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ABSTRACT

Toxic Truth: Lead and Fertility*

Using U.S county level data on lead in air for 1978-1988 and lead in topsoil in the 2000s, this paper examines the impact of lead exposure on a critical human function with societal implications – fertility. To provide causal estimates of the effect of lead on fertility, we use two sets of instruments: i) the interaction of the timing of implementation of Clean Air Act regulations and the 1944 Interstate Highway System Plan for the panel data and ii) the 1944 Interstate Highway System Plan for the cross sectional data. We find that reductions in airborne lead between 1978 and 1988 increased fertility rates and that higher lead in topsoil decreased fertility rates in the 2000s. The latter finding is particularly concerning, because it suggests that lead may continue to impair fertility today, both in the United States and in other countries that have significant amounts of lead in topsoil.

JEL Classification: Q53, J13, N52, N92

Keywords: lead in air, lead in gasoline, lead in topsoil, fertility, Clean Air Act

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1. Introduction

Fertility is important both at the individual level and at the societal level, where it has implications for economic activity. Thus, factors that adversely affect fertility are of significant policy concern. Animal studies and epidemiological research on workers with high occupational exposure have shown that lead can adversely affect both male and female reproductive systems. Whether these effects extend to fertility in the broader population, where exposure levels are lower, and the magnitude of any causal effects are open questions.

Using U.S. county level data on lead in air for 1978-1988 and lead in topsoil in the 2000s, this paper provides causal evidence on the effects of lead exposure on the general fertility rate. Beginning in the 1920s, lead was used as an anti-knock compound in gasoline and was emitted with other particulates from tailpipes. Airborne lead fell rapidly during 1978-1988, in part because of regulatory requirements governing lead in gasoline in the Clean Air Act. Lead in topsoil is the result of naturally occurring lead and long term deposition of lead from a variety of anthropogenic sources including lead smelting, industrial activity, agricultural activity, electricity generation, lead in paint, and gasoline emissions. As a result, there is substantial cross sectional variation in lead in topsoil. Lead in topsoil is resuspended in a number of contexts including during dry or windy periods, during construction, and when it is tracked into houses and takes the form of dust.[1] For both airborne lead and lead in topsoil, exposure occurs through inhalation and consumption. Consumption occurs when food or drink comes in contact with dust or if food is grown in the soil. In 2010, the World Health Organization stated that for the general population "the largest contribution to the daily intake of lead is derived from the ingestion of food, dirt and dust." (WHO 2010).

To examine the impact of exposure to lead on fertility rates, we use U.S. Vital Statistics data on fertility, EPA monitor data on airborne lead, and USGS data on lead in topsoil. The U.S. National Vital Statistics data are monthly county-level data derived from individual birth and mortality records. Readings of the U.S. Environmental Protection Agency's network of airborne lead monitoring stations across the nation over the period 1978-1988 were obtained via a Freedom of Information Act (FOIA) request. Our sample covers over a third of the U.S. population. As part of larger soil sampling projects, the U.S. Geological Survey collected data on

[1] See, for example, Laidlaw et al. (2012), and Zahran et al. (2013).

lead in topsoil in the 2000s. In this case, our sample covers about 70 percent of the U.S. population.

Identification in this setting is known to be challenging because of endogenous sorting related to household preferences for air quality and avoidance behavior (e.g., Chay and Greenstone 2003, 2005, Neidell 2004, 2009, Currie and Neidell 2005, Banzhaf and Walsh 2008, Graff Zivin and Neidell 2009, Moretti and Neidell 2011, and Deschênes, Greenstone, and Shapiro 2017). For airborne lead, we use a fixed-effect instrumental variable approach, leveraging the interaction between the 1944 interstate highway plan and the implementation of federal Clean Air Act (CAA) regulations regarding the phase down and out of lead in gasoline, and stricter oversight for counties out of compliance with the National Ambient Air Quality Standards (NAAQS) for particulate matter (PM). Baum-Snow (2007) and Michaels (2008) use the 1944 interstate highway plan as an instrument for highways, as it was designed primarily for military purposes rather than potential economic outcomes. We also exploit variation arising from the highway plan rather than the actual highways because investments in transportation infrastructure may signal a willingness to invest in other infrastructure projects such as hospital and other health care facilities, which would affect fertility and health outcomes more broadly. For lead in topsoil in the 2000s, we use a cross-sectional intent-to-treat instrumental variable approach relying on the 1944 interstate highway plan.

Across all samples, the IV estimates show that increased lead exposure lowers the general fertility rate for women of childbearing age (15 to 44 years). For airborne lead in 1978-1988, the increase in general fertility implied by the average observed decrease in airborne lead is 4.5 births per 1,000 women per year, which is 6.7 percent of mean fertility. For topsoil in the 2000s, our estimates suggest that counties with lead concentration above the median have general fertility rates that are 7.8 births per 1,000 women per year lower than counties below the median, which is 11 percent of mean fertility. The last finding is particularly concerning, because it suggests that lead may continue to impair fertility today, both in the United States and in other countries that have significant amounts of lead in topsoil.

To put these findings in perspective, we compare the magnitude of our results to the impact of the introduction of the contraceptive pill in the U.S. in 1957 and explore the implications of our findings for the benefits and costs of investments in lead reduction. Bailey (2010, 2013) provides quasi-experimental evidence that the availability of the birth control pill decreased annual general fertility rates by approximately 7 births per 1,000 women of childbearing age (15 to 44 years) in the late 1950s and early 1960s.[2] As a result of the decline in airborne lead, our estimates suggest that 95,000 additional babies would be born annually. Based on USDA estimates of the costs of raising a child from birth to age 18 and assuming parents obtain utility from having children, those additional children imply utility gains of at least $18.3 billion (2013 USD). Relative to EPA (1985) estimates of the additional costs of manufacturing unleaded gasoline, the phase down of lead in gasoline would easily pass a cost-benefit analysis. For lead in topsoil, our estimates suggest that cleaning up the lead concentration in counties with lead concentration above the median would induce 166,000 additional births, implying benefits of approximately $33.4 billion (2013 USD) per year. These benefits would warrant the cleaning of about 878,000 residential contaminated lots, as measured by the costs of the Superfund program (West Oakland Residential Lead Assessment, EPA 2010).

This study contributes to two literatures. The first is the literature on the causes of infertility generally, and to the literature on the effect of lead on fertility in particular. There is a large literature studying determinants of fertility (Bailey 2010, 2012, Bailey et al. 2014), and our findings provide causal estimates of an understudied cause – exposure to lead. Our paper is related to Grossman and Slusky (2017), which studied the effect of an increase in lead in the water system of Flint, Michigan on fertility. The results of their case study are qualitatively similar to our nationwide findings, even though the source of exposure is intrinsically different.[3] Their difference-in-differences estimated effect of the change in the water supply in Flint on the annual general fertility rate was approximately 7.5 live births per 1,000 women ages 15-49, or a 12 percent decrease.

Second, this study adds to a growing body of work investigating the impacts of pollution on economic outcomes. Our findings contribute to the subliteratures on air pollution (e.g., Chay and Greenstone 2003, 2005, Currie and Neidell 2005, Currie and Walker 2011, Currie et al. 2014, Currie et al. 2015, Schlenker and Walker 2016, and Deschenes et al. 2017), and on lead (e.g., Troesken 2006, Reyes 2007, 2015, Clay, Troesken, and Haines 2014, Aizer and Currie

[2] Bailey (2012, 2013) also examines the impact of the federal family planning programs starting in 1964, and finds causal evidence that annual general fertility rates declined by 1.5 births per 1,000 women of childbearing age after those programs reached their full capacity in the late 1960s. Family planning involves distributing contraceptive pills to poor women, but also includes health care provision more broadly.

[3] For example, avoidance is easily achieved by consuming bottled water.

2017, Aizer et al. 2018, Gronqvist et al. 2018, and Billings and Schnepel, forthcoming). It also contributes to a much smaller literature investigating the impact of soil pollution, including Superfund sites, on economic outcomes (e.g., Greenstone and Gallagher 2008, Currie, Greenstone and Moretti 2011, Gamper-Rabindran and Timmins 2013, Rau, Urzúa and Reyes 2015, and Persico et al. 2016). The soil effects, in particular, raise issues related to the legacy impacts of environmental degradation.

The remainder of the paper is organized as follows. Section 2 provides a background discussion on types of lead exposure, and its relationship with fertility. Section 3 describes the data and some summary statistics. Section 4 lays out the empirical strategy, focusing particularly on the two instrumental variable approaches. Section 5 reports and discusses the main findings and robustness checks. Section 6 presents some back of the envelope calculations on the benefits and costs of reducing lead exposure based on the main results. Lastly, Section 7 offers some concluding remarks.

2. Background

Lead in the Human Body

Lead primarily enters the body from breathing in dust or chemicals that contain lead or by ingesting food or liquids that contain lead.[4] Once lead reaches the lungs, it goes quickly to other parts of the body via blood stream. Once lead reaches the stomach, some is absorbed into the bloodstream and the remainder is excreted.[5] Once in the blood, lead travels to the "soft tissues" and organs such as the liver, kidneys, lungs, brain, spleen, muscles, and heart. After several weeks, most of the lead moves into the bones and teeth. The half-life of lead in blood is approximately 30 days.[6] Once it is taken in and distributed to organs, the lead that is not stored in

[4] Lead can enter via skin through some compounds, but this is relatively uncommon in non-occupational settings. Lead can also enter the body if one is shot with lead pellets, but this is relatively uncommon vector of exposure.

[5] Experiments using adult volunteers showed that, for adults who had just eaten, the amount of lead that got into the blood from the stomach was only about 6 percent of the total amount taken in. On the other hand, children absorb about 50 percent of ingested lead (U.S. Dept. of Health and Human Services 2007).

[6] See, for example, Griffin et al. (1975), Rabinowitz, Wetherill and Kopple (1976), and Chamberlain et al. (1978).

bones leaves the body via urine or feces. The primary method for determining lead exposure is measurement of blood lead levels.

Although public discussion has focused on the effects of lead in children, adults are also adversely affected by lead. The focus on young children has been driven by the effects of lead on neurological development, which has implications for IQ, educational outcomes, and behavioral outcomes.[7] According to the Centers for Disease Control and Prevention [CDC 2017], "The National Toxicology Program [NTP 2012], and the American Academy of Pediatrics [AAP 2016] have concluded that there is sufficient evidence for adverse health effects in children and adults at blood lead levels (BLLs) <5 micrograms per deciliter (µg/dL)."[8] Adults can experience a variety of adverse health effects including decreased renal function, high blood pressure, and hypertension. We will discuss fertility further below.

Vectors of Exposure

Lead exposure occurs through a number of channels including air, water, food, paint, and soil. Airborne emissions are driven by industrial activities, coal-fired power plants, and on-road vehicles and small aircraft. Figure 1 from the EPA provides information for 1970-2011 on airborne lead emissions by source.[9] Emissions from on-road vehicles were by far the largest source of lead emissions through 1996, but reached zero in 2002. We discuss the regulation of lead in gasoline later in this section. Lead has not yet been banned in aviation gas (non-road engines) used for small aircraft. In 2011 it was the largest source of airborne lead emissions.

Lead service pipes, lead in food, and lead paint have played different roles in different time periods. Lead service pipes were a major source of exposure in the early twentieth century. The treatment of water to manage pH and the use of other types of pipes reduced water lead levels. To further address remaining issues, lead was banned in plumbing fixtures in 1986. Lead in food most often came from cans or solder. U.S. manufactures stopped using lead solder in

[7] For a detailed review of the literature on these outcomes, see National Toxicology Program (2012).

[8] The U.S. Occupational Safety and Health Administration (OSHA) Lead Standards require workers to be removed from lead exposure when BLLs are equal or greater than 50 µg/dL (construction industry) or 60 µg/dL (general industry) and allow workers to return to work when the BLL is below 40 µg/dL. The number of workers with blood lead levels in this range is very small. Drawing on data from 41 states that participate in the Adult Blood Lead Epidemiology and Surveillance (ABLES) Program, the CDC reports that 11,536 individuals had levels above 40 µg/dL between 2002 and 2011. https://www.cdc.gov/mmwr/preview/mmwrhtml/mm6247a6.htm

[9] This figure is available at https://cfpub.epa.gov/roe/indicator.cfm?i=13# , and it was accessed in September 2017.

1991 and FDA banned the use of lead solder in imported canned goods in 1995. Lead in paint has received considerable attention, particularly in older housing stock. The manufacture of lead paint was banned in 1978.

Lead in soil reflects both naturally occurring lead deposits and deposition from a variety of anthropogenic sources including lead smelting, industrial activity, agricultural activity, electricity generation, lead in paint, and gasoline emissions. As we noted in the introduction, lead in soil is a recognized issue, but little has been done to address it. Lead in soil is resuspended in a number of contexts including during dry or windy periods, during construction, and when it is tracked into houses and takes the form of dust.

Lead Exposure and Fertility

The National Toxicology Program published an exhaustive analysis of existing epidemiological studies on the health effects of low level lead, including studies of the effect of lead on reproduction (NTP 2012). In this section, we summarize some of their key findings. One important point, which the NTP (2012, p. 89) explicitly notes, is: "Because the database of human studies on most reproductive endpoints is limited to occupational exposure studies, many of the available studies are for blood Pb levels >10 μg/dL." For comparison, it is useful to provide evidence on blood lead levels in adults during our sample period. The first nationally representative sample of blood lead levels took place as part of the National Health and Nutrition Examination Survey (NHANES) II, which occurred during 1976-1980. Additional data were collected during NHANES III (1988-1991), and NHANES 1999-2002. In 1976-1980 the geometric mean blood lead level for adults ages 20-74 was 13.1 μg/dL (Pirkle et al. 1994). In 1988-1994 and 1999-2002, the age-standardized geometric mean blood lead levels were 2.76 μg/dL and 1.64 μg/dL (Muntner et al. 2005). In comparison, in the preindustrial period, the natural blood lead level is estimated to have been 0.016 μg/dL (Flegal and Smith 1992).

Lead is associated with delays in puberty. The primary channels through which this occurs appear to be delays in growth and altered hormone concentrations. The NTP (2012, p. 89) concludes: "In children, there is sufficient evidence that blood Pb levels <10 μg/dL are associated with delayed puberty in both boys and girls. Nine studies with mean blood Pb levels <10 μg/dL support the relationship between Pb and delayed puberty." At lead levels below 5 μg/dL the evidence is more mixed, with some studies finding effects and other studies finding no effects.

Lead is associated with reproductive effects in men including fertility. Possible channels include direct effects on testes and indirect effects through hormones. The NTP (2012, p. 90) finds: “There is sufficient evidence that blood Pb levels ≥15 μg/dL are associated with adverse effects on sperm or semen in men, and inadequate evidence for adverse effects on sperm at lower blood Pb levels. Decreased sperm count, density, and/or concentration has been reported in multiple retrospective and cross-sectional occupational studies of men with mean blood Pb levels from 15-68 μg/dL ... There is sufficient evidence that paternal blood Pb levels ≥20 μg/dL are associated with delayed conception time and limited evidence that blood Pb levels ≥10 μg/dL in men are associated with other measures of reduced fertility.”

Fertility of women is more difficult to measure, and they have lower occupational exposure to lead, so there is less evidence on lead and fertility for women. NTP (2012, p. 105) states: “There are not enough studies of fertility with Pb exposure data for women in the general population or even with occupational exposure to evaluate the potential relationship between Pb exposure and fertility in women.” Studies of couples who are at IVF or fertility clinics suggest that blood lead may be associated with infertility. As the NTP (2012, p.106) notes, however, “Results from studies of men or women reporting to IVF or infertility clinics should be interpreted with caution because they may represent a sensitive subpopulation.”

Lead is associated with spontaneous abortions. The channel appears to be the adverse effect of lead on the development of the fetus’s neurological system. The NTP (2012, p. 108) states: “There are few human studies with blood Pb data that evaluate the potential association with spontaneous abortion. The conclusions that there is limited evidence that maternal blood Pb <10 μg/dL and paternal blood Pb >31 μg/dL are associated with spontaneous abortion are based primarily on two key studies: the Borja-Aburto et al. (1999) prospective nested case-control study and Lindbohm et al. (1991a) retrospective nested case control study. Additional support for the association is provided by several studies that determine exposure by occupation or residence rather than by blood Pb data.”

One question that these studies do not address is the extent to which the fertility will increase with declines in lead exposure. Animal studies suggest that the adverse effects of lead on males and females may be reversible. Sokol (1989) provides evidence that serum testosterone and sperm parameters normalized at the end of the recovery period (30 days after discontinuing treatment) in prepubertal animals but not in pubertal animals. Piasek and Kostial (1991) show the effects of lead exposure on reproductive outcomes in female rats were reversible. A few small studies of occupationally exposed male workers provide additional evidence that effects of lead on reproductive outcomes may be reversible (Viskum et al. 1999, Fisher-Fischbein et al. 1987, and Cullen et al. 1984).

Although the previous discussion focused on the effects of blood lead levels on outcomes, in most settings – including the setting we study – only data on airborne lead is available. What is the relationship between air lead levels and blood lead levels? EPA (1986) presented four studies of the blood-air lead relationship for adult males. One of the studies was population based, in which the individuals had personal air monitors, and the other three studies were experimental. The EPA analysis concludes (p.1-98): "Thus, a reasonably consistent picture emerges in which the blood lead-air lead relationship for direct inhalation is approximately linear in the range of normal ambient exposures (0.1-2.0 μg/m3)." The slopes ranged from 1.25-2.14. That is, a 1$\mu g/m^3$ increase in air lead was associated with a 1.25-2.14 μg/dL increase in blood lead. For observational studies, the EPA finds (p. 1-101) that: "Slopes which include both direct (inhalation) and indirect (via soil, dust, etc.) air lead contributions are necessarily higher than those estimates for inhaled air lead alone. Studies using aggregate analyses (direct and indirect air impacts) typically yield slope values in the range of 3-5, about double the slope due to inhaled air lead alone."

Regulation of Lead in Gasoline

As mentioned previously, emissions from on-road vehicles were the largest source of lead emissions through 1996, but reached zero in 2002. This remarkable decline in lead was driven by the introduction of catalytic converters and the phase down of lead in gasoline. Catalytic converters, which became mandatory in model year 1975, were designed to control tailpipe emissions including hydrocarbons, nitrous oxides, and carbon monoxide. Leaded gasoline destroys the ability of catalytic converters to control emissions. [10]

EPA also scheduled performance standards requiring refineries to decrease the average lead content of all gasoline – leaded and unleaded pooled. Initially slated to begin in 1975, the lead standards were postponed until October 1979. Once established, refineries were required to

[10] This discussion draws heavily on Newell and Rogers (2003).

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 provide refineries with the incentive to increase unleaded production. By the early 1980s gasoline lead levels had declined by about 80 percent.

At that point, EPA decided to review and tighten the standards. 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. In light of new evidence on the role of lead in gasoline on mental retardation and elevated blood pressure, 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.

3. Data

Airborne Lead

Our airborne lead data are from EPA air pollution monitors located across the country. The data were obtained by a FOIA request. The monitors measure typically multiple pollutants and were likely to have been sited to meet a variety of goals, such as monitoring compliance with the National Ambient Air Quality Standards (NAAQS), public reporting of the Air Quality Index (AQI), assessment of population exposure to pollutants, assessment of pollutant transport, monitoring of specific emissions sources, monitoring of background conditions, evaluating models, and possibly others.

Only a subset of air pollution monitors measured lead, and the number of lead monitors varied over time. Figure 2 shows that the number of monitors measuring lead gradually increased up to 1978 in anticipation of the implementation of NAAQS for lead, remained relatively stable until 1988, and then sharply declined.[11] Lead measurements are available once every three

[11] According to the EPA (2007), this decline is attributable to the decrease in lead concentration observed during the 1980s and the need to fund new monitoring stations. Lead-TSP monitors in lower concentration areas were shut down to free up resources needed to monitor other pollutants such as PM2.5 and ambient ozone.

months before 1978. Beginning in 1978 the lead measurements are available monthly. Thus, we begin our analysis in 1978 and end it in 1988, when the number of monitors began to decline.

We focus our attention on counties that have at least one lead monitor and have airborne lead measurements before and after key dates for compliance with the phasedown of lead in gasoline (October 1979 and July 1985). To construct our airborne lead measures we aggregate monitor readings to a county level, by taking the average of all monitors in the county. As a result, we have an unbalanced panel of 337 counties observed monthly over the period 1978-1988, covering 35 percent of the U.S. population. Appendix Figure A1 provides a map showing the counties in our sample. Darker color represents the counties for which we have observations approximately two thirds of the time. Our empirical analysis uses the unbalanced panel of 337, but robustness checks are performed using the more balanced panel of 162 counties.[12]

Figure 3 shows the decline in lead concentration in the monitors in our sample over the period 1978-1988. The average lead level was 0.85 $\mu g/m^3$ in 1978, but decreased to 0.10 $\mu g/m^3$ in 1988, the last year of our study. For comparison, the current NAAQS for airborne lead is 0.15 $\mu g/m^3$.

Lead in Topsoil

The data on lead concentration in topsoil are taken from the U.S. Geological Survey. The survey in the 2000s was designed to study the concentration and spatial distribution of chemical elements and minerals in soils of the conterminous United States. The sampling sites (1 site per 1,600 km^2) were selected based on the generalized random tessellation stratified (GRTS) design, which produces a spatially balanced set of sampling points without adhering to a strict grid-based system. Soils samples were collected from topsoil (depth of 0 to 5 cm). For each sample we know the latitude and longitude where it was taken. Appendix Figure A2 provides a map of the 4,857 soil sampling sites in the conterminous United States.

To construct the county level data on topsoil lead concentration, we aggregated lead measurements by taking the average of all available lead samples within a county. As a result,

[12] Of the remaining 175 (=337-162) counties, 111 counties have observations 50 percent of the time and 64 counties have observations 25 percent of the time.

we have 2096 counties, as displayed in Figure A3 in the Appendix .[13] To examine the effect of lead on fertility we constructed an indicator variable for whether the lead concentration in a particular county is above or below the median topsoil lead concentration, calculated using the sample for the whole nation.

Fertility Data

To study the effect of lead on fertility, we use data from the National Vital Statistics of the United States to construct following outcomes: general fertility rate (GFR), age-specific birth rates (ASBR), total fertility rate (TFR), and birth counts by county-month, where county is the county of residence. General fertility rates are constructed by dividing birth counts by the number of females in childbearing age (15-44 years), in thousands, taken from the U.S. County-Level Natality Data, 1978-2007. Age-specific birth rates (ASBR) are the number of live births to women in a specific five-year age group divided by the number of women (in 1,000s) in the same age group. We use the following five-year age groups: 15-19, 20-24, 25-39, 30-34, 35-39, and 40-44 years old. Total fertility rate is the number of children who would be born per woman if they were to live through the reproductive years bearing children according to the contemporaneous age-specific general fertility rates. Specifically, $TFR = 5\Sigma_a ASBR_a$, where *a* represents an age group.

Figure 4 plots the general fertility rate over time. The average monthly general fertility rate is 5.63 births per 1,000 women ages 15-44 over the period 1978-1988, and was increasing over this study period. In 1978 the general fertility rate was 5.58, whereas in 1988 it was 5.78 births per 1,000 females of childbearing age. The average annual general fertility rate is 67.68 births per 1,000 women ages 15-44 in 2005, the year that we focus on the soil analysis.

Additional Data

In our panel data analysis of airborne lead, we include fixed effects, economic controls, climate variables, and mother and child characteristics. Fixed effects are county, month, and year fixed effects. Economic variables are log of county total employment and log of county per capita income. Climate variables are temperature, precipitation, their squares, and year by

[13] As a result of this procedure, we may have more than one measurement for a county with a large area, but may not have information for a county with a small area.

latitude and year by longitude fixed effects. Mother and child characteristics are county averages from the U.S. National Vital Statistics System for 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. Temperature and precipitation data are taken from the PRISM Climate Data. County level employment and per capita income are from the Bureau of Economic Analysis (BEA).

In our cross sectional analysis of lead in topsoil, we include state fixed effects and economic, climate, demographic, housing and other controls. Climate variables are temperature and precipitation, as well as number of heating and cooling degree days in a particular county. Economics variables are county income, employment, and share of people below the poverty level. Demographic variables are the following: share of white people, share of foreign born, 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, and 60-64 years old. 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 cast in the 2008 presidential election, and nonattainment status for any criteria pollutant from EPA. Economic, demographic, and housing controls are from the U.S. Censuses. Climate variables are from the PRISM Climate Data.

Summary Statistics

Table 1 shows the summary statistics for the main variables used in our analysis. All variables are weighed by the number of females of childbearing age (15-44 years). Panel A reports the means and standard deviations for the variables 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 our sample of 337 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, respectively. Average airborne lead is 0.35 μg/m^3. The average general fertility rate per month per county is 5.63 births per 1,000 women ages 15-44. The average total monthly fertility rate is

0.15 births per woman with a standard deviation of 0.02. This implies that the total fertility rate in the sample is about 1.84 births per woman.[14]

Panel B presents the means and standard deviations for the main variables used in the cross sectional analysis. Column 1 presents the summary statistics for all 2,096 counties. Column 2 and 3 show the means and standard deviations for the counties with low and high topsoil lead concentration, respectively. The average annual general fertility rate is 67.68 births per 1,000 women ages 15-44. The fertility rate is is 69.89 births per 1,000 women for the low lead counties, whereas it is 65.52 in the high lead counties.

4. Empirical Strategy

Airborne Lead and Fertility

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

$$N_{c,t+9} = \alpha + \beta AirLead_{ct} + X'_{ct}\gamma + \eta_c + \theta_m + \lambda_y + Z'_c\delta_y + \varepsilon_{ct}, \tag{3}$$

where $N_{c,t+9}$ is a fertility outcome for county *c*, measured nine months in the future (*t* denotes month-year), and *AirLead* is airborne lead pollution measured by EPA monitoring stations in county *c* and month-year *t*.[15]

To understand the timing in this equation along with the monthly variation of our observations, recall that (i) the half-life of lead in blood is approximately 30 days, (ii) about 99 percent of the amount of lead taken into the body of an adult is excreted within a couple of weeks (U.S. Dept. of Health and Human Services 2007), and (iii) the adverse effects of lead on animal serum testosterone and sperm parameters seem to reverse after a recovery period of about 30 days (Sokol 1989).

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[14] Appendix Table A1 shows additional summary statistics on the age-specific birth rates and general fertility by education and by race over the period 1978-1988.

[15] Appendix Table A2 presents the estimated effect for fertility rate measured eight and ten months in the future. The effects are similar to the baseline specification.

Regarding the other variables, X is a set of time-varying controls such as temperature and precipitation, η_c is a set of county fixed effects, θ_m is a set of 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, regulatory, and climatological conditions known to vary over space and time, and ε is an error term.[16]

Our coefficient of interest is β. Because there may be important omitted time-varying factors affecting the outcome variables that are correlated with *AirLead*, such as avoidance behavior, it is likely that $\hat{\beta}_{OLS}$ is biased and inconsistent. In particular, if households avoid exposure more often when lead concentration increases, and avoidance is positively related to fertility, then the bias should be positive, and $\hat{\beta}_{OLS}$ underestimated. In addition, exposure to airborne lead might be measured with error because of the potential disconnection between where it is measured and where people live, leading to attenuation bias in the OLS estimate.

Instead of directly observing (and controlling for) defensive responses in the estimation of the causal effect of lead on fertility, the strategy pursued in this study is to use instruments that shift lead levels but are plausibly unrelated to avoidance behavior. As described in the introduction, we use the phase-out of lead in gasoline and its interaction with the 1944 interstate highway plan, and the enforcement of the NAAQS for particulate matter in counties out of compliance, as instruments for lead concentration.

The main assumption behind this instrumental variable approach is that it takes time for the information about actual changes in lead content due to a policy change to reach households. The regulatory oversight is targeted towards refineries and other major emitters in a county rather than households. As a result, there is likely little change in avoidance response immediately after each policy is implemented. At the same time, a decrease in lead due to policy is reflected immediately in the airborne lead pollution levels, which is likely to start affecting health outcomes immediately. While it is likely that households might have had some information about the harmful effects of lead in gasoline even before the phase-out, it is unlikely they were informed about the amount of lead in the "regular" gasoline, which was the policy

[16] We use a single-pollutant instead of a multi-pollutant approach because, as noted by Dominici et al. (2010), "the results of any regression model become highly unstable when incorporating two or more pollutants that are highly correlated (…). In this case, the regression model cannot reliably estimate the main effects of these two pollutants nor their interaction."

parameter that changed during the phase-out. Households might have had even 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 interstate highway plan, which was developed primarily for military purposes. Therefore, we assume that those instruments allow us to uncover the local average treatment effect.[17]

Based on the Clean Air Act (CAA) regulations described in the background section, 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 have had an interstate highway under the 1944 Interstate Highway System Plan (see Figure 5). Following Baum-Snow (2007) and Michaels (2008), we use the advent of the U.S. Interstate Highway System as a policy experiment.[18] We exploit variation arising from the highway plan instead of the actual construction of interstate highways because the willingness to invest in transportation infrastructure might be associated with investment in other infrastructure projects such as schools, hospitals, and other health care facilities, which would affect fertility and health outcomes more broadly. Since politicians pushed for changes in highway routes in response to

[17] Because the Current Population Survey (CPS) reveals that about nine percent of women in childbearing age (15 to 44 years) moved across counties annually in the 1980s (just below the percentage for men in the same age range), in the results section we examine whether improvements in air quality changed the composition of the female population ages 15-44 in counties with a planned highway or out of compliance with the NAAQS. This would imply that the effects of lead on fertility would be driven in part by changes in the types of mothers giving birth in counties affected by our instruments rather than a credible causal effect of lead exposure. As we explain later on, we provide little evidence for differential sorting along observables that might bias our estimates.

[18] 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. 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". 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.

economic and demographic conditions of their constituencies (see Baum-Snow 2007 and Michaels 2008), other local infrastructure projects might have been affected as well.[19]

The last instrumental variable is related to the CAA regulations for criteria pollutants.[20] In 1978, EPA published a list of all "nonattainment" areas – counties out of compliance with the NAAQS. 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 of enforcement, which began in January 1983.

Given these five instrumental variables, our first stage equation is

$$\begin{aligned} AirLead_{ct} = \alpha &+ \pi_1 LeadPhaseDown\_0.8gpg_t \\ &+ \pi_2 LeadPhaseDown\_0.5gplg_t \\ &+ \pi_3 (LPD\_0.8gpg_t * HWPlan1944_c) \\ &+ \pi_4 (LPD\_0.5gplg_t * HWPlan1944_c) \\ &+ \pi_5 (Attainment_t * CAANAS\_TSP1978_c) \\ &+ X_{ct}'\gamma + \eta_c + \theta_m + \lambda_y + Z_c'\delta_y + \varepsilon_{ct}, \end{aligned}$$

where *c* and *t* denote county and month-year, respectively. *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*.

[19] For completeness, the correlation between highways planned and highways built is only 0.5 in our sample. Less than two thirds of the counties recommended a highway by the 1944 plan actually received a highway, and more than ten percent of the counties that were not supposed to receive a highway by the plan had a highway built.

[20] 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.

LeadPhaseDown_0.5gplg 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 recommended by the 1944 Interstate Highway System Plan. The interactions with *HWPlan1944* are supposed to capture the intent-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 compliance 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.[21]

To illustrate the effects of highways on lead, Figure 6 plots the decline in airborne lead levels over time for counties with and without highways in the 1944 Interstate Highway System Plan. The airborne lead level was initially higher in the counties with highways. During 1980-1986 there was a gradual decline in the lead level. By the end of our study period lead levels were about the same in counties with and without highways.

Figure 7 plots fertility for counties with and without highways as recommended by the 1944 Interstate Highway System Plan. Fertility was initially lower in counties with planned highways. Over time, however, the fertility rate was becoming higher in counties with planned highways than in counties without planned highways.

Soil Lead and Fertility

In addition to our panel data analysis of airborne lead exposure on fertility during 1978-1988, we study the effects of exposure to lead in topsoil on fertility in the 2000s. The advantage

[21] The timing of the policy changes leveraged in our empirical analysis may raise a concern related to the oil shock of 1979. Although this event may have affected vehicle miles traveled (VMT), and consequently local air pollution, we provide suggestive evidence in Figure A4, in the Appendix, that nationwide VMT is stable or slightly growing in our period of study, and has a similar pattern for urban and rural counties. (This figure is available at https://www.fhwa.dot.gov/policyinformation/pubs/hf/pl10023/fig2_4.cfm, and was accessed in March 2018). Nevertheless, in our regressions we include year fixed effects, as well as interactions of year fixed effects with county-centroid latitude and longitude. These explanatory variables should capture the effects of macroeconomic shocks such as the oil crisis, and local shocks as associated with the geographic coordinates of each county centroid.

of this cross-sectional approach is that it allows us to document trends in fertility due to continued exposure to lead pollution on a longer-term basis. We estimate the following model:

$$N_c = \alpha + \beta SoilLead_c + X_c\gamma + \eta_s + \varepsilon_c, \qquad (4)$$

where N_c is a fertility outcome for county c in 2005, *SoilLead* is a dummy variable indicating whether the lead in topsoil in a county c is above the median of lead concentration[22], X_c represents various county level controls such as climate, county specific demographic and economic characteristics (listed in the data section above), and η_s represents state fixed effects.[23]

As before, we estimate this equation using an instrumental variable strategy, using the 1944 Interstate Highway System Plan as an instrument for *SoilLead*. By affecting the location of the major highways built with the funds earmarked by the Federal Aid Highway Act of 1956 (Baum-Snow 2007, Michaels 2008), the 1944 plan generates variation in how much lead from gasoline was deposited and historically accumulated in the topsoil. This is an intent-to-treat (ITT) strategy that addresses the unobserved association between lead in soil and defensive responses. The actual highways would not be a valid instrument because the exact location of a highway within a county might have been influenced by unobserved voters' preference for air quality and other infrastructure projects that affect fertility, such as hospitals. In other words, they would be correlated to avoidance behavior and remediation, therefore not tackling the omitted variable bias associated with defensive investments. In our ITT approach, however, we

[22] Because there are no standards for lead in soil, and we are not aware of any studies finding a "safe cutoff" for topsoil lead concentration, we use the observed median lead level in our sample as a threshold to allow for potential nonlinear effects. Also, because we have only one instrument, we are restricted to have only one measure of topsoil lead. The unreported linear specification coefficients are qualitatively similar, but imprecisely estimated.

[23] Similar to the analysis for airborne lead, we adopt a single pollutant approach to examine the impact of topsoil lead on fertility. The continental-scale soil geochemical survey of the 2000s also collected information on other hazardous chemicals such as cadmium, mercury, and nickel. If a subset of these additional chemicals also affects fertility outcomes negatively, such as potentially cadmium (e.g., Benoff, Jacob and Hurley 2000, Pollack et al. 2014), *SoilLead* may represent a sufficient statistic of exposure to contaminated soil. To the extent that some of the chemicals, such as cadmium, may also be added to soils adjacent to roads – the sources being tires and lubricant oils (Wuana and Okieimen 2011) – our instrumental variable might capture variation on them as well. Table A3 of the appendix shows the positive, but not large correlation between lead in soil and other chemicals. Table A4 shows that lead is a more important predictor of fertility than any other chemicals. The magnitude of the effect of lead does not vary much if other chemicals are also included in the OLS analysis. Although we find that cadmium is also affected by our instrument, as shown in Table A5, which reinforces the idea that soil contamination may be driven by potential road emissions in the counties with a recommended highway by the 1944 plan, evidence from Table A4 suggests that the effect of cadmium included alone captures the effect of lead.

isolate the portion of the cross-sectional variation in lead in topsoil that is related only to the highways that were built following exactly the 1944 plan. This variation should be unrelated to voters' preferences: the design of the 1944 plan was not supposed to reflect local preferences, but rather address primarily national security issues. Therefore, our instrument should satisfy both the relevance condition and the exclusion restriction.

5. Estimated Effects of Airborne Lead Exposure on Fertility

Main Results

We start by reporting our findings for the panel data analysis on the impact of exposure to airborne lead on fertility over the period 1978-1988. Table 2 presents the first stage relationship between our instruments and airborne lead. Columns 1 and 2 include no controls and only county fixed effects. Column 2 shows that airborne lead fell after the two regulatory milestones $LPD_{0.8gpg}$ and $LPD_{0.5gplg}$. Moreover, the interaction terms indicate that it fell more in counties that were to receive highways under the 1944 highway plan and fell more in counties that were out of attainment with the TSP standards, as published by EPA for the first time in 1978. In columns 3-5, the coefficients on $LPD_{0.8gpg}$ and $LPD_{0.5gplg}$ are no longer significant with the inclusion of year and month fixed effects. The coefficients on the interaction terms, however, are quite stable as additional controls are included. The first stage F-statistics on the excluded instruments are all above 20, suggesting relatively strong instruments.

Table 3 presents the OLS and IV results for the general fertility rate. For OLS, the coefficient is not statistically significant in column 1.[24] As additional controls are added in columns 2-5, the coefficient on airborne lead becomes negative and significant. For the IV specifications in columns 6-10, the coefficient on airborne lead is uniformly negative, statistically significant and much larger in magnitude than for OLS.[25] The larger coefficient in the IV specification is consistent with the presence of the household avoidance behavior and/or

[24] In unreported regressions, we also examined the impacts of lead exposure on infant mortality, birth weight and male to female sex ratio. Although with the expected signs, those effects were imprecisely estimated.

[25] Hausman tests of the equality of the OLS and the IV estimates are shown in Appendix Table A6. For airborne lead, the confidence intervals are slightly wider for the IV estimates, so that they marginally do not differ significantly from the OLS estimates (p-value: 0.13, see Table A6).

measurement error associated with the potential disconnection between where airborne lead is measured and where people live.

The IV estimates of lead on fertility rates are sizeable. The airborne lead levels declined on average by 0.75 $\mu g/m^3$ over the study period. Thus, the IV estimates imply an increase in the monthly general fertility rate by 0.38 births per 1,000 women ages 15-44. Given that the average monthly fertility rate in our sample is 5.63 and the standard deviation is 0.92, the increase is 6.7 percent of the mean and 41 percent of a standard deviation.

Using the estimates in Table 3 (column 5), Figure 8 illustrates the effects of the decline in airborne lead on fertility rate and number of births. The left-hand-side panels show that although the fertility rate would have fallen had lead remained at its 1978 level. The right-hand-side panels show the number of births. The decline in lead increased the number of births by about 95,000 per year by the end of our sample period relative to what they would have been had lead remained at its 1978 level.

To better understand the magnitude of our estimates, we compare them to the impact of two important events affecting fertility behavior in 20th century U.S.: the introduction of the contraceptive pill in 1957, and the implementation of federal family planning programs in 1964. Bailey (2010, 2013) provides quasi-experimental evidence that the availability of the birth control pill decreased annual general fertility rates by approximately 7 births per 1,000 women of childbearing age (15 to 44 years) in the late 1950s and early 1960s. Bailey (2012, 2013) also finds causal evidence that annual general fertility rates declined by 1.5 births per 1,000 women of childbearing age after family planning programs reached their full capacity in the late 1960s. Our estimates imply that the average reduction of airborne lead in 1978-1988 increased annual general fertility rates by approximately 4.5 births per 1,000 women of childbearing age. Therefore, our estimated impacts are large, but less than the effect of the pill.[26]

Alternative Measures of Fertility and Sample Restrictions

Our main analysis is robust to alternative measures of fertility and to sample restrictions. Table 4 shows the OLS and IV results for another measure of fertility: total fertility rate. As in

[26] Also, it is important to point out that while Bailey's analysis includes the entire country, our airborne lead analysis includes only 337 counties that have air quality monitors, representing 35 percent of the population. Because lead monitoring likely targeted more polluted areas, our fertility results for lead in air might not be representative for the whole country.

the previous table, the IV estimates are much larger than OLS. The magnitudes of the effects are similar as well. For the most restrictive specification in column 5, the implied effect for the average decline in airborne lead concentration over the study period is 7 percent of the mean of total fertility rate and 53 percent of a standard deviation. Table A7 in the Appendix presents OLS and IV estimates for the effect of lead on additional measures of fertility: number of births, log of number of births, and log of the general fertility rate. The estimated effects are negative and qualitatively similar.[27]

Table A9 restricts attention to a more balanced sample. Specifically, we use only counties with airborne lead monitor readings for two-thirds of the months between 1978 and 1988. The estimated effects are also negative and qualitatively similar, suggesting that the attrition and addition of airborne lead monitors over time, as illustrated in Figure 2, are unlikely to significantly bias our main findings.

Table A10 presents IV estimates for the effect of lead on fertility if only urban monitors are used to construct the county level airborne lead measure.[28] The concern is that monitors in suburban and rural locations are noisier measures of population lead exposure. The similarity of these estimates and our main results suggests that measurement error due to the disconnection between where airborne lead is measured and where people live is small.

Table A11 provides evidence that what we estimate is indeed the fertility effect of lead and not other pollutants measured in total suspended particulates (TSP). In column 1 we repeat our main specification. In column 2 we estimate the effect of TSP on fertility. The coefficient is negative but not significant. This could be because our instruments are better predictors for lead than for TSP. In column 3 we include both lead and the part of TSP without lead, constructed as a residual of a regression of TSP on lead. The coefficient on lead in column 3 is not statistically significant, but is similar in magnitude to the coefficient in column 1.

Heterogeneity of the Effects by Age and Education.

[27] Table A8 in the Appendix provides the estimates of the effect of lead on the cumulative fertility rate, which is defined as total number of children born per 1,000 women 35-44 years old. Although imprecisely estimated, those results provide suggestive evidence that our findings for the general fertility rate are not driven by displacement of childbearing.

[28] The sample is slightly smaller, because we drop counties with only one monitor.

Table 5 explores the effects of airborne lead on fertility by age. Columns 1 through 6 shows the effects of airborne lead on age specific birth rates. In particular, we consider the following five-year age groups: 15-19, 20-24, 25-29, 30-34, 35-39, and 40-44 years old. The coefficient on lead is negative and statistically significant for younger women, ages 15-19 and 20-24. At the same time, younger women are responsible for more births. Women ages 20-24, who are at peak fertility, are responsible for 30 percent of the births in our sample.[29] The coefficient on airborne lead for these women is negative and statistically significant. Given that the mean fertility rate for this group is 8.95 and the standard deviation is 2.24, the increase is 10 percent of the mean and 42 percent of a standard deviation.

The coefficients on airborne lead for older women are negative but not statistically significant. Older women may have had longer exposure to airborne lead pollution than younger women. If there is a cumulative negative effect of lead on fertility, then fertility rate among older women might be less responsive to the short-term lead fluctuations. Alternatively, if there is greater measurement error for older mothers, older mothers engage in greater avoidance behavior due to greater income, or both, we would expect to observe greater attenuation bias for this group.[30]

Table 6 examines the effects of airborne lead on fertility by education. Educational attainment is not available for all mothers due to missing data. To perform this analysis, we restrict the sample to the births for which we have complete information.[31] Column 1 shows the result for all mothers using this restricted sample. Column 2 shows the effect for women who are high school dropouts. They account for 21 percent of the total number of births in the sample. Given that the mean fertility rate for this group is 6.02 and the standard deviation is 1.58, the increase is 5.3 percent of the mean and 20 percent of a standard deviation due to the average lead reduction over the study period (0.75 $\mu g/m^3$). Column 3 shows the effect for women who have high school education or higher. Given that the mean fertility rate for this group is 5.70 and the

[29] The mean age at first birth in 1978 was 22.4 (see https://www.cdc.gov/nchs/data/nvsr/nvsr51/nvsr51_01.pdf).

[30] There may be greater measurement error if older mothers live further from lead monitors than younger mothers. If air pollution monitors are concentrated in cities more often than in suburban areas, and older mothers are more likely to live in the suburbs, this pattern could be potentially explained by such time-varying mismatch.

[31] Specifically, the sample is restricted to counties with the education information available for 97 percent of the total birth records in a county-month-year.

standard deviation is 0.91, the increase is 5.7 percent of the mean and 35 percent of a standard deviation. Results from this table suggest that lead has similar effects for lower and high educated mothers.[32]

Changes in County Composition in Response to Policy Changes

An important concern for our study is that improvements in air quality might change the composition of the population in counties with a planned highway or counties that are out of compliance with the NAAQS. This could lead to changes in the characteristics of the mothers in these counties. For example, families may respond to the phase-down of lead in gasoline or the enforcement of the air quality standards by differentially moving in or out of the counties with clean air. This is particularly relevant as Chay and Greenstone (2005) find that CAAA nonattainment designation is associated with increases in housing values nearly 10 years after the legislation went into effect. If these increases in housing values reflect that higher socioeconomic status families are migrating to counties with cleaner air (Banzhaf and Walsh 2008), then we may observe changes in the underlying population characteristics.[33] This would imply that the effects of lead on fertility may be driven in part by changes in the types of mothers giving birth in counties affected by our instruments rather than a causal effect of lead exposure.

Appendix Table A13 investigates whether our instrumental variables led to a compositional shift in the underlying female population in counties with a planned highway or in nonattainment. The results provide little evidence for differential sorting along observables that might bias our estimates. Most point estimates are statistically insignificant and small in magnitude, and the signs of the coefficients suggest that our estimates, if anything, may be only slightly biased. For instance, the enforcement of the NAAQS for PM in nonattainment counties might have led to slightly more single-mother households in those counties, which could slightly bias our estimates upward (in absolute terms), and more whites, which could slightly bias our estimates downward.

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[32] Although we cannot perform the analysis by bins of education and race due to data limitations, we did the analysis separately by race groups to examine the effect of airborne lead on fertility rates among white and non-white mothers. The point estimates suggest the effects are coming primarily from white mothers. Nevertheless, we cannot rule out that the effects are statistically similar for white and non-white mothers as shown in the Appendix Table A12.

[33] The proportion of houses built in the 1980s is similar across counties with and without highways as recommended by the 1944 Interstate Highway System Plan, and across counties with different nonattainment status for TSP.

6. Estimated Effects of Topsoil Lead Exposure on Fertility

Table 7 presents the first stage relationship between our instrument and the indicator for having a lead concentration in topsoil above the national median in 2005. In columns 1-6, the coefficients on the indicator for Highway Plan 1944 are positive and statistically significant. The coefficient in column 6 is 0.104. This means that having a highway recommended by the 1944 plan increases the probability of experiencing lead concentrations in topsoil above the national median by 10.4 percent on average. The first stage F-statistics for the excluded instrument are all above the rule-of-thumb 10, suggesting a strong instrumental variable.

Table 8 shows the effect of lead in topsoil on the 2005 general fertility rate.[34] Panel A presents the results estimated using OLS. Panel B reports the results estimated by IV.[35] As in the panel analysis, both OLS and IV estimates are negative, and OLS estimates are much smaller in magnitude than IV estimates. Column 1 presents the estimated effect only controlling for state fixed effects and climate variables to account for unobserved state specific variables. Columns 2-5 add controls. The IV coefficients on topsoil lead is negative, statistically significant, and stable across specifications. If lead concentration in counties with lead concentration above the median were to decrease to the levels in counties with lead concentration below the median, the fertility rate would increase by 7.8 births per 1,000 women ages 15-44, which is 11 percent of the mean of fertility rate.

To put our result in perspective, it is useful to consider the increase in the number of babies implied by our coefficients and compare the estimated effects with the impact of the introduction of the contraceptive pill in 1957. Given that there were about 21 million women of childbearing age living in counties with lead concentration above the median in 2005, the estimated effect would imply about 166 thousand more babies would be born if lead concentrations in those counties were reduced. This would represent a 5 percent increase in the overall number of newborns. Recall that Bailey (2010, 2013) found the availability of the birth control pill decreased annual general fertility rates by approximately 7 births per 1,000 women of

[34] We report similar estimates for the 2004 and 2006 cross sections in Appendix Table A14.

[35] Hausman tests of the equality of the OLS and the IV estimates are shown in Table A6. For topsoil, the IV estimates differ significantly from the OLS estimates.

childbearing age in the late 1950s and early 1960s. Our estimate of 7.8 births per 1,000 women is similar in magnitude to the effect of the pill.

Our results are in line with results from a soil survey done the 1970s. Tables A15 and A16 show the effect of lead in soil on fertility in the 1970s. Topsoil lead concentrations in the 1970s come from an earlier survey from the U.S. Geological Survey. These data, however, are much more restrictive in terms of coverage and measurement. Only 834 counties were surveyed, lead in soil is measured at a depth of 20 cm rather than at the 0-5 cm as in our main sample, and measurements are reported in ranges. Therefore, it is not surprising that the results in this sample are imprecisely estimated. Notwithstanding, they are qualitatively similar to our main results for the 2000s.

7. Back-of-the-Envelope Calculations of Benefits and Costs of Reducing Lead Exposure

This study's results allow us to conduct a simple cost-benefit analysis for policies reducing lead in the air and in topsoil. An important caveat is that benefits from reductions in lead are much broader than just the benefits from improvements in fertility. They include, for example, improvements in IQ and school outcomes and reductions in crime.

One way to monetize the implied benefits of the effects of exposure to lead on fertility is to assume that parents obtain utility from children over their lifetime. Let us assume that on average the satisfaction parents would obtain from having children would be at least the amount spent in bringing them up. If this is true, then we can multiply the number of additional babies by the cost of raising a child from the U.S. Department of Agriculture (USDA).[36] The total annual benefits for airborne lead based on births in 1988 would be $18.3 billion (2013 USD), as shown in Table 9, Panel A, column 1.[37] The total annual benefits for lead in topsoil based on births in 2005 would be $33.4 billion (2013 USD), as reported Table 9, Panel B, column 1.

[36] This value is computed for every year, and can be accessed at https://www.usda.gov/media/blog/2017/01/13/cost-raising-child . An alternative would be to use the value of a statistical life (VSL) recommended by EPA ($6 million (2013 USD) in 1980s and $7.7 million (2013 USD) in the early 2000s). If that is the case, the annual benefits would be $565 billion (2013 USD) for the reduction in airborne lead and $1.3 trillion (2013 USD) for the reduction in topsoil lead.

[37] For comparison, EPA estimated nationwide ex-ante benefits of approximately $16.6 billion (2013 USD) for 1988 in their cost-benefit analysis of the reduction of lead in gasoline (EPA 1985). Because EPA did not consider fertility impacts, our findings would double the annual overall benefits.

The willingness to pay for reductions in lead should also include the amount spent to avoid exposure.[38] Building on Moretti and Neidell (2011), we provide a measure of such cost by comparing the OLS and IV estimates for the impact of lead exposure on fertility rates, and multiplying the implied number of additional babies by the USDA value of raising a child. The idea behind that comparison is that the OLS estimate might reflect the causal effect of lead on fertility plus the (positive) bias arising from unobserved avoidance behavior. Under the assumption that our instruments are unrelated to household avoidance responses, the IV estimate would reflect only the causal effect of lead exposure on fertility. Hence, the difference should represent the implied amount invested in avoiding exposure.[39]

To provide estimates of the costs incurred in reducing lead in the air and in topsoil, we rely on the policies associated with our instrumental variables. During much of our sample period, refineries produced both leaded and unleaded gasoline. Assuming that the prices faced by consumers reflected the marginal cost by refineries, the difference between the prices of leaded and unleaded gasoline may represent a measure of the costs of those regulations. In the late 1980s, this difference was 10 cents per gallon (2013 USD) (EIA). Multiplying this difference by the consumption of unleaded gasoline (Newell and Rogers 2003), a back of the envelope calculation of the annual costs during the 1980s would be $3 billion (2013 USD).[40] This measure might be an underestimation of the true costs. We are not including potential productivity effects for the refineries and automakers or the direct implementation costs by EPA. For soil, we use the

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[38] Appendix Table A17 presents state level evidence from the National Survey of Family Growth (NSFG) that high airborne lead concentration is associated with higher probability of seeking an infertility treatment.

[39] The drawback of the OLS-IV comparison is that both avoidance behavior and measurement error in lead exposure generate a bias in the (negative) coefficient of interest towards zero. Thus, one should use caution in interpreting this back of the envelope calculation. Nevertheless, it is straightforward to assume that a proportion of the OLS-IV difference is due to attenuation bias, and still obtain a measure for the investment in avoidance. For example, using Aizer et al. (2018)'s largest increase in the coefficients of interest when instrumenting to correct for measurement error – IV estimates three times larger than OLS – we would find that avoidance benefits would be $7.6 billion (2013 USD). In the robustness check using only city monitors in Table A5, however, we find suggestive evidence of a limited role for measurement error in this analysis.

[40] For comparison, EPA estimated nationwide ex-ante social costs of reducing lead in gasoline of approximately $1.2 billion (2013 USD) for 1988 in their cost-benefit analysis (EPA 1985). They explain that their "estimates of these costs are based on estimates of changes in the costs of manufacturing gasoline (and other petroleum products). In the long run in a competitive market, the change in manufacturing costs is likely to be fully reflected in changes in the amounts paid by consumers. In the short run, however, the total amount paid by consumers may be less than or greater than the change in manufacturing costs, depending on supply and demand elasticities and other factors." (EPA 1985, p. II-2)

average cost per household of cleaning up lead contaminated soil based on EPA estimates associated with the Superfund program (West Oakland Residential Lead Assessment, EPA 2010): $38,000 (2013 USD) per residential lot, assuming the average lot size is 15,300 square feet and cleaning is happening at a depth of 8-9 inches.

The fertility benefits from reductions in airborne lead alone appear to exceed the costs associated with unleaded gasoline. For soil, the relationship between costs and benefits are not as clear, because cleanup has not actually occurred. The annual value of the fertility benefits would be sufficient to fund the cleanup of about 878,000 residential lots annually. Overall, it appears that policies reducing concentration of lead in the air and in topsoil generate large benefit-cost ratios.

7. Conclusion

This study presents causal evidence on the relationship between lead exposure and fertility rates in the United States between 1978 and 1988 and in the mid-2000s. In both periods, the effects of lead on fertility are meaningful. From the airborne lead panel data analysis over the period 1978-1988, the increase in fertility implied by the average decrease in airborne lead is 4.5 births per 1,000 women per year, which is 6.7 percent of mean fertility. For the topsoil cross-sectional analysis in the mid-2000s, the fertility rate in high lead counties – counties with lead concentration in topsoil above the national median – is lowered by 7.8 births per 1,000 women, which is 11 percent of the mean in those counties.

Although leaded automobile gasoline was banned in the U.S. in 1996, our findings are still relevant today: deposition in soil remains a public health issue, and gasoline for small aircraft is still leaded. Zahran et al. (2017) provides evidence that leaded gasoline, which is still not regulated by the U.S. EPA but used in a large fraction of piston-engine aircraft, may affect millions of people living close to large and small airports. Moreover, many high and medium income countries have significant levels of lead in topsoil. So lead exposure may continue to impair fertility today. This is a concern, because fertility has implications for economic activity, aging populations, and society more broadly.

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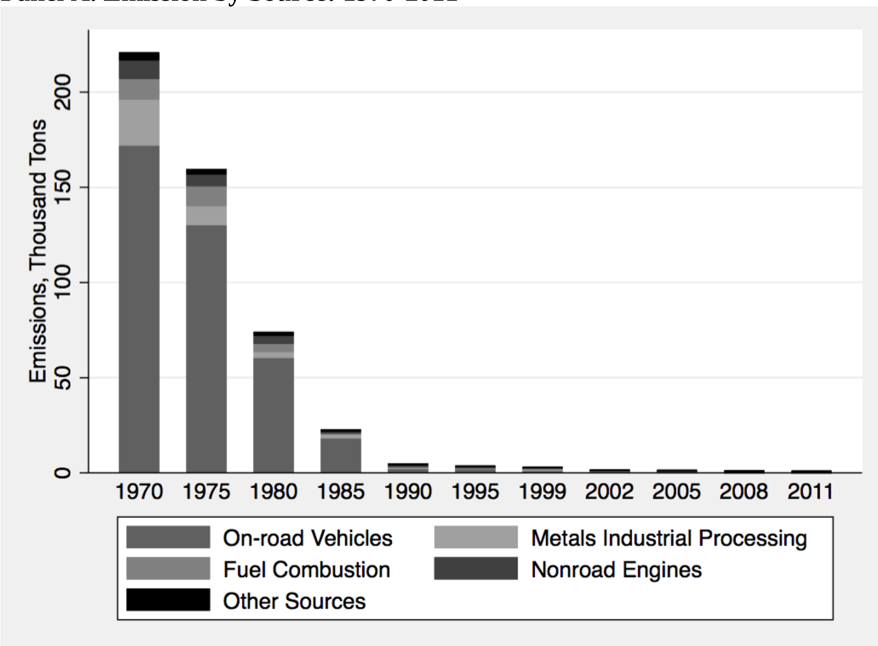
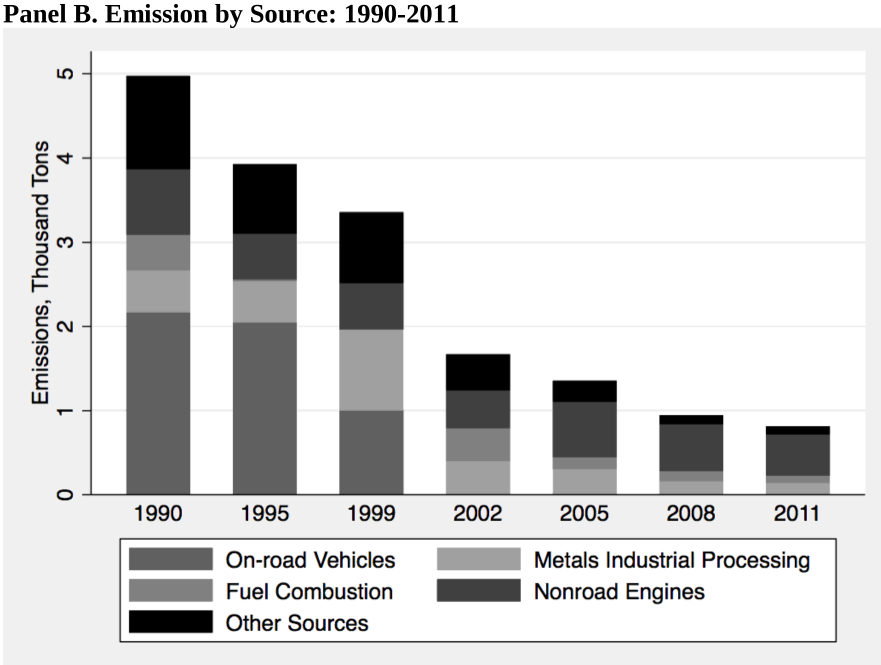
Tables and Figures

Figure 1 – Anthropogenic Lead Emissions in the U.S. by Source Category, 1970-2011

Panel A. Emission by Source: 1970-2011

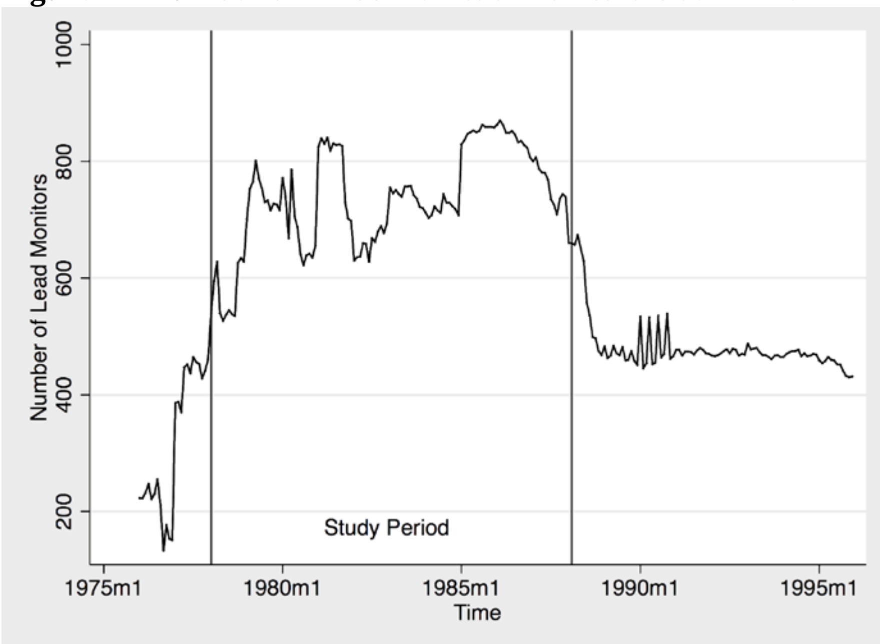


Panel B. Emission by Source: 1990-2011



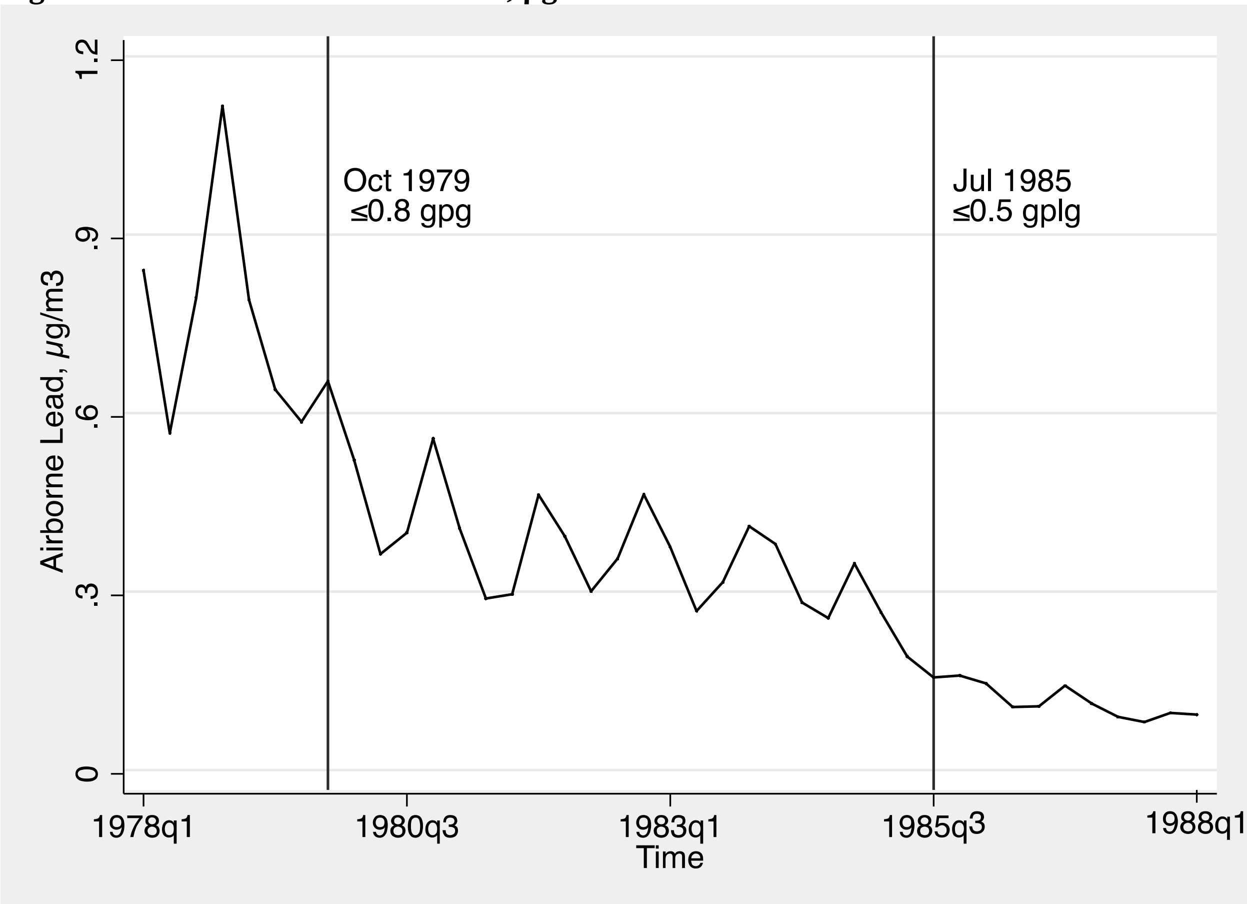
Notes: Data are taken from the U.S. EPA, 2014. Emissions inventory data presented for years that allow reliable estimation of long-term trends. Changes shown reported for 1970-2011 include both emissions changes and methods changes. While the trends displayed in the figure are generally representative, actual changes from year to year could have been larger or smaller than those reported here.

Figure 2 – Number of Airborne Lead Monitors Over Time



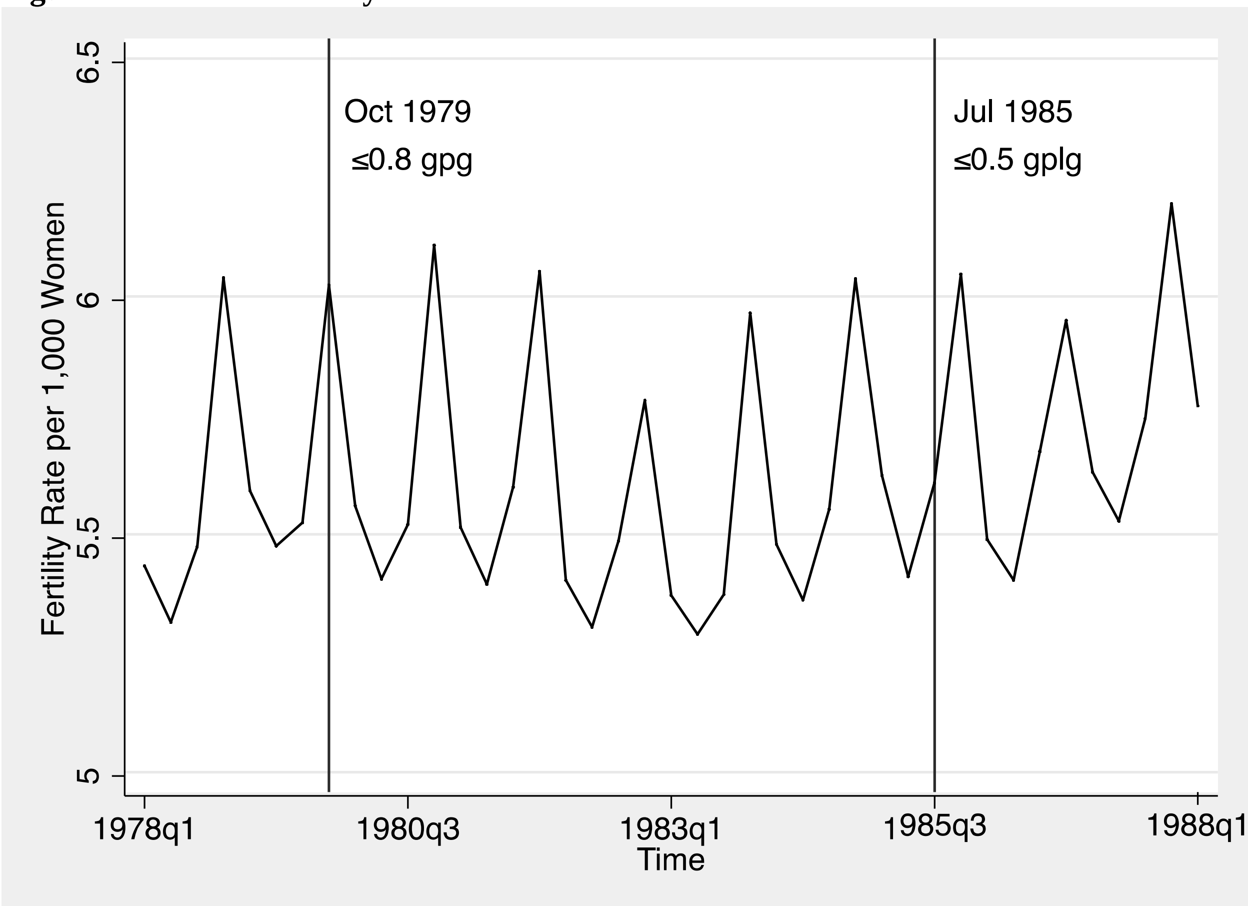
Notes: This figure shows the number of EPA airborne lead monitors over the period 1975-1996. “Study period” is the time period used in the main analysis of the effect of airborne lead exposure on fertility: 1978-1988.

Figure 3 – Airborne Lead Over Time, μg/m³



Notes: This figure shows the concentration of lead in air over time during the study period 1978-1988. Lead in air is weighted by number of women of childbearing age (15 to 44 years). The 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 of lead per gallon (gpg) among total gasoline output, and July 1985, when the standards were tightened to 0.5 grams of lead per leaded gallon (gplg).

Figure 4 – General Fertility Rate Over Time

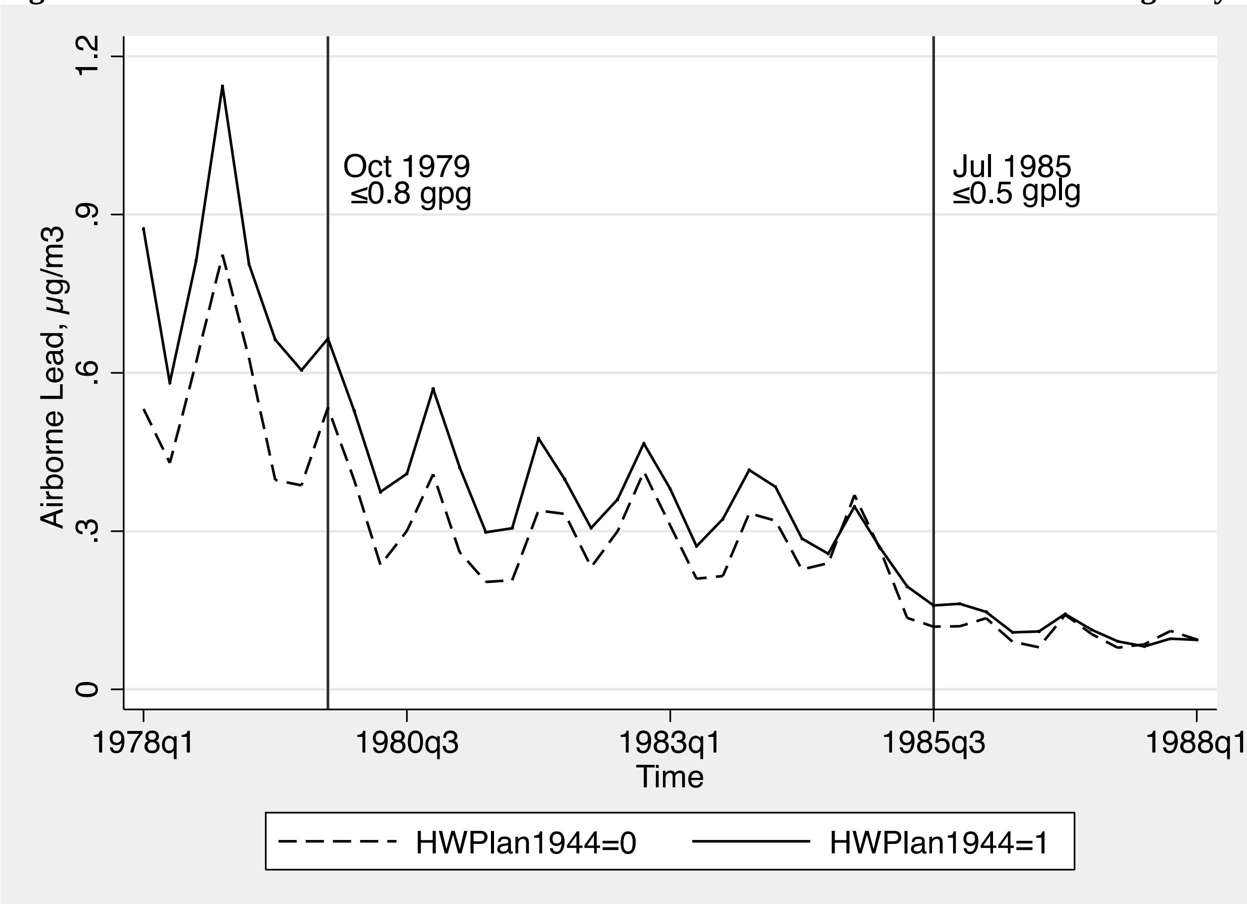


Notes: This figure shows the general fertility rate during the study period 1978-1988 (weighted by number of women of childbearing age). General fertility rate is defined as total number of births per 1,000 females 15-44 years old, measured nine months in the future. The two vertical lines show the time 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 grams per leaded gallon (gplg).

Figure 5 – Routes of the Recommended Interregional Highway System: "1944 Plan"

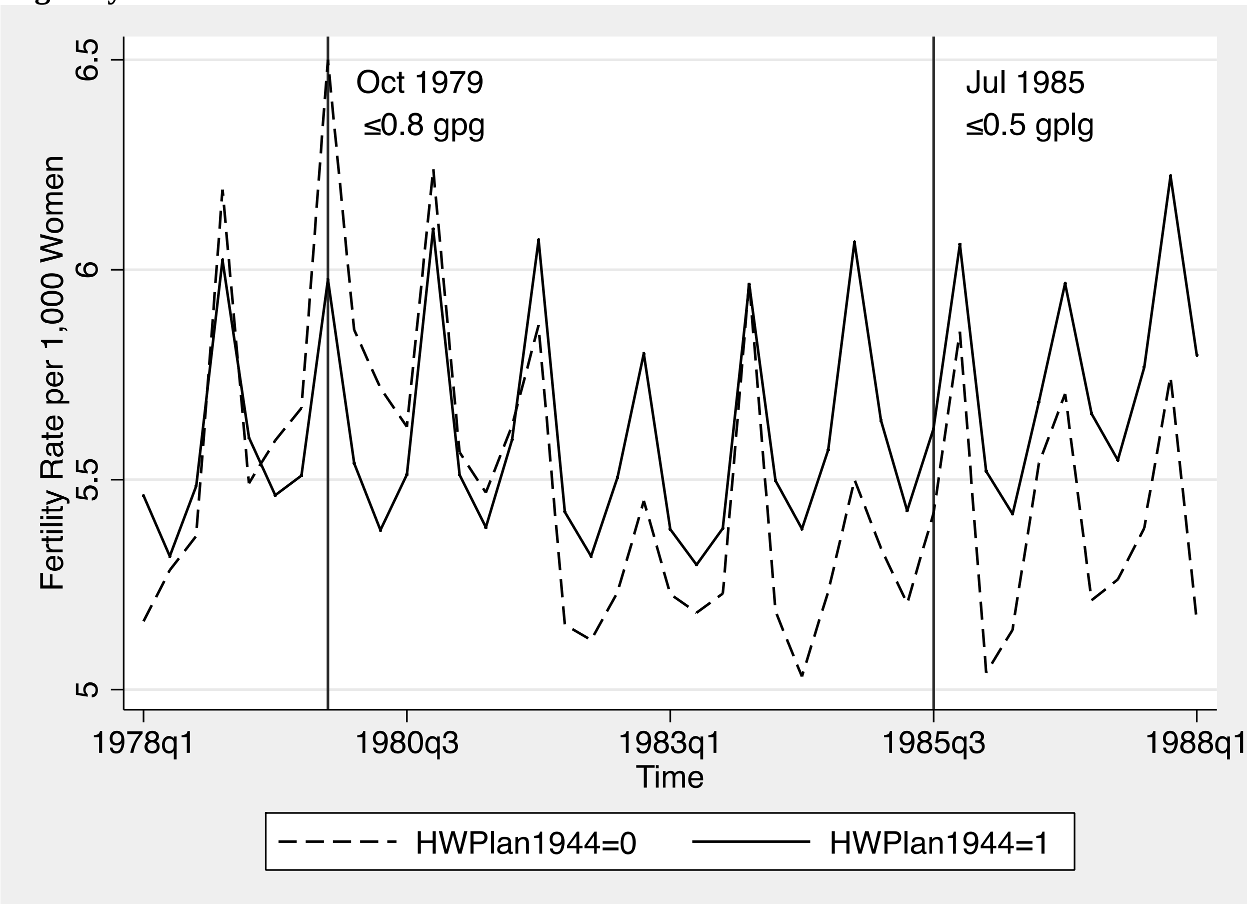
Notes: This figure shows the 1944 Interstate Highway System Plan Map (Michaels 2008). In 1941, President Roosevelt appointed a National Interregional Highway Committee to design a interregional highway system addressing three policy goals (Michaels, 2008): (i) to improve the connection between major metropolitan areas in the U.S., (ii) to serve U.S. national defense, and (iii) to connect with major routes in Canada and Mexico. 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".

Figure 6 – Airborne Lead Over Time: Counties with and without Recommended Highway



Notes: This figure shows airborne lead levels over time in counties with and without highway as planned in the 1944 Interstate Highway System Map during the study period 1978-1988. The series are weighted by number of women of childbearing age (15 to 44 years). The 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 grams per leaded gallon (gplg).

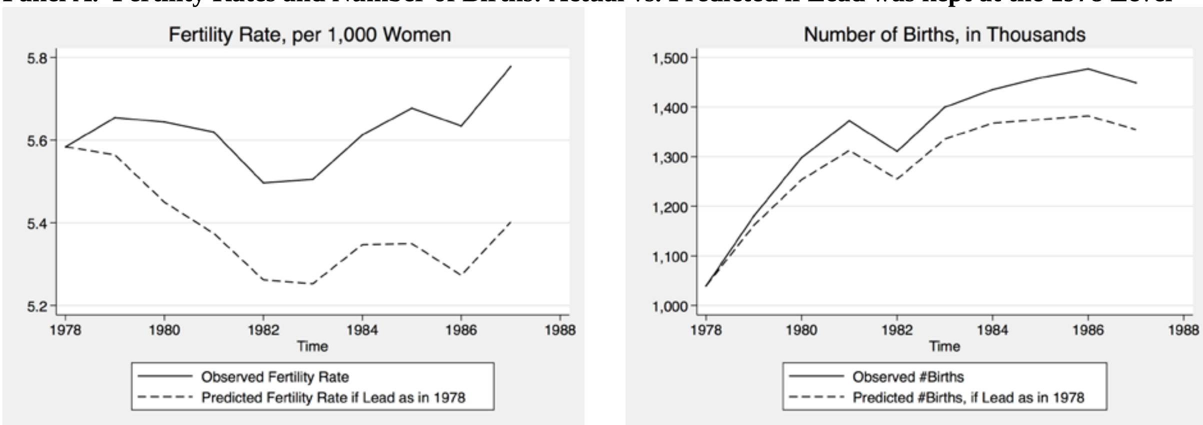
Figure 7 – General Fertility Rates Over Time: Counties with and without Recommended Highway



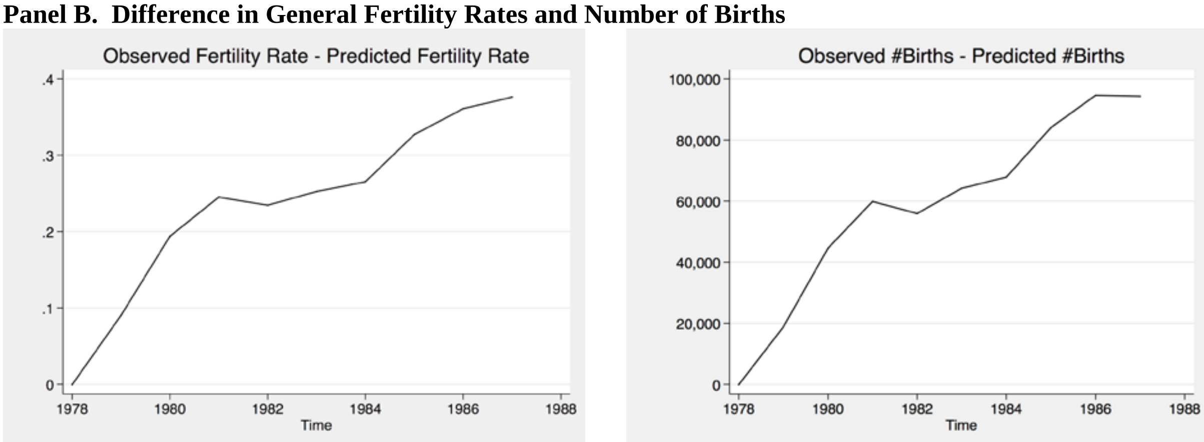
Notes: This figure shows the general fertility rate over time in counties with and without highway as planned in the 1944 Interstate Highway System Map during the study period 1978-1988. General fertility rate is defined as total number of births per 1,000 females 15-44 years old, measured nine months in the future. The series are weighted by number of women of childbearing age. The 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 grams per leaded gallon (gplg).

Figure 8 – Counterfactual Analysis: Keeping Airborne Lead at the 1978 Level

Panel A. Fertility Rates and Number of Births: Actual vs. Predicted if Lead was kept at the 1978 Level



Panel B. Difference in General Fertility Rates and Number of Births



Notes: This figure displays the results of the counterfactual analysis. Panel A shows the results for the general fertility rate and number of births if airborne lead was kept at the average 1978 level, and the general fertility rate and number of births using actual (realized) airborne lead data. General fertility rate is defined as total number of births per 1,000 females 15-44 years old, measured nine months in the future. Panel B presents the difference between the two curves from Panel A. Specifically, the left figure depicts the extra fertility rate due to the decline in airborne lead concentration relative to the fertility rate if airborne lead was kept at the 1978 level. The right figure in Panel B presents the extra number of births.

Tables

Table 1 – County-level Summary Statistics

Panel A. Monthly Statistics for the Panel Data over the period 1978-1988			
Variables	*1978-1988*	*1978*	*1988*
Airborne Lead	0.35	0.85	0.10
	(0.39)	(0.54)	(0.14)
General Fertility Rate	5.63	5.58	5.78
	(0.92)	(1.05)	(0.83)
Total Fertility Rate	0.15	0.15	0.16
	(0.02)	(0.03)	(0.02)
Panel B. Annual Statistics for the Cross-Sectional Data: 2005			
Variables	*All Counties*	*Low Lead Counties*	*High Lead Counties*
Topsoil Lead Indicator	0.51	0	1
	(0.50)		
Topsoil Lead	24.92	14.84	34.77
	(14.94)	(5.02)	(14.86)
General Fertility Rate	67.68	69.89	65.52
	(11.25)	(11.73)	(10.31)
Observations	2,096	1,249	847

Notes: This table shows the summary statistics for the main variables used in our analysis. Panel A 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. General fertility rate is defined as total number of births per 1,000 females 15-44 years old. Total fertility rate is defined as the number of children who would be born per woman if they were to live through the reproductive years bearing children according to the contemporaneous age-specific general fertility rates. Panel B presents the mean and standard deviations (in parentheses) for our cross sectional analyses using 2005 data for all counties, as well as separately for low and high lead counties. Topsoil Lead Indicator is an indicator for whether topsoil lead concentration above or below the median lead in soil. Low and high lead counties are counties with topsoil lead concentration below and above the median respectively. Lead is measured from 0-5 cm deep.

Table 2 – 1st Stage IV – Airborne Lead on Instruments

Variables	(1)	(2)	(3)	(4)	(5)
Attainment X CAANAS_TSP$_{1978}$	-0.041*	-0.133***	-0.097**	-0.061*	-0.071**
	(0.023)	(0.043)	(0.048)	(0.037)	(0.035)
$LPD_{0.8gpg}$ *X HWPlan1944*	0.083*	-0.107**	-0.103**	-0.090**	-0.092**
	(0.042)	(0.049)	(0.043)	(0.042)	(0.041)
$LPD_{0.5gplg}$ *X HWPlan1944*	0.022	-0.161**	-0.156**	-0.149**	-0.149**
	(0.026)	(0.078)	(0.068)	(0.062)	(0.063)
$LPD_{0.8gpg}$	-0.458***	-0.260***	0.020	-0.001	0.001
	(0.068)	(0.032)	(0.034)	(0.040)	(0.037)
$LPD_{0.5gplg}$	-0.631***	-0.410***	-0.030	-0.045	-0.042
	(0.062)	(0.059)	(0.051)	(0.053)	(0.052)
County FE		x	x	x	x
Year FE, Month FE			x	x	x
Economic Variables			x	x	x
Climate Variables				x	x
Mother and Child Characteristics					x
Observations	23,317	23,317	23,317	23,317	23,317
R-squared	0.266	0.336	0.396	0.430	0.432
First Stage F Stat	63.62	119.8	27.68	23.13	23.49

Notes: This table presents the first stage relationship between the instruments and airborne lead. The dependent variable in all columns is airborne lead. The independent variables are as discussed in the main text. *Attainment X CAANAS_TSP*$_{1978}$ 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. $LPD_{0.8gpg}$ 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. $LPD_{0.5gplg}$ is a dummy variable for the period starting in July 1985, when the standards were tightened to 0.5 gplg. $LPD_{0.8gpg}$ *X HWPlan1944* and $LPD_{0.5gplg}$ *X HWPlan1944* are dummy variables for the two policies interacted with the 1944 Interstate Highway System Map. Economic Variables are log of county total employment and log of county per capita income. Climate variables are temperature, precipitation, their squares, and year by latitude and year by longitude fixed effects. Mother and Child Characteristics are county averages for 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 15-44 years old. Standard errors are clustered at the county level and are in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels, respectively.

Table 3 – Airborne Lead and General Fertility Rate: 1978-1988

Panel A. General Fertility Rate - OLS					
Variables	(1)	(2)	(3)	(4)	(5)
Airborne Lead	0.106	-0.010	-0.073	-0.056*	-0.054*
	(0.086)	(0.050)	(0.054)	(0.030)	(0.030)
Observations	23,317	23,317	23,317	23,317	23,317
R-squared	0.002	0.730	0.837	0.847	0.851
Panel B. General Fertility Rate - IV					
Variables	(6)	(7)	(8)	(9)	(10)
Airborne Lead	-0.323***	-0.200**	-0.623***	-0.534**	-0.505***
	(0.105)	(0.101)	(0.215)	(0.215)	(0.195)
County FE		x	x	x	x
Year FE, Month FE			x	x	x
Economic Variables			x	x	x
Climate Variables				x	x
Mother and Child Characteristics					x
Observations	23,317	23,317	23,317	23,317	23,317
First Stage F Stat	63.62	119.8	27.68	23.13	23.49

Notes: This table presents the OLS and IV using instruments discussed in the identification section results for the general fertility rate, measured nine months in the future. General fertility rate is the total number of live births per 1,000 female population 15-44 years old. Economic Variables are log of county total employment and log of county per capita income. Climate variables are temperature, precipitation, their squares, and year by latitude and year by longitude fixed effects. Mother and Child Characteristics are county averages for 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 15-44 years old. Standard errors are clustered at the county level and are in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels, respectively.

Table 4 – Airborne Lead and Total Fertility Rate: 1978-1988

Panel A. *Total* Fertility Rate - OLS					
Variables	(1)	(2)	(3)	(4)	(5)
Airborne Lead	-0.001	-0.004***	-0.002	-0.001	-0.001
	(0.002)	(0.001)	(0.001)	(0.001)	(0.001)
Observations	23,317	23,317	23,317	23,317	23,317
R-squared	0.000	0.706	0.834	0.844	0.848
Panel B. *Total* Fertility Rate - IV					
Variables	(6)	(7)	(8)	(9)	(10)
Airborne Lead	-0.020***	-0.017***	-0.017***	-0.015**	-0.014**
	(0.002)	(0.002)	(0.006)	(0.007)	(0.006)
County FE		x	x	x	x
Year FE, Month FE			x	x	x
Economic Variables			x	x	x
Climate Variables				x	x
Mother and Child Characteristics					x
Observations	23,317	23,317	23,317	23,317	23,317
First Stage F Stat	63.62	119.8	27.68	23.13	23.49

Notes: This table presents the OLS and IV using instruments discussed in the identification section results for the total fertility rates, measured nine months in the future. Total fertility rate is the number of children who would be born per woman if they were to live through the reproductive years bearing children according to the contemporaneous five-year age specific fertility rates. Namely, $TFR=5\sum_{a}ASFR_{a}$, where age specific birth rates are defined as number of live births to women in a specific age group divided by the number of women (in 1,000s) in same age group. The following five-year age groups are used to construct the total fertility rate: 15-19, 20-24, 25-39, 30-34, 35-39, and 40-44 years old. Economic Variables are log of county total employment and log of county per capita income. Climate variables are temperature, precipitation, their squares, and year by latitude and year by longitude fixed effects. Mother and Child Characteristics are county averages for 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 15-44 years old. Standard errors are clustered at the county level and are in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels, respectively.

Table 5 – Airborne Lead and Age Specific Birth Rates: IV

Variables	(1) ASBR 15-19	(2) ASBR 20-24	(3) ASBR 25-29	(4) ASBR 30-34	(5) ASBR 35-39	(6) ASBR 40-44
Airborne Lead	-0.753**	-1.247**	-0.632	-0.296	0.142	0.024
	(0.355)	(0.628)	(0.394)	(0.298)	(0.193)	(0.065)
County FE	x	x	x	x	x	x
Year FE, Month FE	x	x	x	x	x	x
Economic Variables	x	x	x	x	x	x
Climate Variables	x	x	x	x	x	x
Mother and Child Characteristics	x	x	x	x	x	x
Observations	23,317	23,317	23,317	23,317	23,317	23,317
First Stage F	24.54	22.87	22.69	23.28	23.58	23.88

Notes: This table reports the effects of lead exposure on age specific birth rates (ASBR) using instruments discussed in the identification section. Columns 1-6 present the result for the women 15-29 years old, 20-24 years old, 25-29 years old, 30-34 years old, 35-39 years old, and 40-44 years old respectively. All dependent variables are measured nine months in the future. Economic Variables are log of county total employment and log of county per capita income. Climate variables are temperature, precipitation, their squares, and year by latitude and year by longitude fixed effects. Mother and Child Characteristics are county averages for 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 women in each age category. Standard errors are clustered at the county level and are in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels, respectively.

Table 6 – Airborne Lead and Fertility Rate by Education: IV

Variables	(1) GFR, All IV	(2) GFR, HS Drop IV	(3) GFR, HS+ IV
Airborne Lead	-0.433*	-0.421	-0.429*
	(0.252)	(0.481)	(0.248)
County FE	x	x	x
Year FE, Month FE	x	x	x
Economic Variables	x	x	x
Climate Variables	x	x	x
Mother and Child Characteristics	x	x	x
Observations	18,162	18,162	18,162
First Stage F	21.41	20.73	21.26

Notes: This table shows the effect of airborne lead on general fertility rates (GFR). Columns 1 presents the result for all mothers with non missing education, column 2 presents the results for mothers with less than high school education, and column 3 reports the results for mothers with completed high school or more (more than 12 years of schooling). The sample is restricted to counties with the education information available for 97 percent of the total birth records in each county-month-year cell. All dependent variables are measured nine months in the future. The number of females used in the denominator of GFR calculations is interpolated data based on information about females 18-44 years old in 1980 and 1990. 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 the number of female population 18-44 years old in each education group. Standard errors are clustered at the county level and are in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels, respectively.

Table 7 – 1st Stage IV – The 2000s Lead in Topsoil on Instrument

Variables	(1)	(2)	(3)	(4)	(5)
HW Plan 1944	0.131***	0.113***	0.118***	0.102***	0.104***
	(0.031)	(0.028)	(0.030)	(0.029)	(0.030)
State FE	x	x	x	x	x
Climate Variables	x	x	x	x	x
Demographic Variables		x	x	x	x
Economic Variables			x	x	x
Housing Variables				x	x
Other Controls					x
Observations	2,096	2,096	2,096	2,096	2,096
R-squared	0.405	0.444	0.502	0.516	0.517
First Stage F Stat	18.15	16.34	15.98	12.18	12.13

Notes: This table presents the first stage relationship between the instruments and lead in topsoil. The dependent variable in all columns is an indicator variable for whether the topsoil lead concentration is above the national median. The independent variable of interest is the HW Plan 1944, a dummy variable for whether a county was supposed to get a highway based on the 1944 Interstate Highway System Map. Climate Variables are temperature and precipitation, as well as number of heating and cooling degree days in a particular county. Demographic Variables are the 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, and 60-64 years old. Economics variables are income, employment, percent of people below the 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 EPA criteria pollutant. Regressions are weighted by number of females 15-44 years old. Standard errors are clustered at the state level and are in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels, respectively.

Table 8 – Lead in Topsoil and Fertility in 2005

Panel A. General Fertility Rate - OLS					
Variables	(1)	(2)	(3)	(4)	(5)
Topsoil Lead	-2.397**	-0.306	-0.494	-0.481	-0.474
	(0.935)	(0.338)	(0.332)	(0.316)	(0.292)
Observations	2,096	2,096	2,096	2,096	2,096
R-squared	0.407	0.464	0.924	0.928	0.929
Panel B. General Fertility Rate - IV					
Variables	(6)	(7)	(8)	(9)	(10)
Topsoil Lead	-10.508*	-7.949***	-7.052***	-7.645***	-7.762***
	(6.229)	(2.832)	(2.364)	(2.717)	(2.816)
State FE	x	x	x	x	x
Climate Variables	x	x	x	x	x
Demographic Variables		x	x	x	x
Economic Variables			x	x	x
Housing Variables				x	x
Other Controls					x
Observations	2,096	2,096	2,096	2,096	2,096
First Stage F Stat	18.15	16.34	15.98	12.18	12.13

Notes: This table shows the OLS and IV cross sectional effects of lead in topsoil on fertility for 2005. GRF (General Fertility Rate) is the number of children born in per 1,000 female population ages 15-44. Topsoil Lead is an indicator variable for whether the topsoil lead concentration is above the national median. 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 the 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, and 60-64 years old. Economics variables are income, employment, percent of people below the 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 EPA criteria pollutant. Regressions are weighted by number of females 15-44 years old. Standard errors are clustered at the state level and are in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels, respectively.

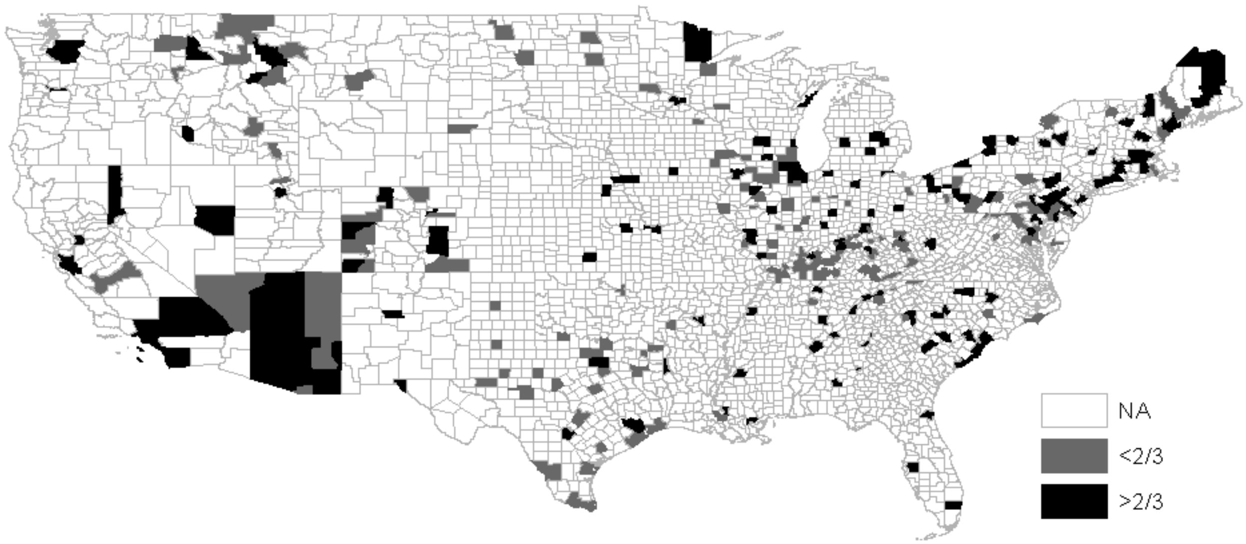
Table 9 – Back of the Envelope Calculation of Benefits-Costs of Reducing Lead Exposure

Panel A.	**Airborne Lead: 1978-1988**		
	35% population		
	337 counties		
	(1)	(2)	(3)
Annual Benefits	**IV**	**OLS**	**IV - OLS**
Babies (in thousands in 1988)	95	10	85
Value (in billions)	$ 18.29	$ 2.04	$ 16.25
Costs (in billions)	$ 3.0		
Panel B.	**Lead in Topsoil: 2005**		
	70% population		
	2096 counties		
Benefits	**IV**	**OLS**	**IV - OLS**
Babies (in thousands in 2005)	166	10	156
Value (in billion)	$ 33.38	$ 2.04	$ 31.34
Break Even Costs	Cleaning ~878,000 residential lots		

Notes: This table presents the back of the envelope benefit-cost calculations based on the estimated effects of lead exposure on fertility. All amounts are expressed in 2013 USD. Column 1 calculates the benefits based on IV estimates, column 2 presents the estimates based on OLS, and column 3 reports the difference between the two. Panel A shows the monetized benefits of cleaner air. In particular, it computes the benefits of having more children as a result of the airborne lead reduction compared to the airborne lead level in 1978. Benefits are total benefits in all counties in 1988. Costs in the Panel A are the average annual costs in all counties in the sample. Costs are estimated based on the airborne lead reduction due to the introduction of unleaded gasoline, and are computed using the difference in prices between leaded and unleaded gasoline in 1988 (10 cents in 2013 USD), share of unleaded gasoline used in 1988 (80 percent), the amount of gasoline used based on the average MPG of the car fleet in 1988, and vehicle miles traveled in 1988. Panel B presents the estimates of benefits and costs using the 2000 cross sectional data on lead in soil. Benefits are calculated based on the assumption of bringing the lead concentrations from above the median to below the median. Beak even costs are calculated based on the costs of cleaning the soil from lead used in the superfund program in the East West Oakland, CA Site (West Oakland Residential Lead Assessment, EPA 2010). The estimates of costs assume an average yard size of 15,300 square feet per site with cleaning at 8-9 inches depth. Costs of cleaning is $38,000 in 2013 USD per residential lot.

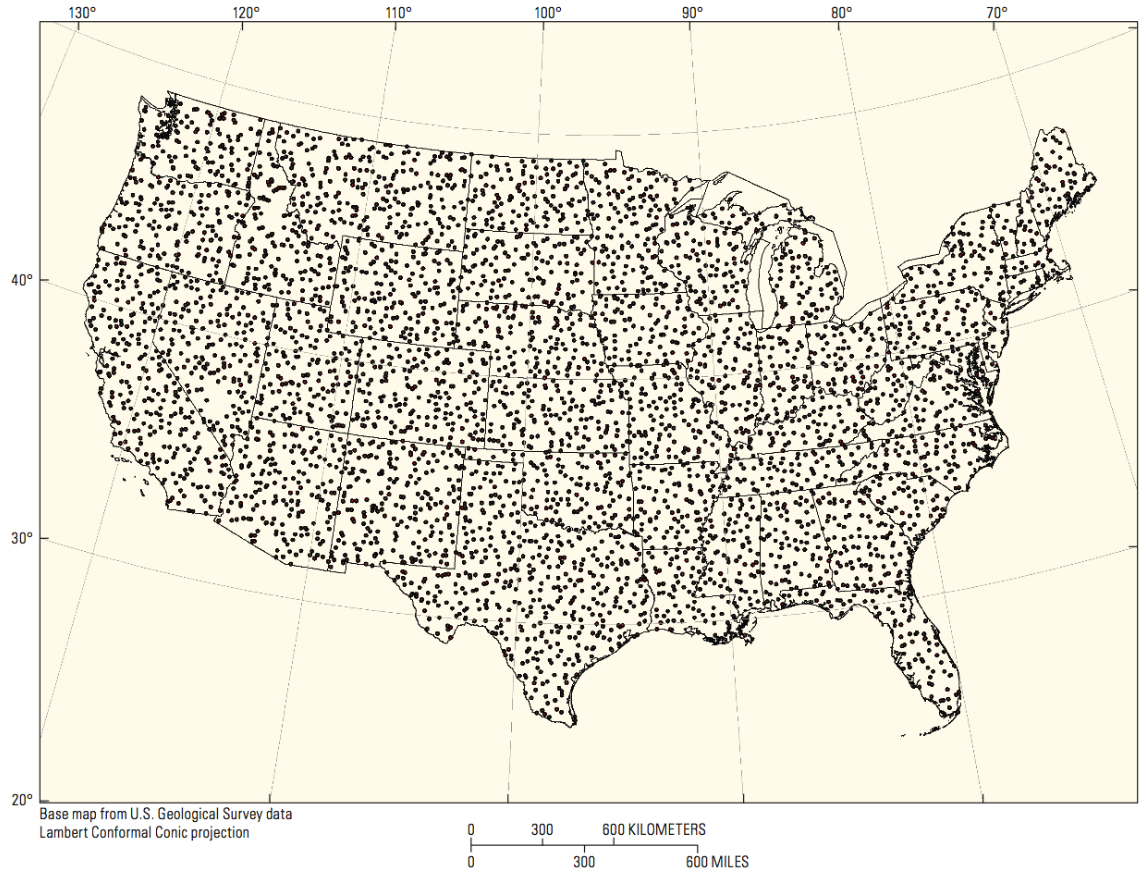
Appendix Figures

Figure A1 – Counties in Our Sample



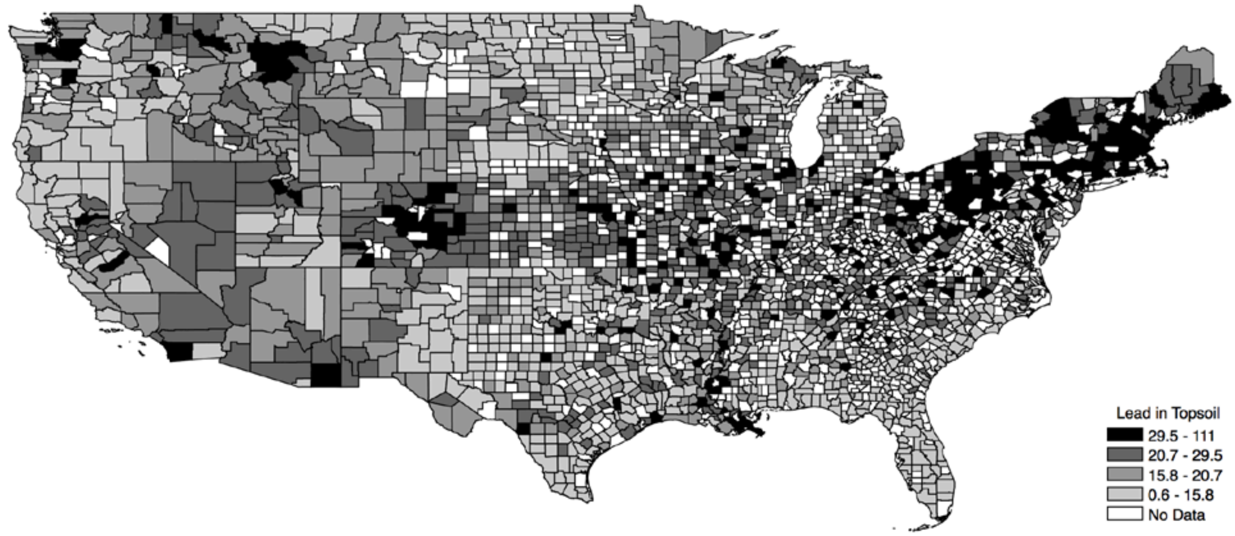
Notes: This map shows the counties in our sample. As discussed in the data section, we have an unbalanced panel of 337 counties. Darker color represents counties that appear approximately two thirds (64%) of the time in our sample.

Figure A2 – Soil Sampling Sites



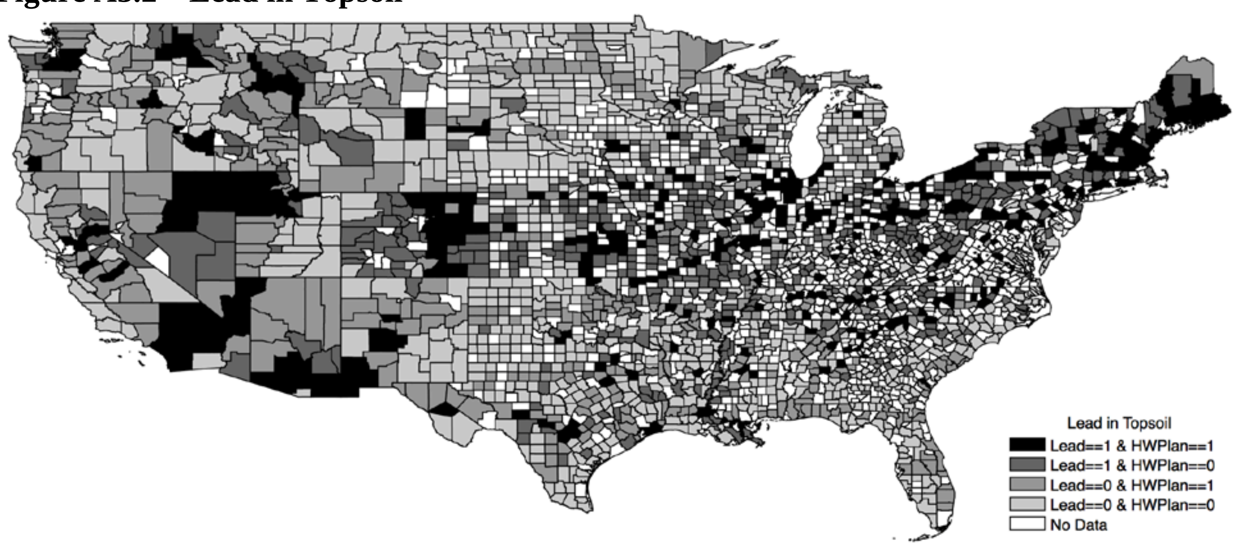
Notes: This map shows the location of 4,857 soil sampling sites in the conterminous United States. Source: Smith, D.B., Cannon, W.F., Woodruff, L.G., Solano, Federico, Kilburn, J.E., and Fey, D.L., 2013, Geochemical and mineralogical data for soils of the conterminous United States: U.S. Geological Survey Data Series 801, 19 p., http://pubs.usgs.gov/ds/801/.

Figure A3.1 – Lead in Topsoil (mg/kg) in the 2000s



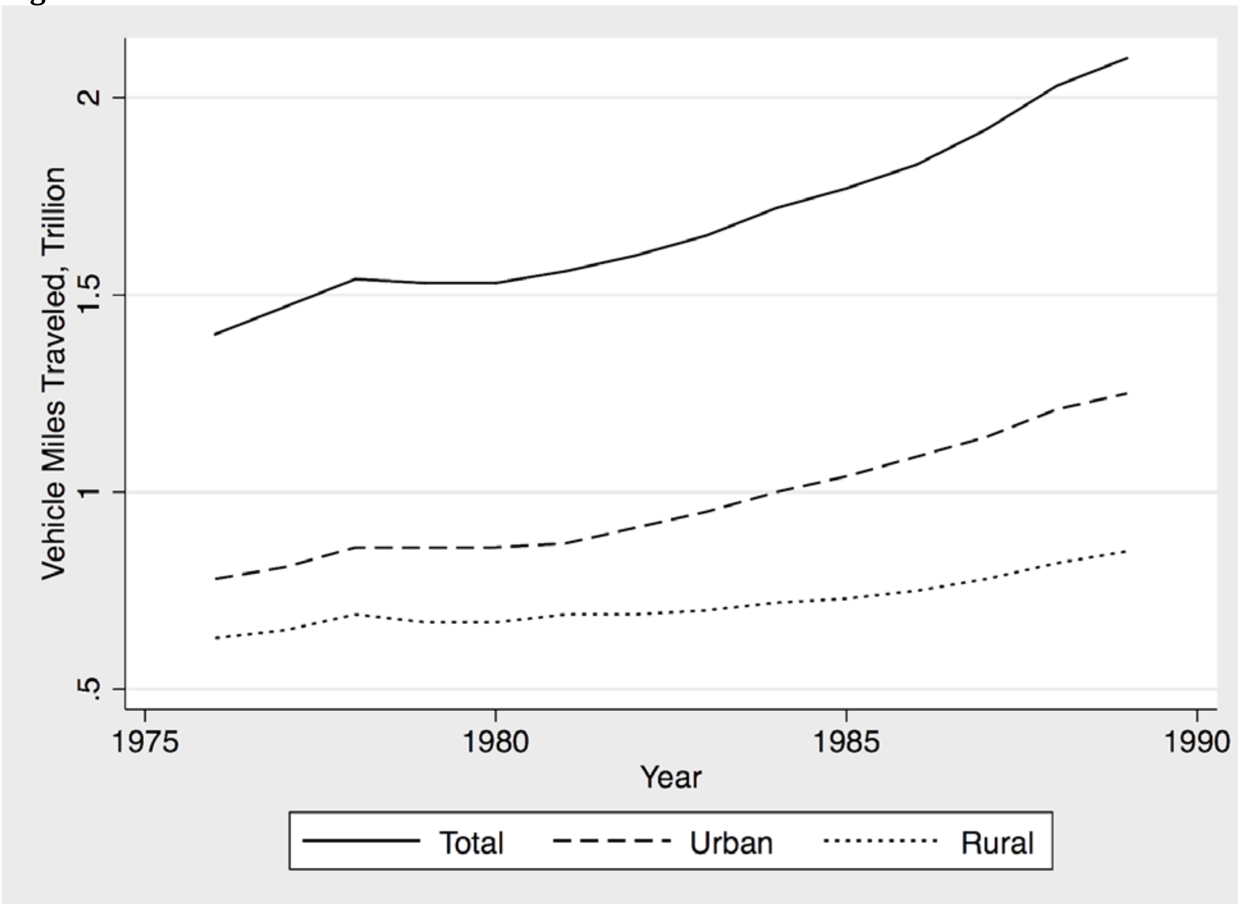
Notes: This figure shows the lead concentration (mg/kg) in topsoil, at a depth of 0-5 cm. Data are taken from U.S. Geological Survey. Soils samples started to be collected for pilot studies from 2004 to 2007, but the main samples were collected by state with the last one collected in late 2010.

Figure A3.2 – Lead in Topsoil



Notes: This figure shows the distribution of counties with topsoil lead concentration above the median (Lead=1) and below the median (Lead=0), as well as counties with and without highway as planned in the 1944 Interstate Highway System Map (HWPlan=1 and HWplan =0 respectively).

Figure A4 – Annual Vehicle Miles Traveled on Rural and Urban Public Roads



Notes: This figure shows Annual Vehicle Miles Traveled (VMT) on Rural and Urban Public Roads. For any given segment of roadway, the VMT is obtained by multiplying the Annual Average Daily Traffic (AADT) by the length of the roadway segment. For example, on a 5-mile highway segment traveled by 5,000 vehicles daily (an average obtained over a year), the VMT would be 25,000. VMT is a measure of total vehicle activity. Source: US Department of Transportation, Federal Highway Administration, Office of Highway Policy Information, Highway Statistics.

Appendix Tables

Table A1 – Summary Statistics

Variable	Mean	Std. Dev.
Age Specific Birth Rates (ASBR)		
15-19	4.31	1.52
20-24	8.95	2.24
25-29	9.18	1.34
30-34	5.94	1.17
35-39	2.14	0.73
40-44	0.39	0.22
General Fertility Rate (GFR)		
HS drop	6.02	1.58
HS +	5.70	0.91
White	5.29	1.55
Non-White	6.71	1.28
Cumulative Fertility Rate (CFR)	4.31	1.90

Notes: This table shows the mean and standard deviations for the Age Specific Birth Rates (ASBR) for the whole period 1978-1988, General fertility rates by education and Cumulative Fertility Rate (CFR). Age Specific Birth Rates are defined as number of live births to women in specific age group (15-19, 20-24, 25-39, 30-34, 35-39, and 40-44 years old) divided by the number of women (in 1,000s) in same age group.

Table A2 – Airborne Lead and Fertility in Alternative Time Windows: 1978-1988

Panel A. General Fertility Rate - OLS			
Variables	(1)	(2)	(3)
	F8	F9	F10
Airborne Lead	-0.053**	-0.054*	-0.053**
	(0.026)	(0.030)	(0.025)
Observations	23,317	23,317	23,317
R-squared	0.848	0.851	0.847
Panel B. General Fertility Rate - IV			
Variables	(4)	(5)	(6)
	F8	F9	F10
Airborne Lead	-0.325*	-0.505***	-0.446**
	(0.185)	(0.195)	(0.193)
County FE	x	x	x
Year FE, Month FE	x	x	x
Economic Variables	x	x	x
Climate Variables	x	x	x
Mother and Child Characteristics	x	x	x
Observations	23,317	23,317	23,317
First Stage F	23.49	23.49	23.49

Notes: This table presents the OLS and IV using instruments discussed in the identification section results for the general fertility rate, measured eight (F8), nine (F9, preferred specification), and ten (F10) months in the future in columns 1, 2 and 3 respectively. General fertility rate is the total number of live births per 1,000 female population 15-44 years old. Economic Variables are log of county total employment and log of county per capita income. Climate variables are temperature, precipitation, their squares, and year by latitude and year by longitude fixed effects. Mother and Child Characteristics are county averages for 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 15-44 years old. Standard errors are clustered at the county level and are in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels, respectively.

Table A3 – Correlation between Hazardous Chemicals in Topsoil in the 2000s

	Lead	Cadmium	Mercury	Nickel	Zinc
Lead	1				
Cadmium	0.274	1			
Mercury	0.376	0.345	1		
Nickel	0.127	0.418	0.262	1	

Notes: This table shows the correlation (weighted by female population ages 15-45) between different Hazardous Chemicals in Soil in 2005. All variables are indicators for whether a county has the chemical concentration above or below the national median.

Table A4 – Hazardous Chemicals in Topsoil and Fertility in the 2000s: OLS

Variables	(1) GFR	(2) GFR	(3) GFR	(4) GFR	(5) GFR
Lead	-0.496*	-0.544*	-0.442	-0.409	-0.540*
	(0.284)	(0.299)	(0.289)	(0.248)	(0.302)
Cadmium	0.071				0.119
	(0.368)				(0.379)
Mercury		0.175			0.167
		(0.244)			(0.226)
Nickel			-0.229		-0.275
			(0.282)		(0.289)
State FE	x	x	x	x	x
Climate Variables	x	x	x	x	x
Demographic Variables	x	x	x	x	x
Economic Variables	x	x	x	x	x
Housing Variables	x	x	x	x	x
Other Controls	x	x	x	x	x
Observations	2,096	2,096	2,096	2,096	2,096
R-squared	0.930	0.930	0.930	0.930	0.930

Notes: This table shows the OLS cross sectional effects of hazardous chemicals in topsoil on fertility for 2005. All dependent variables are indicators for whether a county has chemical concentration above or below the national meadin. GFR (General Fertility Rate) is the number of children born in each specific year divided by female population ages 15-45 in that 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 the 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 EPA criteria pollutant. Regressions are weighted by number of females 15-44 years old. Standard errors are clustered at the state level and are in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels, respectively.

Table A5 – Hazardous Chemicals in Topsoil and Fertility in the 2000s

Panel A. OLS	(1)	(2)	(3)	(4)
Variables	GFR	GFR	GFR	GFR
Lead	-0.474			
	(0.292)			
Cadmium		-0.063		
		(0.371)		
Mercury			-0.034	
			(0.249)	
Nickel				-0.287
				(0.288)
Observations	2,096	2,096	2,096	2,096
R-squared	0.930	0.930	0.930	0.930
Panel B. IV	(1)	(2)	(3)	(4)
Variables	GFR	GFR	GFR	GFR
Lead	-7.762***			
	(2.816)			
Cadmium		-7.362**		
		(3.632)		
Mercury			-15.908	
			(11.966)	
Nickel				-11.864
				(8.907)
State FE	x	x	x	x
Climate Variables	x	x	x	x
Demographic Variables	x	x	x	x
Economic Variables	x	x	x	x
Housing Variables	x	x	x	x
Other Controls	x	x	x	x
Observations	2,096	2,096	2,096	2,096
First Stage F	12.13	11.37	2.512	3.315

Notes: This table shows the OLS and IV cross sectional effects of hazardous chemicals in topsoil on fertility for 2005. All dependant variables are indicators for whether a county has chemical concentration above or below the meadin. GFR (General Fertility Rate) is the number of children born in each specific year divided by female population ages 15-45 in that 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 the 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 EPA criteria pollutant. Regressions are weighted by number of females 15-44 years old. Standard errors are clustered at the state level and are in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels, respectively.

Table A6 – Hausman Test

	Airborne Lead		Lead in Soil	
	OLS	IV	OLS	IV
	(1)	(2)	(3)	(4)
Lead	-0.054*	-0.505***	-0.474	-7.762***
	(0.030)	(0.195)	(0.292)	(2.816)
Observations	23,317	23,317	2,096	2,096
Hausman test (Chi-squared)		2.245		5.834
P-value		0.134		0.015

Notes: Table reports the Hausman tests of the equality of the OLS and IV estimates. The null hypothesis for the Hausman test is that the difference in the coefficients is not systematic. Columns 1 and 2 report the OLS and IV estimates from Table 3, specifications 3 and 4. Columns 3 and 4 repeats the estimates from Table 8, specifications 5 and 10 respectively.

Table A7 – Airborne Lead and Alternative Measures of Fertility: 1978-1988

Variables	(1) # Births OLS	(2) # Births IV	(3) Log (# Births) OLS	(4) Log (#Births) IV	(5) Log (GFR) OLS	(6) Log (GFR) IV
Airborne Lead	-159.05*	-890.75*	-0.011**	-0.107**	-0.008*	-0.061**
	(84.678)	(538.71)	(0.005)	(0.051)	(0.004)	(0.028)
County FE	x	x	x	x	x	x
Year FE, Month FE	x	x	x	x	x	x
Economic Variables	x	x	x	x	x	x
Climate Variables	x	x	x	x	x	x
Mother and Child Characteristics	x	x	x	x	x	x
Observations	23,317	23,317	23,317	23,317	23,317	23,317
R-squared	0.991		0.994		0.805	
First Stage F		23.49		23.49		23.49

Notes: This table presents the estimated impact of airborne lead on alternative outcomes. All dependent variables are measured nine months in the future. #Births is the monthly number of children born in a county. GFR (General Fertility Rate) is the number of children born divided by 1,000 females ages 15-44. The 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 county total employment and log of county per capita income. Climate variables are temperature and precipitation and their squares. Mother and Child Characteristics are county averages for 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 15-44 age old. Standard errors are clustered at the county level and are in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels, respectively.

Table A8 – Airborne Lead and Cumulative Fertility: 1978-1988

Variables	(1) CFR	(2) CFR	(3) CFR	(4) CFR	(5) CFR
Airborne Lead	-1.023***	-0.802***	-0.739	-0.643	-0.510
	(0.160)	(0.147)	(0.586)	(0.567)	(0.494)
County FE		x	x	x	x
Year FE, Month FE			x	x	x
Economic Variables			x	x	x
Climate Variables				x	x
Mother and Child Characteristics					x
Observations	21,345	21,345	21,345	21,345	21,345
First Stage F	63.11	118.0	27.80	23.10	23.30

Notes: This table presents the IV using instruments discussed in the identification section results for the cumulative fertility rate, measured nine months in the future. Cumulative fertility rate is the cumulative number of children among mother ages 35-45 per 1,000 female population 35-44 years old. Economic Variables are log of county total employment and log of county per capita income. Climate variables are temperature, precipitation, their squares, and year by latitude and year by longitude fixed effects. Mother and Child Characteristics are county averages for 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 35-44 years old. Standard errors are clustered at the county level and are in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels, respectively.

Table A9 – Airborne Lead and Fertility: More Balanced Panel

Panel A. General Fertility Rate - OLS			
Variables	(1)	(2)	(3)
Airborne Lead	-0.067	-0.051*	-0.052*
	(0.055)	(0.030)	(0.030)
Observations	17,369	17,369	17,369
R-squared	0.860	0.872	0.873
Panel B. General Fertility Rate - IV			
Variables	(4)	(5)	(6)
Airborne Lead	-0.573**	-0.457**	-0.423*
	(0.235)	(0.225)	(0.217)
County FE	x	x	x
Year FE, Month FE	x	x	x
Economic Variables	x	x	x
Climate Variables		x	x
Mother and Child Characteristics			x
Observations	17,369	17,369	17,369
First Stage F	26.80	21.13	21.50

Notes: This table presents the OLS and IV estimates using 162 counties for which there are observations approximately two thirds (64%) of the time. Instrumental variables are the same as in Table 3. GFR (General Fertility Rate) is the total number of live births per 1,000 female population 15-44 years old, measured nine months in the future. Economic Variables are log of county total employment and log of county per capita income. Climate variables are temperature, precipitation, their squares, and year by latitude and year by longitude fixed effects. Mother and Child Characteristics are county averages for 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 15-44 years old. Standard errors are clustered at the county level and are in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels, respectively.

Table A10 – Airborne Lead and Fertility: All Monitors vs. Monitors Located in Cities

Panel A. All monitors Variables	(1) GFR	(2) GFR	(3) GFR	(4) GFR	(5) GFR
Airborne Lead	-0.343***	-0.204**	-0.590***	-0.531**	-0.497***
	(0.104)	(0.101)	(0.213)	(0.207)	(0.189)
Observations	22,124	22,124	22,124	22,124	22,124
First Stage F Stat	63.45	116.8	27.14	23.17	23.71
Panel B. Monitors in Cities Variables	(6) GFR	(7) GFR	(8) GFR	(9) GFR	(10) GFR
Airborne Lead	-0.337***	-0.201**	-0.582***	-0.528**	-0.492***
	(0.104)	(0.100)	(0.212)	(0.208)	(0.188)
County FE		x	x	x	x
Year FE, Month FE			x	x	x
Economic Variables			x	x	x
Climate Variables				x	x
Mother and Child Characteristics					x
Observations	22,124	22,124	22,124	22,124	22,124
First Stage F Stat	64.90	115.1	27.13	23.33	24.39

Notes: This table presents the IV using instruments discussed in the identification section results for the general fertility rate, measured nine months in the future. General fertility rate is the total number of live births per 1,000 female population 15-44 years old. Sample includes only counties with monitors located in the cities. Panel A shows the results if all monitors in these counties are used to construct airborne lead measure. Panel B presents the result if lead measure is constructed based only on monitors located in cities. Economic Variables are log of county total employment and log of county per capita income. Climate variables are temperature, precipitation, their squares, and year by latitude and year by longitude fixed effects. Mother and Child Characteristics are county averages for 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 15-44 years old. Standard errors are clustered at the county level and are in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels, respectively.

Table A11 – Airborne Lead vs. TSP and Fertility

Variables	(1) GFR IV	(2) GFR IV	(3) GFR IV
Airborne Lead	-0.505***		-0.421
	(0.195)		(0.274)
TSP w/ Airborne Lead		-0.030	
		(0.018)	
TSP w/o Airborne Lead			-0.027
			(0.044)
County FE	x	x	x
Year FE, Month FE	x	x	x
Economic Variables	x	x	x
Climate Variables	x	x	x
Mother and Child Characteristics	x	x	x
Observations	23,317	23,218	23,218
First Stage F	23.49	2.326	0.270

Notes: This table presents IV results comparing the effects of exposure to airborne lead vis-à-vis exposure to total suspended particulates (TSP). Column 1 repeats the results from Table 3, column 2 estimates the effect of TSP (including lead particulates) on fertility, and column 3 the results of Lead and TSP without lead particulates (TSP w/o Airborne Lead). GFR (General Fertility Rate) is the total number of live births per 1,000 female population 15-44 years old, measured nine months in the future. Economic Variables are log of county total employment and log of county per capita income. Climate variables are temperature, precipitation, their squares, and year by latitude and year by longitude fixed effects. Mother and Child Characteristics are county averages for 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 15-44 years old. Standard errors are clustered at the county level and are in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels, respectively.

Table A12 – Airborne Lead and Fertility by Race: 1978-1988

Panel A. General Fertility Rate - OLS

Variables	(1)	(2)	(3)
	All	White	Non-White
Airborne Lead	-0.054*	-0.059*	-0.039
	(0.030)	(0.035)	(0.056)
Observations	23,317	23,317	23,317
R-squared	0.851	0.852	0.675

Panel B. General Fertility Rate - IV

Variables	(4)	(5)	(6)
	All	White	Non-White
Airborne Lead	-0.505***	-0.677***	-0.165
	(0.195)	(0.246)	(0.388)
County FE	x	x	x
Year FE, Month FE	x	x	x
Economic Variables	x	x	x
Climate Variables	x	x	x
Mother and Child Characteristics	x	x	x
Observations	23,317	23,317	23,317
First Stage F	23.49	25.04	13.30

Notes: This table presents the OLS and IV using instruments discussed in the identification section results for the general fertility rate, measured nine months in the future. Column 1 repeats the result from Table 3 column 5. Columns 2 and 3 study the effects of airborne lead on general fertility rate among white mothers and general fertility rate among non-white mothers. General fertility rate among white mothers is defined as the total number of live births among white mothers per 1,000 white female population 15-44 years old, measured nine months in the future. General fertility rate among non-white mothers is defined as the total number of live births among non-white mothers per 1,000 non-white female population 15-44 years old, measured nine months in the future. Economic Variables are log of county total employment and log of county per capita income. Climate variables are temperature, precipitation, their squares, and year by latitude and year by longitude fixed effects. Mother and Child Characteristics are county averages for 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 15-44 years old. Standard errors are clustered at the county level and are in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels, respectively.

Table A13 – Effects of Instruments on County Population Characteristics

VARIABLES	(1) Age	(2) Education	(3) Married	(4) White Child
Attainment X CAANAS_TSP$_{1978}$	-0.052	0.090	-0.012**	0.005*
	(0.033)	(0.065)	(0.005)	(0.003)
$LPD_{0.8gpg}$ *X HWPlan1944*	0.055	0.155	-0.041	0.003*
	(0.034)	(0.106)	(0.035)	(0.002)
$LPD_{0.5gplg}$ *X HWPlan1944*	0.055	0.115	-0.048	-0.003
	(0.063)	(0.081)	(0.039)	(0.004)
$LPD_{0.8gpg}$	-0.020	-0.240**	0.028	-0.002
	(0.034)	(0.108)	(0.033)	(0.002)
$LPD_{0.5gplg}$	-0.055	-0.197	0.028	0.003
	(0.060)	(0.146)	(0.036)	(0.004)
County FE	x	x	x	x
Year FE, Month FE	x	x	x	x
Economic Variables	x	x	x	x
Climate Variables	x	x	x	x
Mother and Child Characteristics	x	x	x	x
Observations	23,317	23,317	23,317	23,317
R-squared	0.938	0.272	0.605	0.986
Mean of Dep. Variable	25.69	12.62	0.771	0.809
Std. Dev. of Dep. Variable	0.922	0.976	0.108	0.144

Note: This table presents the effects of the instrumental variables used in the main time-series analysis on population characteristics of counties: age, measured as the average age of mothers in a given county, education, measured as the average educational attainment (in years) of mothers, average marital status of mothers and the skin color of children. Economic Variables are log of county total employment and log of county per capita income. Climate variables are temperature, precipitation, their squares, and year by latitude and year by longitude fixed effects. Mother and Child Characteristics are indicator for whether the birth was given at a hospital, dummy for whether the physician was present, dummy for twin births, dummy for previous dead child, dummy for previous child alive, controls for the start of prenatal care. Regressions are weighted by number of females 15-44 years old. Standard errors are clustered at the county level and are in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels, respectively.

Table A14 – Lead in Topsoil and Fertility in Alternative Cross Sections in the 2000s

	(1)	(2)	(3)
	GFR	GFR	GFR
	2004	2005	2006
Variables	IV	IV	IV
Topsoil Lead	-6.136***	-7.762***	-7.185***
	(2.350)	(2.816)	(2.693)
State FE	x	x	x
Climate Variables	x	x	x
Demographic Variables	x	x	x
Economic Variables	x	x	x
Housing Variables	x	x	x
Other Controls	x	x	x
Observations	2,102	2,096	2,100
First Stage F	10.81	12.13	9.971

Notes: This table shows the IV cross sectional effects of lead in topsoil on fertility separately for 2004, 2005 (our main results), and 2006. GFR (General Fertility Rate) is the number of children born in each specific year divided by female population ages 15-45 in that 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 the 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 EPA criteria pollutant. Regressions are weighted by number of females 15-44 years old. Standard errors are clustered at the state level and are in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels, respectively.

Table A15 – 1st Stage IV: The 1970s Lead in Topsoil on Instrument

Variables	(1) Topsoil Lead	(2) Topsoil Lead
HW Plan 1944	0.156***	0.100*
	(0.047)	(0.056)
State FE	x	x
Climate Variables		x
Demographic Variables		x
Economic Variables		x
Housing Variables		x
Other Controls		x
Observations	834	834
R-squared	0.437	0.573
First Stage F	11.16	3.117

Notes: This table presents the first stage relationship between the instruments and lead in topsoil. The dependent variable in all columns is the dummy variable indicating whether the topsoil lead concentration in a county above the national median lead concentration. The independent variable of interest is the HW Plan 1944, a dummy variable for whether a county was supposed to get a highway based on the 1944 Interstate Highway System Map. GFR (General Fertility Rate) is the number of children born in per 1,000 female population ages 15-44. Climate Variables are temperature and precipitation, as well as number of heating and cooling degree days in a particular county. Demographic Variables are the 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, and 60-64 years old. Economics variables are income, employment, percent of people below the 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. Other controls include share of Democratic votes and nonattainment status for any EPA criteria pollutant. Regressions are weighted by number of females 15-44 years old. Standard errors are clustered at the state level and are in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels, respectively.

Table A16 – Lead in Topsoil and Fertility Rate in 1978

Variables	(1) GFR OLS	(2) GFR OLS	(3) GFR IV	(4) GFR IV
Topsoil Lead	-2.569*	0.111	-22.614	-14.138*
	(1.282)	(0.758)	(27.455)	(8.298)
State FE		x		x
Climate Variables		x		x
Demographic Variables		x		x
Economic Variables		x		x
Housing Variables		x		x
Other Controls		x		x
Observations	834	834	834	834
First Stage F			11.16	3.117

Notes: Table shows cross sectional results for the topsoil lead exposure on general fertility rate (GFR) in 1978. GFR (General Fertility Rate) is the number of children born in 1978 divided by number of female population in 1,000 ages 15-44 in 1978. Topsoil Lead is an indicator variable for whether the topsoil lead concentration is above the national median. Climate Variables are temperature and precipitation, as well as number of heating and cooling degree days in a particular county. Demographic Variables are the 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, and 60-64 years old. Economics variables are income, employment, percent of people below the 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. Other controls include share of Democratic votes and nonattainment status for any EPA criteria pollutant. Regressions are weighted by number of females 15-44 years old. Standard errors are clustered at the state level and are in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels, respectively.

Table A17 – State-Level Infertility Services

Ever Had Infertility Services	**1988**
Above Median of State Airborne Lead	0.017**
	(0.008)
Ages 25 to 29	0.029**
	(0.013)
Ages 30 to 34	0.092***
	(0.013)
Ages 35 to 39	0.119***
	(0.022)
Ages 40 to 44	0.108***
	(0.027)
Married	0.080***
	(0.010)
High School Completed	0.005
	(0.011)
Some College or College Graduate	0.014
	(0.014)
African American	-0.001
	(0.008)
Hispanic	-0.017
	(0.018)
Smoker	0.009
	(0.016)
Diabetes	0.049
	(0.043)
Number of Miscarriages	0.117***
	(0.029)
Number of Stillbirths	0.065
	(0.040)
Number of Abortions	0.014
	(0.037)
Working Full time	-0.012
	(0.009)
Other Individual Characteristics	Yes
Climate and Geographic Variables	Yes
Region Fixed Effects	Yes
Observations	4,116
R-squared	0.110

Notes: Data are from the National Survey of Family Growth (NSFG). The sample is only for females 15-44 years old, and stayers (women who have been living in their state of birth all their lives), which represents half of the 1988 NSFG sample. Dependent variable is a dummy whether an individual ever had an infertility services. Robust standard errors in parentheses. ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels, respectively.