	-0.272***	-0.295***	-0.299***
	(0.100)	(0.089)	(0.080)	(0.089)	(0.111)	(0.110)
State FEs	Yes	Yes	Yes	Yes	Yes	Yes
Climate Variables		Yes	Yes	Yes	Yes	Yes
Demographic Variables			Yes	Yes	Yes	Yes
Economic Variables				Yes	Yes	Yes
Housing Variables					Yes	Yes
Other Controls						Yes
Observations	2,113	2,112	2,112	2,100	2,100	2,100
R-squared	0.395	0.429	0.871	0.878	0.871	0.870
First Stage F	65.58	81.52	24.29	19.95	14.03	14.42

Notes: Table shows cross sectional results for 2005. Birth Rate is the number of children born in 2005 divided by female population aged 15-45. Climate Variables are temperature and precipitation and their squares, as well as number of heating and cooling degree days in a particular county. Demographic Variables are following: share of white people, percent of foreign people, share of people with completed high school, share of people with completed college, share of people in different age groups: below 5, 5-9, 10-14, 15-19, 20-24, 25-29, 30-34, 35-39, 40-44, 45-49, 50-54, 55-59, 60-64. Economics variables are income, employment, percent of people below poverty level. Housing Controls include share of houses build before 1939, between 1940 and 1949, between 1950 and 1959, between 1960 and 1969, between 1970 and 1979, between 1980 and 1989, between 1990 and 1999, between 2000 and 2004, number of total houses build, medium number of rooms in 2005-2009 per house. Other controls include share of democratic votes and nonattainment status for any pollutant.

Table 5: Lead in Soil and Fertility by Education

VARIABLES	(1) Birth Rate IV	(2) Birth Rate IV	(3) Birth Rate IV	(4) Birth Rate IV	(5) Birth Rate IV	(5) Birth Rate IV
Soil Lead	0.084	-0.050	-0.274***	-0.250***	-0.272***	-0.280***
	(0.094)	(0.084)	(0.076)	(0.078)	(0.096)	(0.096)
Soil Lead X	-0.196***	-0.162***	0.000	-0.021	-0.019	-0.016
(share HS>84.3)	(0.023)	(0.023)	(0.018)	(0.020)	(0.021)	(0.021)
Climate Variables		Yes	Yes	Yes	Yes	Yes
Demographic Variables			Yes	Yes	Yes	Yes
Economic Variables				Yes	Yes	Yes
Housing Variables					Yes	Yes
Other Controls						Yes
Observations	2,113	2,112	2,112	2,100	2,100	2,100
R-squared	0.418	0.466	0.871	0.881	0.875	0.873
First Stage F	34.87	42.93	12.56	11.12	7.926	8.150

Notes: Table shows cross sectional results for 2005. Soil Lead X (share HS>84.3) shows differential effects for counties with the share of high school graduates higher than 84.3%, which is the median value for 2005-2009. Birth Rate is the number of children born in 2005 divided by female population aged 15-45. Climate Variables are temperature and precipitation and their squares, as well as number of heating and cooling degree days in a particular county. Demographic Variables are following: share of white people, percent of foreign people, share of people with completed high school, share of people with completed college, share of people in different age groups: below 5, 5-9, 10-14, 15-19, 20-24, 25-29, 30-34, 35-39, 40-44, 45-49, 50-54, 55-59, 60-64. Economics variables are income, employment, percent of people below poverty level. Housing Controls include share of houses build before 1939, between 1940 and 1949, between 1950 and 1959, between 1960 and 1969, between 1970 and 1979, between 1980 and 1989, between 1990 and 1999, between 2000 and 2004, number of total houses build, medium number of rooms in 2005-2009 per house. Other controls include share of democratic votes and nonattainment status for any pollutant.

Table 6: Lead in Soil and Infant Mortality

VARIABLES	(1) IMR IV	(2) IMR IV	(3) IMR IV	(4) IMR IV	(5) IMR IV	(5) IMR IV
Soil Lead	0.070**	0.040	0.087*	0.073	0.068	0.066
	(0.030)	(0.027)	(0.050)	(0.055)	(0.064)	(0.063)
State FEs	Yes	Yes	Yes	Yes	Yes	Yes
Climate Variables		Yes	Yes	Yes	Yes	Yes
Demographic Variables			Yes	Yes	Yes	Yes
Economic Variables				Yes	Yes	Yes
Housing Variables					Yes	Yes
Other Controls						Yes
Observations	2,120	2,119	2,119	2,106	2,106	2,106
R-squared	0.148	0.202	0.263	0.294	0.306	0.308
First Stage F	73.32	86.33	25.89	22.37	16.34	16.79

Notes: Tabels shows cross sectional results for 2005. IMR is the infant mortality rate. Climate Variables are temperature and precipitation and their squares, as well as number of heating and cooling degree days in a particular county. Demographic Variables are following: share of white people, percent of foreign people, share of people with completed high school, share of people with completed college, share of people in different age groups: below 5, 5-9, 10-14, 15-19, 20-24, 25-29, 30-34, 35-39, 40-44, 45-49, 50-54, 55-59, 60-64. Economics variables are income, employment, percent of people below poverty level. Housing Controls include share of houses build before 1939, between 1940 and 1949, between 1950 and 1959, between 1960 and 1969, between 1970 and 1979, between 1980 and 1989, between 1990 and 1999, between 2000 and 2004, number of total houses build, medium number of rooms in 2005-2009 per house. Other controls include share of democratic votes and nonattainment status for any pollutant.

Appendix Tables

Table A4: Lead in Soil and Fertility Over Time

VARIABLES	(1) Birth Rate 2003 IV	(2) Birth Rate 2004 IV	(3) Birth Rate 2005 IV	(4) Birth Rate 2006 IV	(5) Birth Rate 2007 IV
Soil Lead	-0.147*	-0.253**	-0.299***	-0.281**	-0.133
	(8.390)	(10.071)	(10.967)	(11.251)	(9.521)
State FEs	Yes	Yes	Yes	Yes	Yes
Climate Variables	Yes	Yes	Yes	Yes	Yes
Demographic Variables	Yes	Yes	Yes	Yes	Yes
Economic Variables	Yes	Yes	Yes	Yes	Yes
Housing Variables	Yes	Yes	Yes	Yes	Yes
Other Controls	Yes	Yes	Yes	Yes	Yes
Observations	2,105	2,104	2,100	2,103	2,106
R-squared	0.919	0.887	0.870	0.866	0.903
First Stage F	14.45	14.44	14.42	14.44	14.45

Notes: Table shows cross sectional results for 2003-2007. Birth Rate is the number of children born in 2007 divided by female population aged 15-45. Climate Variables are temperature and precipitation and their squares, as well as number of heating and cooling degree days in a particular county. Demographic Variables are following: share of white people, percent of foreign people, share of people with completed high school, share of people with completed college, share of people in different age groups: below 5, 5-9, 10-14, 15-19, 20-24, 25-29, 30-34, 35-39, 40-44, 45-49, 50-54, 55-59, 60-64. Economics variables are income, employment, percent of people below poverty level. Housing Controls include share of houses build before 1939, between 1940 and 1949, between 1950 and 1959, between 1960 and 1969, between 1970 and 1979, between 1980 and 1989, between 1990 and 1999, between 2000 and 2004, number of total houses build, medium number of rooms in 2005-2009 per house. Other controls include share of democratic votes and nonattainment status for any pollutant.

Table A6: Lead in Soil and Mortality Over Time

VARIABLES	(1) IMR 2003 IV	(2) IMR 2004 IV	(3) IMR 2005 IV	(4) IMR 2006 IV	(5) IMR 2007 IV
Soil Lead	-0.004	-0.031	0.066	-0.038	0.103
	(0.061)	(0.061)	(0.063)	(0.057)	(0.066)
State FEs	Yes	Yes	Yes	Yes	Yes
Climate Variables	Yes	Yes	Yes	Yes	Yes
Demographic Variables	Yes	Yes	Yes	Yes	Yes
Economic Variables	Yes	Yes	Yes	Yes	Yes
Housing Variables	Yes	Yes	Yes	Yes	Yes
Other Controls	Yes	Yes	Yes	Yes	Yes
Observations	2,106	2,106	2,106	2,106	2,106
R-squared	0.355	0.345	0.308	0.355	0.191
First Stage F	16.79	16.79	16.79	16.79	16.79

Notes: Table shows cross sectional results for 2003-2007. Mortality is the number of cdeath in year t divided by number of birth in the same year. Climate Variables are temperature and precipitation and their squares, as well as number of heating and cooling degree days in a particular county. Demographic Variables are following: share of white people, percent of foreign people, share of people with completed high school, share of people with completed college, share of people in different age groups: below 5, 5-9, 10-14, 15-19, 20-24, 25-29, 30-34, 35-39, 40-44, 45-49, 50-54, 55-59, 60-64. Economics variables are income, employment, percent of people below poverty level. Housing Controls include share of houses build before 1939, between 1940 and 1949, between 1950 and 1959, between 1960 and 1969, between 1970 and 1979, between 1980 and 1989, between 1990 and 1999, between 2000 and 2004, number of total houses build, medium number of rooms in 2005-2009 per house. Other controls include share of democratic votes and nonattainment status for any pollutant.