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TOXIC TRUTH: LEAD AND FERTILITY

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ABSTRACT

Using U.S county level data on lead in air for 1978-1988, this paper provides the first causal evidence on the effects of airborne lead exposure on the general fertility rate and the completed fertility rate in the broad population. Instrumental variable estimates show the increase in completed fertility implied by the average observed decrease in airborne lead is 0.14 children per woman, which is 6.4 percent of mean fertility. To explore the current relevance of our findings, we estimate the effect of lead historically accumulated in topsoil on fertility in the 2000s. The results suggest 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.

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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 small samples of workers self-selected into high occupational exposure have shown that lead can adversely affect both male and female reproductive systems. The causal effects of lead on fertility in the broader population, where exposure levels are lower, and the magnitude of those effects are open questions.

Using U.S. county level data on airborne lead for 1978-1988, this paper provides the first causal evidence on the effects of lead exposure on the general fertility rate and the completed fertility rate in the broad population. Lead exposure declined over this period as a result of the phase down of lead in gasoline and broader efforts to reduce air pollution. The phase down of lead in gasoline had two major EPA regulatory deadlines during this period. Beginning October 1979, refineries were required to produce a quarterly average of no more than 0.8 grams per gallon for all gasoline. In July 1985 the standard was reduced to 0.5 grams per gallon of leaded gasoline. A third EPA deadline was also relevant for lead. Counties out of compliance with TSP standards under the 1977 Clean Air Act Amendments were required to come into compliance by January 1983. Lead was a component of TSP and so fell as a result of efforts to reduce TSP.

To examine the impact of exposure to lead on fertility rates, we use U.S. Vital Statistics data on fertility, data on children ever born from the 1980 and 1990 Censuses of Population, and EPA monitor data on airborne lead. The U.S. National Vital Statistics data are monthly county-level data derived from individual birth and mortality records. The census data are decennial, but ask women about the number of children ever born. 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. The airborne lead sample covers around 40 percent of the U.S. population.

To address endogenous sorting related to household preferences for air quality and avoidance behavior, and measurement error associated with the potential disconnection between pollution readings from the EPA monitors and the actual pollution exposure faced by individuals, we use instrumental variables (IV).[1] The first stage of the IV takes a difference-in-differences

[1] 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).

approach. The comparison is before and after implementation of the October 1979 and July 1985 deadlines regarding the phase down of lead in gasoline, in counties with and without interstates in the 1944 interstate highway plan. We use the 1944 highway plan rather than counties with and without actual interstate highways, because the highway plan was designed primarily for military purposes rather than potential economic outcomes (Baum-Snow 2007, Michaels 2008). The siting of the actual highways may be influenced by local political forces (Carter 2018), potentially reflecting household preferences for air quality. In addition, local 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. Because lead is a component of particulate matter, the first stage also includes the differences between counties in and out of attainment with TSP under the 1977 Clean Air Act Amendments before and after the January 1983 deadline for compliance. Although previous work has documented correlations between other pollutants and fertility (Carré et al. 2017, Casey et al. 2018), when we decompose TSP into lead and non-lead chemicals, airborne lead appears to be driving our results.

The IV estimates show that increased lead exposure lowers not only short-run fertility as measured by the general fertility rate, but also completed fertility as measured by children ever born. For airborne lead in 1978-1988, the increase in the general fertility rate for women ages 15-44 years 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. Using the 1980 and 1990 census data on children ever born, IV estimates also show the increase in completed fertility implied by the average observed decrease in airborne lead is 0.14 children per woman, which is 6.4 percent of mean fertility. The surprisingly similar percent changes in the general fertility rate and completed fertility suggest that the short-run effects might not be offset by a reversion-to-the-mean behavior in later years of the reproductive cycle.

To explore the current relevance of our findings for 1978-1988, we estimate the effect of lead in topsoil on fertility in the 2000s. Exposure to lead in topsoil occurs through occurs through inhalation, when soil is resuspended, and consumption, when food or drink comes in contact with dust or if food is grown in the soil. As part of larger soil sampling projects, the U.S. Geological Survey collected data on lead in topsoil in the 2000s. The soil lead sample covers about 70 percent of the U.S. population. The fertility analysis uses Vital Statistics data and data from the Current Population Survey on children ever born. Differently from our main empirical strategy, the instrumental variable approach in this case uses a cross sectional intent-to-treat approach leveraging variation in topsoil lead arising from the 1944 interstate highway plan. In counties with a highway recommended by the plan, lead was potentially accumulated in the soil in a manner plausibly unrelated to local preferences for environmental quality. 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.[2] 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 the effects of lead on the general fertility rate to the impact of the introduction of the contraceptive pill in the U.S. in 1957. 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.[3] With the caveat that contraceptives are used voluntarily, and lead exposure is almost surely involuntary, the fertility effects of airborne lead in 1978-1988 and lead in soil in the 2000s are similar in magnitude to the impact of the pill.

It is also useful to consider the private and social costs of lead exposure. As a result of the decline in airborne lead between 1978 and 1988, 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 private utility gains of at least $18.3 billion (2013 USD). How these private utility gains translate into social benefits from the births of additional children is an open question. Whatever the social benefits of fertility, it is worth noting that reductions in lead have large social benefits, because of the adverse lead effects on infant and child development. If the

[2] In the robustness checks, we provide evidence that the fertility effects of topsoil lead are not sensitive to including and instrumenting other two variables potentially affected by transportation infrastructure and plausibly related to fertility: average commuting time, and access to health care.

[3] 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.

fertility benefits were counted as social benefits, the phase down of lead in gasoline would pass a cost-benefit analysis based on these benefits alone.

This study contributes to two literatures. The first is the literature on the causes of infertility generally, and on the effect of lead on fertility in particular. There is a large literature studying determinants of fertility (Schmidt 2005, 2007, Bitler and Schmidt 2006, 2012, 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 the general fertility rate. The results of their case study are qualitatively similar to our nationwide findings on the general fertility rate, even though the source of exposure is intrinsically different. 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. Our paper is the only paper we are aware of to examine the effects of lead on completed fertility.

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 (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 (Troesken 2006, Reyes 2007, 2015, Clay, Troesken, and Haines 2014, Aizer and Currie 2017, Sauve-Syed 2017, Aizer et al. 2018, Gronqvist et al. 2018, and Billings and Schnepel, 2018). It also contributes to a much smaller literature investigating the impact of soil pollution, including Superfund sites, on economic outcomes (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 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 our instrumental variable approach. Section 5 reports and discusses the main findings and robustness checks for the effects of airborne lead on fertility. Section 6 explores the current relevance of our main findings by estimating the effects of exposure to lead accumulated in topsoil on fertility. Section 7 presents some back of the envelope calculations on the benefits and costs of reducing lead exposure based on the main results. Lastly, Section 8 offers some concluding remarks.

2. Background

To understand the relationship between lead exposure and fertility, we start by describing how lead enters the human body, the vectors of exposure, and finally the mechanisms through which fertility is affected. Because the major source of exposure in the 1970s and 1980s was vehicle emissions due to leaded gasoline, at the end of this section we discuss the policies phasing down lead in gasoline in the United States. Those policy changes will be at the center of our empirical analysis later on, when we uncover the causal effects of airborne lead on fertility.

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 the bloodstream. 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 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

[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).

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 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.

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[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.

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).[10] 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

[10] The conclusions reported in this NTP Monograph were based on a review of the primary epidemiological literature, scientific input from technical advisors that reviewed pre-public release drafts of each chapter summarizing the evidence for specific health effects associated with low-level Pb, public comments received during the course of the evaluation, and comments from an expert panel of *ad hoc* reviewers during a public meeting to review the Draft NTP Monograph on November 17-18, 2011. The selection of panel members and conduct of the peer review were performed in accordance with the Federal Advisory Committee Act and Federal policies and regulations. The panel members served as independent scientists, not as representatives of any institution, company, or governmental agency. Panel members had two major responsibilities in reviewing the draft NTP Monograph: (1) to determine whether the scientific information cited in the draft monograph is technically correct, clearly stated, and objectively presented and (2) to determine whether the scientific evidence presented in the draft monograph supports the NTP's conclusions regarding health effects of low-level lead (Pb). Given such a meticulous scientific review, we refer to the monograph for a comprehensive list of references. In any case, Hauser and Sokol (2008) and Mendola, Messer, and Rappazzo (2008) also provide reviews of the science linking environmental contaminant exposures with fertility and reproductive health impacts in adult males and adult females, respectively.

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. The male reproductive system has been shown to be affected by occupational lead exposure (Joffe et al. 2003, Hamilton and Hardy 1983, Lin 1996, Lin et al. 1998, Sallmén 2001, Sallmén, Lindbhm, and Nirumnem 2000, Shiau, Wang, and Chen 2004, Vigeh, Smith, and Hsu 2011, Winder 1993). Possible channels include direct effects on testes and indirect effects through hormones. Several studies document the negative relationship between lead exposure and sperm count and density (Alexander et al. 1996, Apostoli, Porru, and Bisanti 1999, Apostoli et al. 2000, Assennato et al. 1987, Paul 1860, Wu et al. 2012). The NTP (2012, p. 90) finds: “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 (Hertz-Picciotto 2003, Vigeh 2010) and has adverse health effects during pregnancy (Amaral et al. 2010, Bellinger 2005, Cleveland et al. 2008, Hu et al. 2006, Rudge et al. 2009, Schell et al. 2003, Taylor, Golding, and Emond 2015, Zhu et al. 2010). 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 1μg/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. [11]

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 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 Freedom of Information Act (FOIA) request. The monitors measure typically multiple pollutants and were likely to have been sited to meet a variety of goals, such as

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

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.[12] Lead measurements are available once every three 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 over 40 percent of the U.S. population. Appendix A1 Figure A1.1 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.[13]

Figure 3 Panel A 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 $\mu g/m^3$.

[12] 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.

[13] 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. It is important to mention that the 337 counties account for about 44 percent of the U.S. population over the period 1978-1988. Later on, when we restrict attention to the subset of 170 counties with completed fertility data, those counties will represent about 39 percent of the U.S. population over the census years 1980 and 1990.

Fertility Data

To study the effect of lead on short-run fertility, we use data from the National Vital Statistics of the United States to construct the following outcomes: general fertility rate (GFR), age-specific birth rates (ASBR), 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, 25-29, 30-34, 35-39, and 40-44 years old.

To study the effect of lead on completed fertility, we use data from the 1980 and 1990 Censuses of Population, which asked women about children ever born. Because the IPUMS dataset provides county identifiers only for counties with 100,000 population or more, we end up with 252 counties. Although we run the analysis with all of them for comparison purposes, we focus on the 170 counties overlapping with the 337 counties satisfying the restrictions for availability of airborne lead information.[14]

Additional Data

We include a number of control variables in the analysis: economic and demographics covariates, climate variables, and mother and child characteristics. Economic and demographic controls are from the U.S. Censuses, the Bureau of Economic Analysis (BEA), and the EPA. Climatic variables are from the PRISM Climate Data. Mother and child characteristics are county averages from the U.S. National Vital Statistics System.

[14] We cannot use census data to run similar analysis for topsoil lead because the 2000 and 2010 Census did not ask about children ever born. Nevertheless, we use the much smaller samples from the Current Population Survey (IPUMS-CPS) – Fertility Supplement for June 2000, 2002, 2004, 2006, 2008, and 2010 – to examine the effect of exposure to topsoil lead on completed fertility in the 2000s. The average number of children ever born in this CPS derived sample is 1.89. It contains 233 counties with population of 100,000 population or more, all of which overlap with the counties in the main dataset for the topsoil lead analysis. For comparison purposes, our sample derived from the two censuses (1980 and 1990) has 517,958 observations, whereas our CPS derived sample for the period 2000-2010 has only 15,855 observations. Therefore, we may lack statistical power to estimate the effects of interest precisely.

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). Table 1 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 *monthly* general fertility rate was 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. Figure 3 Panel B plots the general fertility rate over time. Regarding completed fertility, the average number of children ever born by women 35-44 years old in the 1980 and 1990 Censuses of Population is 2.15, dropping from 2.58 in 1980 to 1.89 in 1990.[15]

4. Empirical Strategy

Airborne Lead and the General Fertility Rate

To uncover the causal effect of airborne lead pollution on fertility, we start by specifying the following equation:

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

where $N_{c,t+9}$ is a fertility outcome for county c, measured nine months in the future (t denotes month-year),[16] *AirLead* is airborne lead pollution measured by EPA monitoring stations in county c and month-year t, X is a set of time-varying controls such as temperature and

[15] Appendix A1 Table A1.1 shows additional summary statistics on the age-specific birth rates and general fertility by education and by race over the period 1978-1988.

[16] Appendix A2 Figure A2.1 displays the estimated lead effect on alternative lags and leads of the general fertility rate. The effects are similar to the baseline specification.

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.[17]

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).

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.

Instrumental Variable Approach

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 and measurement error. As described in the introduction, we use the phasedown of lead in gasoline and its heterogeneous effects depending on the quasi-experimental allocation of interstate highways according to the

[17] 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." Nevertheless, since lead affects the efficiency of catalytic converters, as noted previously, it is important to at least control for multiple pollutants. An area experiencing a decrease in lead would also see a decrease in other emissions, such as particulates, and it could be that particulates affect the health of family members. In robustness checks reported in the appendix, we provide suggestive evidence that it is lead rather than particulates the main criteria pollutant affecting fertility.

1944 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 phasedown, it is unlikely they were informed about the amount of lead in the "regular" gasoline, which was the policy parameter that changed during the phasedown. 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. Therefore, we assume that those instruments allow us to uncover the local average treatment effect.[18]

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 4). Following Baum-Snow (2007) and Michaels (2008), we use the advent of the U.S. Interstate Highway System Plan as a quasi-experimental allocation of highways to counties.[19] We exploit heterogeneity of the policy

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[18] 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. Table A4.1 shows that there was very little differential sorting based on observables.

[19] In 1941, President Roosevelt appointed a National Interregional Highway Committee. This committee 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

changes based on 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 economic and demographic conditions of their constituencies (see Baum-Snow 2007 and Michaels 2008), other local infrastructure projects might have been affected as well.[20]

The last instrumental variable is related to the CAA regulations for criteria pollutants. 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.[21]

By exploiting these policy changes in our instrumental variable approach, our first stage equation is essentially a difference-in-differences equation. Counties recommended an interstate highway by the 1944 plan are "treatment" counties, and counties without recommended interstates are "control" counties. The "post" variables refer to the periods when the policy changes were implemented. Likewise, counties out of compliance with the NAAQS are

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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.

[20] 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.

[21] In an alternative specification where we decompose TSP into lead and other particles, we provide evidence that lead is what drives the impacts on fertility (Appendix A2 Table A2.4). In the same table, we report similar estimates for the lead effects when eliminating data for 1980-1982, a period of economic recessions that have been shown to affect TSP concentration locally (Chay and Greenstone 2003). In another specification where we do not include this instrument in the first stage, the main results are statistically the same (Appendix A2 Table A2.5, column 2). In the last column of this last table, we also report estimates for the case where the first stage includes only the CAA instrument. The IV estimate is noisier, but of comparable magnitude.

"treatment" counties, and counties in compliance are "control" counties. The "post" variable is when the compliance with the NAAQS was expected, which in this case is colinear with year fixed effects. The 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*. *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 heterogenous effects 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.[22]

[22] 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, the nationwide VMT is stable or slightly growing in our period of study, and has a similar pattern for urban and rural counties. (The 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.

To illustrate the heterogeneous effects of the phasedown of lead in gasoline based on highways, Figure 5 Panel A 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.

Likewise, Figure 5 Panel B plots fertility for counties with and without highways as recommended by the 1944 Interstate Highway System Plan along with the timing of the phasedown of lead in gasoline. Before the policy change, fertility was 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.[23]

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.[24] 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.

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[23] Appendix A1 Figure A1.4 plots annual general fertility rates for counties with and without highways as recommended by the 1944 Interstate Highway System Plan for the longer period 1972-1998, providing suggestive evidence that fertility trends in those two groups of counties were similar for several years before and after our period of analysis (1978-1988). Appendix A1 Figure A1.5 displays similar information for airborne lead concentration. Again, there seems to be no differential trends for those two groups of counties before and after our period of analysis.

[24] 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.

Appendix A4 Table A4.1 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.

Airborne Lead and Completed Fertility

To examine the impact of exposure to airborne lead on completed fertility (number of children ever born by women 35-44 years old), we combine the individual level data from the 1980 and 1990 Censuses of Population. Although we cannot follow each woman over time, by stacking those two cross-sections together we are able to include county fixed effects in the regression model for completed fertility, controlling for a number of observable and unobservable time-invariant factors affecting fertility behavior of all women living in the same county, either in 1980 or 1990. Our estimating equation is:

$$F_{icy} = \alpha + \beta AirLead_{cy} + X'_{icy}\gamma + \eta_c + \lambda_y + Z'_c\delta_y + \varepsilon_{icy}, \quad (4)$$

where F_{ict} is the number of children a woman has ever had, excluding stillbirths. Notice that this analysis is done with individual-level data: i represents a woman living in county c during census year y. *AirLead* is the county-level average of all EPA lead monitor readings for the years 1978-1984 (for Census year 1980), and 1985-1990 (for Census year 1990). X includes all the meteorological variables from equation (3) and a number of characteristics of the woman and her household such as age, education, race, marital status, socioeconomic status, and household income (a detailed list of these variables is provided in the notes of the results table). Again, η_c is a set of county fixed effects, λ_y is a set of year fixed effects, Z represents latitude and longitude interacted with year fixed effects, and ε is an error term.

Because of similar identification issues discussed in the previous subsection, we implement an IV approach to estimate the parameter of interest β. We use as instrument the phasedown of lead in gasoline in the 1980s particularly in counties receiving a highway as recommended by the 1944 Interstate Highway System Plan. In practice, we interact a dummy variable for 1990 with *HWPlan1944*. The intuition is that by 1990 the phasedown of lead in gasoline would be already in effect, hence affecting more the air quality in counties with potential roads. The relevance condition is satisfied empirically: a relatively strong first-stage F-statistic will be reported later. We then assume that the exclusion restriction also holds in this context. In fact, as argued in the previous subsection, it is unlikely that reductions in gasoline lead would affect fertility behavior differentially in counties with a highway from the 1944 plan other than via reductions in air pollution.

5. Impacts of Airborne Lead Exposure on Fertility

Effects on the General Fertility Rate

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 $LPD_{0.5gplg}$. The reduction associated with the second milestone, however, was over 50 percent larger than the first one, likely due to the more stringent standards. 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.[25]

[25] In Appendix A2 Table A2.8, we compare the first stage estimates for airborne lead with corresponding estimates for sulfur dioxide (SO_2), and ambient ozone. Sulfur dioxide is a gas primarily emitted from fossil fuel combustion at power plants and other industrial facilities. Only a small fraction of SO_2 emissions in the United States come from transportation. Ozone is not emitted directly; instead formation occurs due to a complex combination of nitrogen

Table 3 presents the OLS and IV results for the general fertility rate.[26] For OLS, the coefficient is not statistically significant in column 1. 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.[27] The larger coefficient in the IV specification is consistent with the presence of the household avoidance behavior and/or measurement error associated with the potential disconnection between where airborne lead is measured and where people live.

Table A2.1 reports results estimated by two-stage least squares (2SLS) versus limited information maximum likelihood (LIML), and for eastern versus western U.S. counties.[28] The LIML estimates in column 2 are remarkably similar to the 2SLS ones in column 1, revealing once again that our instruments are relatively strong, and that despite being much larger than OLS, our 2SLS estimates are reliable. Two reasons why the 2SLS estimates are over nine times larger than OLS may be the presence of nonclassical measurement error and heterogeneous effects. In fact, the estimates for eastern versus western U.S. in columns 3 and 4 provide suggestive evidence on those issues.

Because airborne lead concentration is measured in places where EPA has pollution monitors, but individuals usually cross county boundaries when commuting to work or engaging in leisure activities, exposure to airborne lead might be more severely mismeasured in the eastern part of the country, where commuting zones are geographically smaller (see a detailed discussion

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oxides (NOx) and volatile organic compounds (VOCs) and sunlight. Although on-road vehicles contribute to emissions of both ozone precursors, meteorological conditions are important confounders in the relationship between these pollutants and ambient ozone concentration. Therefore, it is not surprising that there seems to be no systematic relationship between the policy changes used in the first stage lead regressions and SO_2 and ozone concentration, as reported in referred table.

[26] 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. It is important to notice, however, that recent research by Sauve-Syed (2017) has revealed impacts of cumulative blood lead exposure on another short-run outcome in older children – academic achievement of elementary school students. She exploited an exogenous, heterogeneous shock of lead-in-water levels within classrooms at Flint Community Schools to overcome the selection and endogeneity issues found in other studies.

[27] Hausman tests of the equality of the OLS and the IV estimates are shown in Appendix A4 Table A4.2. 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 A4.2).

[28] LIML is a one-stage IV estimator that provides more reliable point estimates and test statistics with potentially weak instruments. It is known to be less precise but also less biased than 2SLS.

on the definitions of commuting zones in Foote, Kutzbach, and Vilhuber (2017), including a map of commuting zones in their Figure 1). By driving regularly across county boundaries, individuals are likely to be exposed not only to the lead measured in their county of residence but also to the lead present in highways, including in neighboring counties. Therefore, measurement error might be systematically associated with location, which we approximate by the dichotomy eastern versus western U.S.

Despite the relatively large standard errors, the estimates in columns 3 and 4 of Table A2.1 are indeed consistent with worse measurement problems in the eastern U.S. The interactions of the indicator for a highway recommended by the 1944 plan and policy changes regarding the phase-down of lead in gasoline, which are used as instruments, should capture the variation in exposure to airborne lead more accurately than just the readings of the EPA monitors, and even more so in eastern counties. The estimates in columns 3 and 4 also indicate the presence of heterogeneous effects. To the extent that residents in the western part of the country seem to be willing to drive longer distances (again, see the map of commuting zones in Foote, Kutzbach, and Vilhuber (2017)), they might be exposed to less airborne lead because emissions should be more spread out. Though imprecisely estimated, the effect of airborne lead in western counties appears to be much smaller than in eastern counties. Therefore, our estimates might reveal only *local* average treatment effects.[29]

That said, the IV estimates of lead on fertility rates are sizeable. The airborne lead levels declined on average by 0.75 μg/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 6 illustrates the effects of the decline in airborne lead on fertility rate and number of births. The left-hand-side panels show that 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

[29] It is worth mentioning that the difference between the OLS and IV estimates found here are in the range published elsewhere in the economics literature. Madestam et al. (2013), for instance, report IV estimates up to over 28 times larger than OLS. They also explain their results based on nonclassical measurement error and heterogenous effects.

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 on general fertility, 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. It is worth explicitly noting that the effects of lead in 1978-1988 are quite different from these two events, because they involve involuntary exposure of large populations. 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 sizeable, but less than the effect of the pill.[30]

Robustness Checks: Alternative Measures of Fertility, Sample Restrictions, and Other Pollutants

Our main analysis is robust to alternative measures of fertility, sample restrictions, and the inclusion of other air pollutants in the analysis. Table A2.2 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.

Table A2.3 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.

[30] 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 44 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.

Table A2.4 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 statistically 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. Lastly, in column 4 we report estimates for lead but eliminating data for the years 1980-1982, which have been shown to affect TSP due to the economic recessions occurring in that period (Chay and Greenstone 2003). We cannot rule out that these estimates are the same as our main results.

Heterogeneity Analysis: Effects of Lead on General Fertility by Age and Education

Table 4 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.[31] 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 the fertility rate among older women might be less responsive to the short-term lead fluctuations. Alternatively, if older mothers engage more in avoidance behavior due to greater income, or there is greater

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

measurement error for older mothers potentially because of more relocations, or both, we would expect to observe greater attenuation bias for this group.[32]

Table 5 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.[33] 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 μg/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 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 more highly educated mothers.[34]

Short-term Effects on General Fertility versus Completed Fertility

One concern regarding our main results on the effects of lead on the general fertility rate is that they might reflect only a short-term impact on fertility. Women who would not have a successful pregnancy early on in the reproductive cycle would keep trying having babies until later years. Therefore, the short-term effects of lead on fertility would be reversed, and there would be no impact on completed fertility. That does not seem the case in our analysis using Census data. Table 6 presents the OLS and IV results for completed fertility for women ages 35-44. Results are presented for two groups: all women in the age range, and only stayers – women

[32] 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.

[33] 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.

[34] 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 A2 Table A2.6.

who were living in the same county five years before and in their state of birth. Panel A presents the OLS specifications. For all women and stayers, the coefficient on airborne lead is negative and statistically significant. Moreover, the coefficients are similar in magnitude. Panel B presents the first stage relationship between our Highway 1944 instrument and airborne lead. The first-stage F-statistic is above 15 in both specifications. Panel C presents the IV estimates on completed fertility. The airborne lead levels declined on average by 0.32 for the full sample and 0.29 for stayers over the study period. Thus, the IV estimates imply an increase in cumulative fertility of 0.14 children for all women ages 35-44 and 0.18 children for stayers. These represent increases in cumulative fertility of 6.4 percent for all women and 8.7 percent for stayers. The effects on cumulative fertility for all women are very similar in magnitude to the effects found on the general fertility rate in Table 3 (6.4 percent vs. 6.7 percent).

6. Current Impacts: Exposure to Lead in Soil and Fertility

To explore the current relevance of our findings, and shed light on the legacy effects of airborne lead, we estimate the effect of lead topsoil on fertility in the 2000s. Historical airborne lead emissions were deposited and accumulated in topsoil for several decades (Mielke, Laidlaw, and Gonzales 2011), and have been shown to affect other important societal outcomes (Clay, Portnykh, and Severnini 2019). For this analysis, we use data on lead concentration in soil from the U.S. Geological Survey. A survey was carried out in the 2000s to study the concentration and spatial distribution of chemical elements and minerals in soils of the conterminous United States. Soils samples were collected from a depth of 0 to 5 cm. Appendix Figure A1.2 displays a map of the 4,857 soil sampling sites in the conterminous United States.[35]

To generate county-level data on topsoil lead concentration, we average the measurements of all available samples within a county. We observe the latitude and longitude of each site. As a result, we have information for 2096 counties, as shown in Figure A1.3 in the

[35] 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.

Appendix.[36] To explore the potentially nonlinear effects of topsoil lead on fertility, we create 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. Table A1.2 reports the summary statistics for the topsoil lead analysis. The average annual general fertility rate is 67.68 births per 1,000 women ages 15-44. The fertility rate is 69.89 births per 1,000 women for the low lead counties, whereas it is 65.52 in the high lead counties.

Because we have only one measurement of lead in topsoil, we use a cross-sectional approach. This empirical strategy allows us to document trends in fertility due to continued exposure to lead pollution on a longer-term basis. We estimate the following regression model:

$$N_c = \alpha + \beta SoilLead_c + X_c\gamma + \eta_s + \varepsilon_c, \quad (5)$$

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[37], 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.[38]

We estimate this equation using another instrumental variable strategy, using only 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

[36] 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.

[37] Because there is considerable heterogeneity in guidelines for "safe levels" of topsoil lead concentration (Jennings 2013), 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 coefficient generate qualitatively similar results, but is imprecisely estimated (-0.367 S.E. 0.224).

[38] 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. In the appendix table A3.1, we report a horserace analysis. The results indicate that lead is the main driving force behind our findings.

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, and measurement error associated with the potential disconnection between soil sampling sites and household residences. 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 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.

Effects on the General Fertility Rate

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 percentage points 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.[39] Panel A presents the results estimated using OLS. Panel B reports the results estimated by IV. As in the panel analysis, both OLS and IV estimates are negative, and OLS estimates are much smaller in magnitude than IV estimates. In this case, the Hausman test rejects the equality of the OLS and the IV estimates, as reported in Appendix in Table A4.2. Column 1 presents the estimated effect only controlling for state fixed effects and climate variables to account for unobserved state

[39] We report similar estimates for the 2004 and 2006 cross sections in Appendix Table A3.2.

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.

Again, measurement error and heterogeneous effects may explain the large difference between the IV and OLS estimates. With respect to measurement, to the extent that the soil samples were spatially balanced (see Figure A1.2 for the location of all sampling points), the distinction between the lead effects in eastern versus western counties becomes less important, as we can see in column 2 of Table A3.3.[40] In fact, both estimates are somewhat similar to the overall estimate reported in column 1 for comparison. Nevertheless, given the guidelines for the site selection process, and the randomness of the GRTS design, the USGS measurements might not reflect the true exposure to topsoil lead that households face on a regular basis. Rather, they may imply severe classical measurement error. Therefore, it is not surprising that we find a large difference between IV and OLS estimates, even larger than in the context of airborne lead.[41]

Such a difference might also be due to heterogeneous effects. In particular, our estimate might reflect a *local* treatment effect associated with lead deposited in topsoil from gasoline-powered vehicles before the ban of leaded gasoline. Because our instrument – an indicator for potentially receiving a highway from the 1944 plan – might capture better the lead deposited in topsoil that was emitted decades ago by vehicles versus stationary sources, we should expect the IV estimate for places with high gasoline consumption to be larger than for places with low consumption. Indeed, using a state-level measure of the amount of gasoline lead released into the immediate environment of the average individual based on the different grades of gasoline and the shares of those grades used in each state (see Reyes 2008), we find an IV estimate for counties located in states with that measure of lead above the median to be much larger than for counties in low-lead states, as reported in column 3 of Table A3.3. Although imprecisely

[40] The U.S. Geological Survey carried out a survey of soils using a generalized random tessellation stratified (GRTS) design to produce a spatially balanced set of sampling points without adhering to a strict grid-based system. Also, to ensure that samples were not collected from obviously contaminated areas, no sample was collected within (i) 200 meters of a major highway; (ii) 50 meters of a rural road; (iii) 100 meters of a building or structure; or (iv) 5 kilometers downwind of active major industrial activities such as power plants or smelters.

[41] As noted before, the difference found here is still much smaller than the difference between OLS and IV estimates found elsewhere in the broad economics literature (e.g., Madestam et al. 2013).

estimated, those point estimates suggest the presence of considerable heterogeneity in the effects of topsoil lead on fertility. Moreover, they indicate that our instrument does capture variation in topsoil lead emitted in previous decades by an important source: gas-powered vehicles.

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 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.[42]

Robustness Checks: Addressing Additional Sources of Endogeneity

A nontrivial threat to our identification strategy regards two other potential channels through which the 1944 interstate highway plan might affect fertility: impacts on commuting time, and impacts on access to health care. If the interstate highway system simultaneously reduces commuting time, then female labor force participation might increase (Black, Kolesnikova, and Taylor 2014), and fertility might decrease. Likewise, if highways also reduce the cost to seek infertility treatment and prenatal care in locations nearby, then fertility might increase.

To isolate the effect of exposure to topsoil lead on fertility from the potential impacts of commuting time and access to health care, we consider an alternative specification in the appendix including these two additional variables, and using alternative instruments for them. We instrument commuting time with county-level hydropower potential. Severnini (2014) shows that economic activity historically concentrated around hydroelectric dams due to transmission

[42] The 2000 and 2010 Census did not ask about children ever born, so instead we use the much smaller samples from the Current Population Survey (CPS) – Fertility Supplement for June 2000, 2002, 2004, 2006, 2008, and 2010 – to provide suggestive evidence that exposure to topsoil lead above the national median decreases completed fertility by 0.17 children per woman, which is 9.3 percent of mean fertility. Given that the sample size here is less than five percent the sample size derived from the Census, it is not surprising that our estimates are imprecisely estimated, as shown in the Appendix Table A3.4.

constraints, which could potentially reduce urban sprawl. We instrument the number of physicians per 100,000 population, which we use a proxy for access to health care, with the funds distributed by the Hill-Burton Free and Reduced-Cost Health Care of 1946. Those funds are associated with the construction of new hospitals, and expansion of the number of hospital beds in the U.S. (Chung, Gaynor, and Richards-Shubik 2017).

Importantly, conditional on the other instruments, our original instrument (1944 Interstate Highway Plan) is not statistically significantly correlated to commuting time and the rate of physicians (see Appendix A4 Table A4.3). Furthermore, the impact of exposure to topsoil lead on fertility is similar to our main estimates, and the coefficients of commuting time and the rate of physicians are not statistically significant (see Appendix A4 Table A4.4). Therefore, our main specification appears robust to this alternative specification.

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. As we noted in the introduction, how these private utility gains translate into social benefits from the births of additional children is an open question. Whatever the social benefits of fertility, reductions in lead have large social benefits including improvements in IQ and school outcomes and reductions in crime (e.g., Needleman 2004, Aizer and Currie 2017, Sauve-Syed 2017, Aizer et al. 2018, Gronqvist et al. 2018, and Billings and Schnepel, 2018). For the sake of argument, we assume below that fertility benefits are counted as social benefits.

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).[43] The total annual

[43] 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

benefits for airborne lead based on births in 1988 would be at least $18.3 billion (2013 USD), as shown in Table 9, Panel A, column 1.[44] 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.[45]

The willingness to pay for reductions in lead should also include the amount spent to avoid exposure.[46] 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.[47]

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

be $565 billion (2013 USD) for the reduction in airborne lead and $1.3 trillion (2013 USD) for the reduction in topsoil lead.

[44] For comparison, EPA estimated nationwide ex-ante benefits of approximately $1.2 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 increase the annual overall benefits considerably.

[45] Because abortion has been legalized in the U.S. since the landmark ruling by the Supreme Court in 1973, and the pill and family planning services were disseminated before our period of analysis, we have assumed that all those additional babies were not unwanted.

[46] Appendix A2 Table A2.7 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. This evidence actually inspires another way to monetize the benefits of lead reduction. Indeed, both private households and society (via publicly funded health services organizations) incur high costs to treat infertility (Bitler and Schmidt 2012, Chambers, Adamson, and Marinus 2013). As an example, a fresh in vitro fertilization (IVF) cycle costs approximately $13,000 in the United States. Therefore, one could multiply the number of additional babies born because of the lead reduction by the average cost of infertility treatment to obtain an alternative measure of those benefits.

[47] 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)..

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).[48] 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 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.

8. Conclusion

This study presents causal evidence on the relationship between lead exposure and fertility rates in the United States between 1978 and 1988. 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 the mean general fertility rate. Analysis of completed fertility using census data for 1980 and 1990 finds increases of 0.14 children, which is 6.4 percent of the mean completed fertility.

[48] 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)

Although leaded automobile gasoline was banned in the U.S. in 1996, our findings are still relevant today. Our estimates for lead in topsoil suggest that deposition in soil remains a public health issue. Moreover, 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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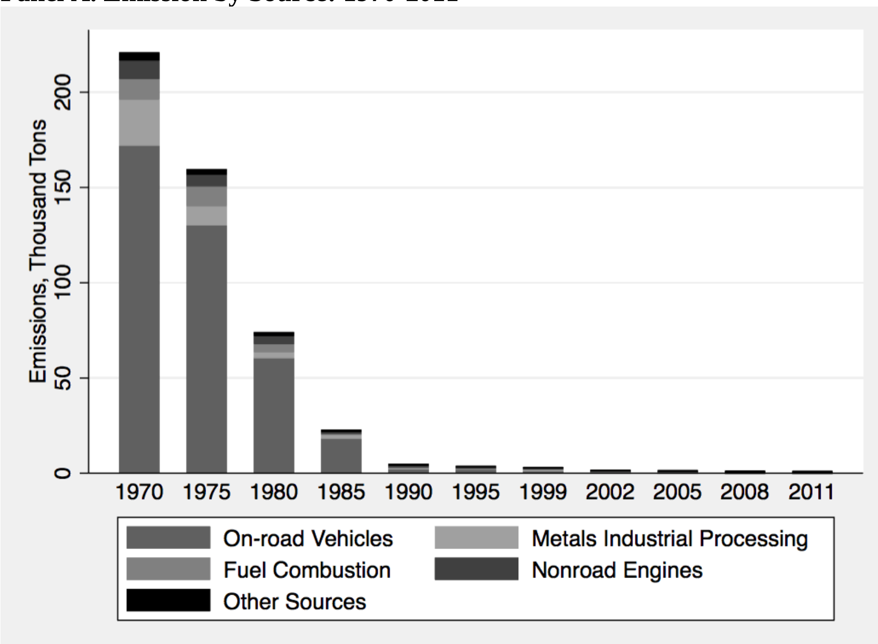
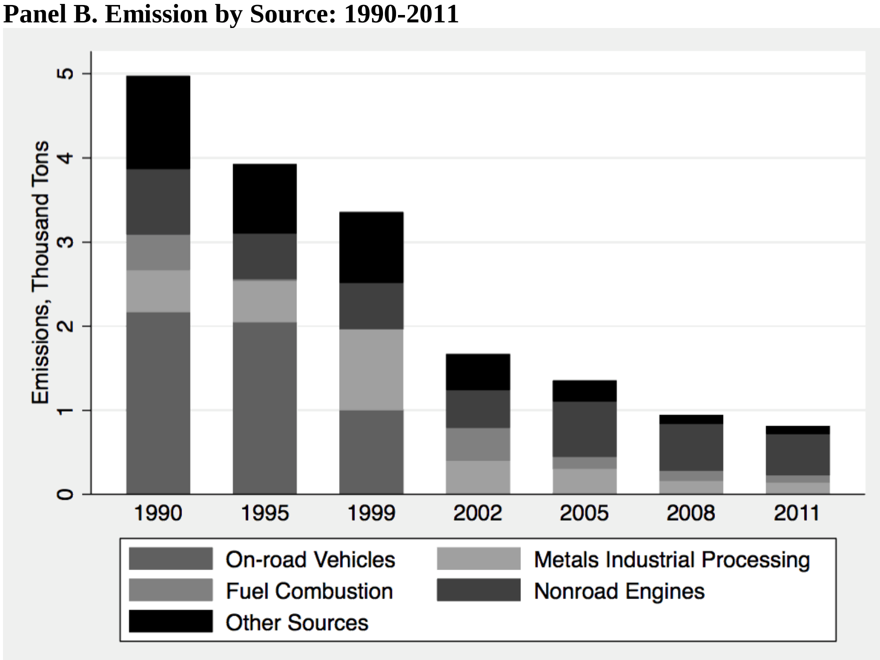
Figures

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

Panel A. Emission by Source: 1970-2011

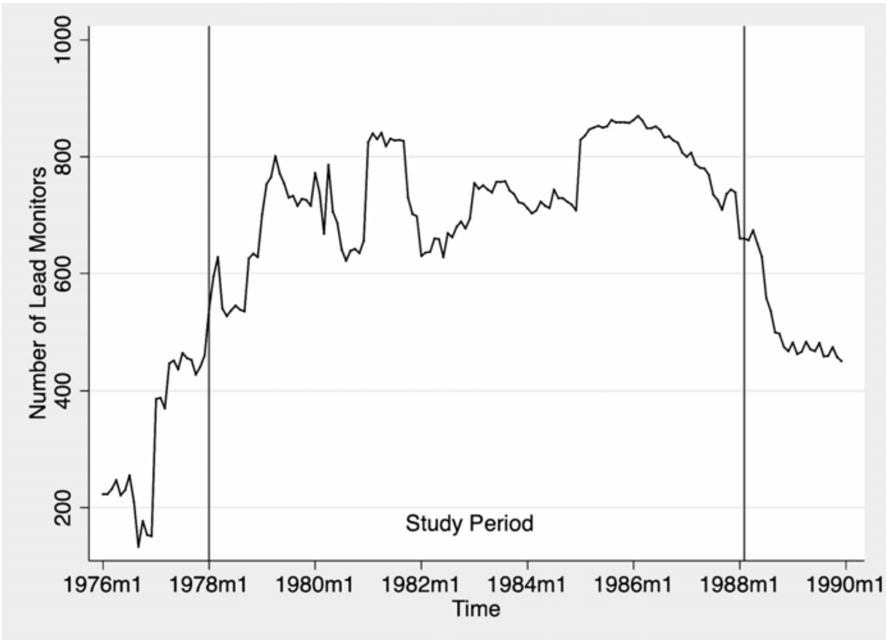


Panel B. Emission by Source: 1990-2011



Notes: Data are taken from the U.S. EPA, 2014. Changes 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.

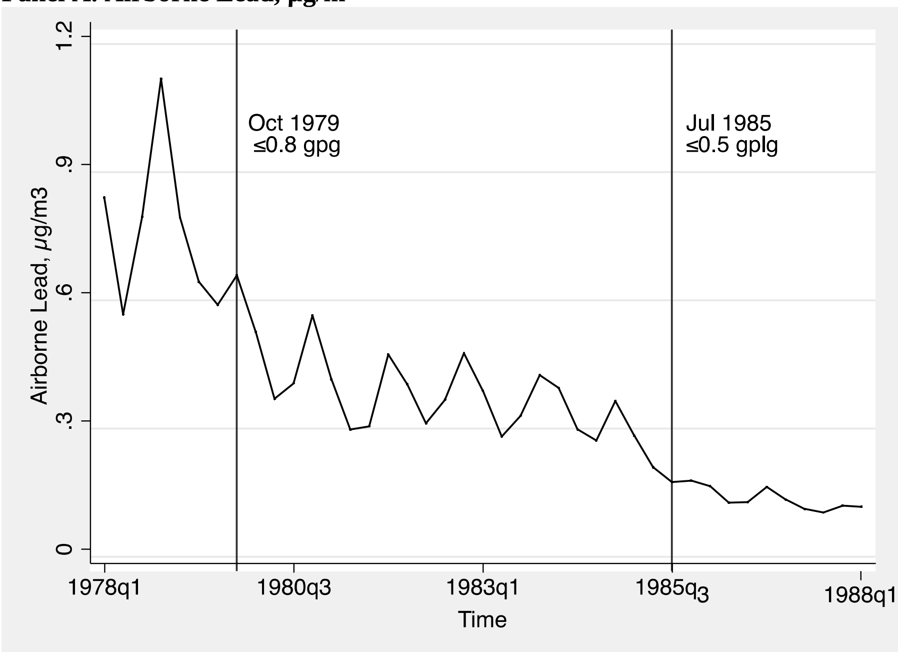
Figure 2 – Number of Airborne Lead Monitors Over Time



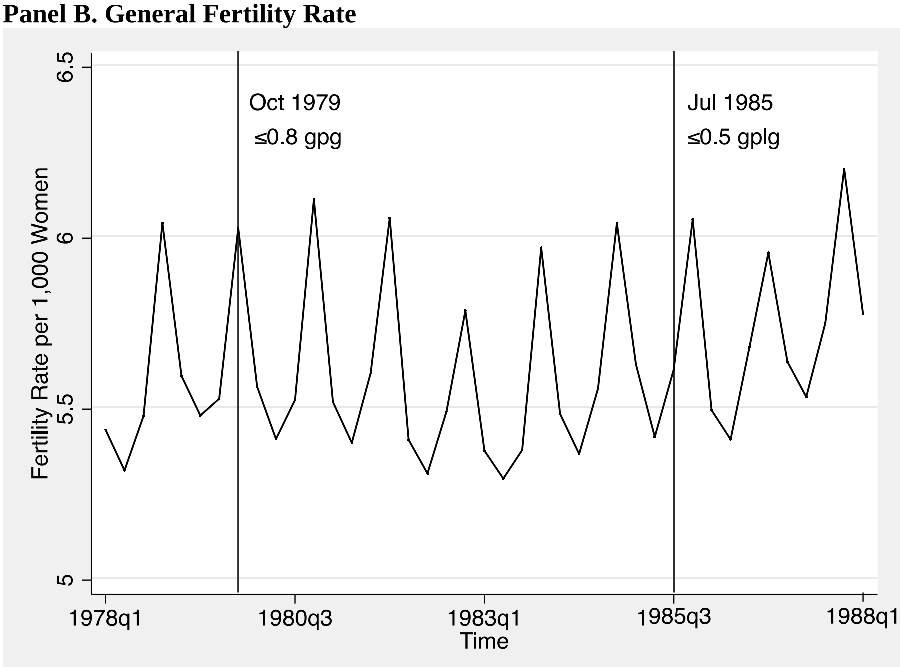
Notes: This figure shows the number of EPA airborne lead monitors over the period 1975-1996. “Study period” is the time period used in the main analysis of the effect of airborne lead exposure on fertility: 1978-1988.

Figure 3 – Airborne Lead and General Fertility Rate Over Time

Panel A. Airborne Lead, µg/m³



Panel B. General Fertility Rate



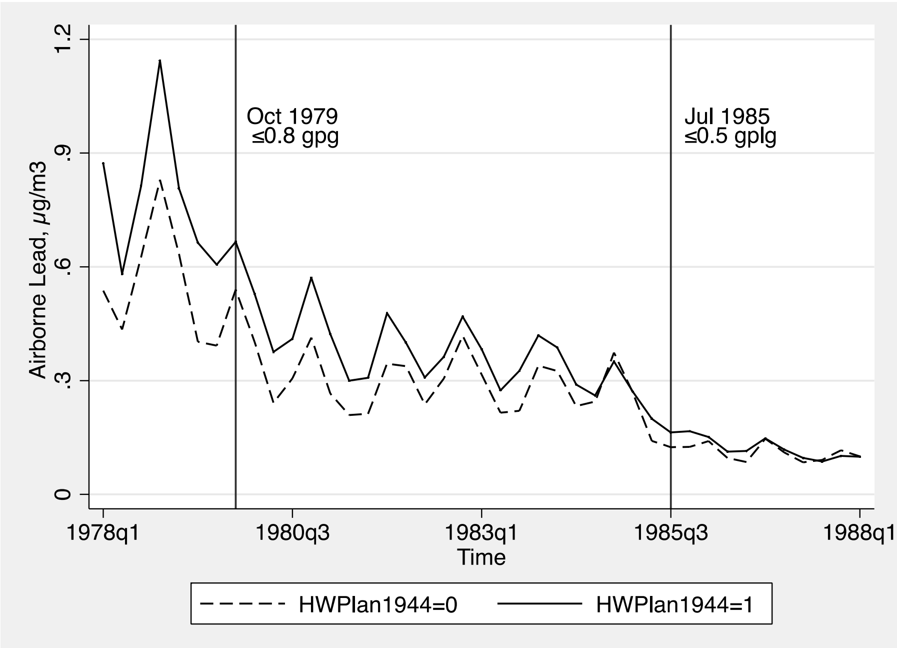
Notes: Panel A. shows the concentration of lead in air over time during the study period 1978-1988. Lead in air is weighted by number of women of childbearing age (15 to 44 years). Panel B shows the general fertility rate during the study period 1978-1988 (weighted by number of women of childbearing 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 4 – Routes of the Recommended Interregional Highway System: “1944 Plan”

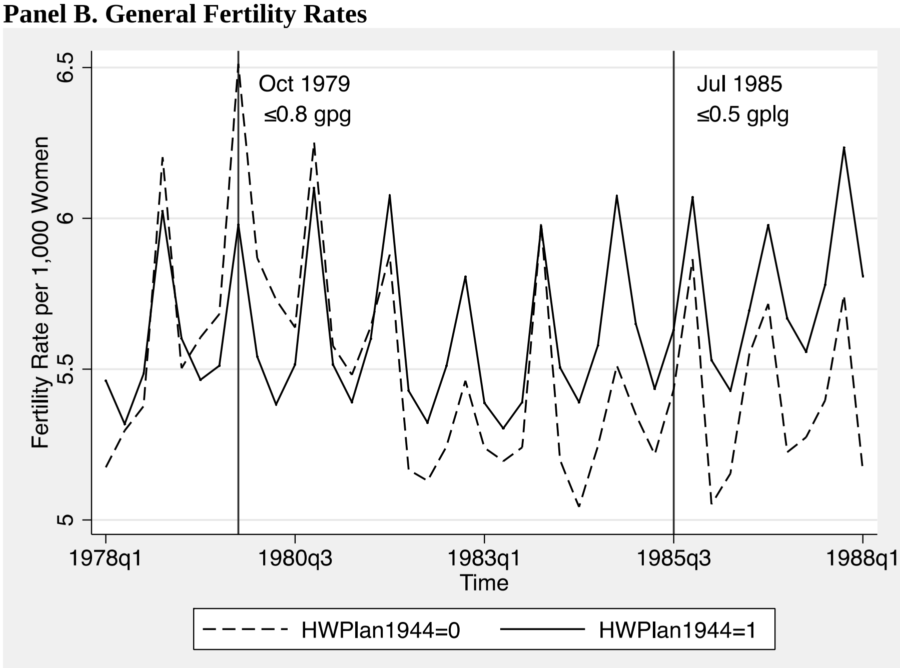
Notes: This figure shows the 1944 Interstate Highway System Plan Map (Michaels 2008). In 1941, President Roosevelt appointed a National Interregional Highway Committee to design a interregional highway system addressing three policy goals (Michaels, 2008): (i) to improve the connection between major 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 5 – Airborne Lead and General Fertility Rate: Counties *With* and *Without* Recommended Highway, *Before* and *After* Policy Changes

Panel A. Airborne Lead



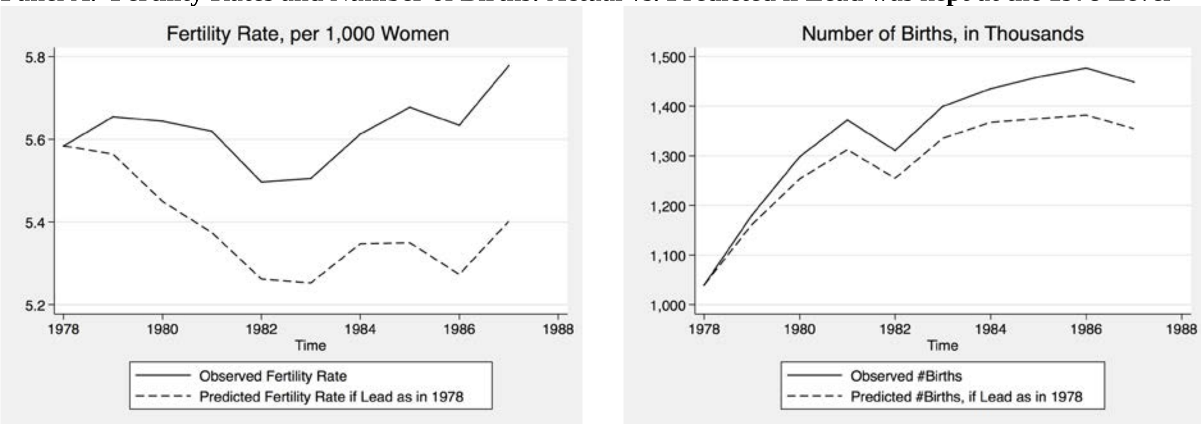
Panel B. General Fertility Rates



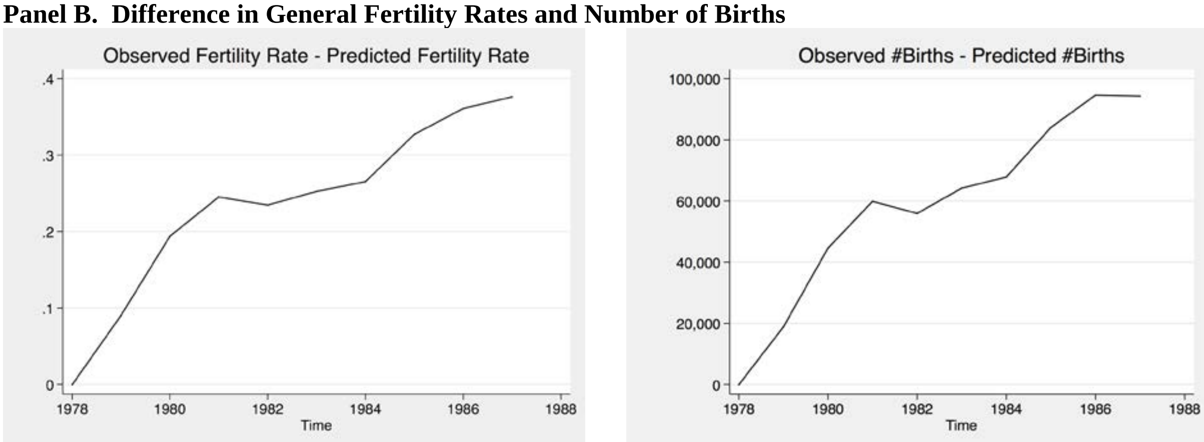
Notes: Panel A shows airborne lead levels over time in counties with and without highway as planned in the 1944 Interstate Highway System Map during the study period 1978-1988. The series are weighted by number of women of childbearing age (15 to 44 years). Panel B shows the general fertility rate over 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 6 – 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

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)
Completed Fertility	2.15	2.58	1.89
(Census 1980 & 1990)	(1.64)	(1.81)	(1.46)

Notes: This table 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. Completed fertility is defined as the number of children ever born by women 35-44 years old. This last measure is only available for the census years 1980 and 1990.

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 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 5 – 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 6 – Airborne Lead and Completed Fertility: 1980-1990

Samples: Women 35-44 Years Old	**All**	**Stayers**	**All**	**Stayers**
	Overlap Counties		**Identifiable Counties**	
Panel A. Completed Fertility - OLS				
Variables	(1)	(2)	(7)	(8)
Airborne Lead	-0.361***	-0.343***	-0.201***	-0.201***
	(0.061)	(0.090)	(0.058)	(0.065)
R-squared	0.304	0.310	0.304	0.311
Panel B. First Stage - Airborne Lead				
Variables	(3)	(4)	(9)	(10)
HWPlan1944 x 1(Year=1990)	-0.207***	-0.184***	-0.160***	-0.139***
	(0.045)	(0.046)	(0.038)	(0.041)
R-squared	0.963	0.957	0.942	0.935
First Stage F Stat	21.48	15.84	17.75	11.38
Panel C. Completed Fertility - IV				
Variables	(5)	(6)	(11)	(12)
Airborne Lead	-0.419***	-0.628***	-0.334**	-0.323
	(0.106)	(0.200)	(0.159)	(0.212)
County FE	x	x	x	x
State-by-Year FE	x	x	x	x
Geographical Variables	x	x	x	x
Mother and Household Characteristics	x	x	x	x
Observations	517,958	133,275	704,674	181,084

Notes: This table presents the OLS, first stage, and IV estimates using instruments discussed in the identification section for completed fertility - the number of children a woman has ever had, excluding stillbirths. The sample is restricted to the female population 35-44 years old from the Census 1980 and 1990. "All" includes every woman in that age range, "Stayers" includes only women who were living in the same county for at least five years, and were living in their state of birth, "Overlap Counties" refers to the 170 counties that matched among the 337 counties used for the analysis of the effects of airborne lead on the general fertility rate over the period 1978-1988, and "Identifiable Counties" refers to all 252 (170 + 82) counties in the IPUMS with FIPS available - counties with 100,000 population or more. Airborne lead is the county-level average of all EPA lead monitor readings for the years 1978-1984 (for Census year 1980), and 1985-1990 (for Census year 1990). HWPlan1944 x 1(Year=1990) is an interaction between the indicator for whether a county was recommended to receive a highway as part of the 1944 Interstate Highway System Map, and an indicator for the year 1990, when the phase-down of lead in gasoline, and the NAAQS for particulate matter had already been effective. Geographical variables are average temperature, degree days below 10C, degree days above 29C, precipitation, their squares, and year by latitude and year by longitude fixed effects. Mother and Household Characteristics are education attainment (12 categories), age (10 age indicators, one for each age), marital status (6 categories), race (9 groups), hispanic origin (6 categories), poverty status, socioeconomic index, and household income and its square. Regressions are weighted by person weight provided by the Census Bureau. 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

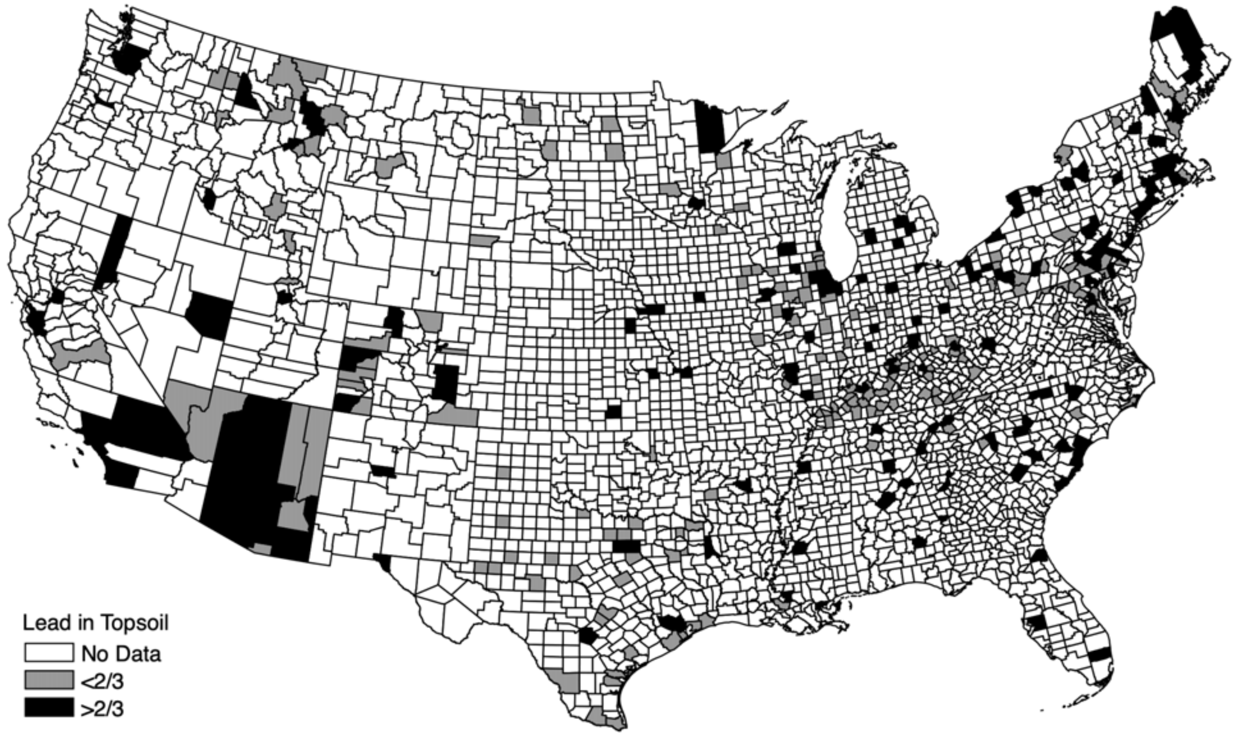
Panel A.	**Airborne Lead: 1978-1988**		
	35% population		
	337 counties		
	(1)	(2)	(3)
Annual Benefits	**IV**	**OLS**	**IV - OLS**
Babies (in thousands in 1988)	95	10	85
Value (in billions)	$ 18.29	$ 2.04	$ 16.25
Costs (in billions)	$ 3.0		
Panel B.	**Lead in Topsoil: 2005**		
	70% population		
	2096 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. Alternatively, in the last two rows, it reports the benefits of having more children based on the completed fertility results. 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 for online publication only)

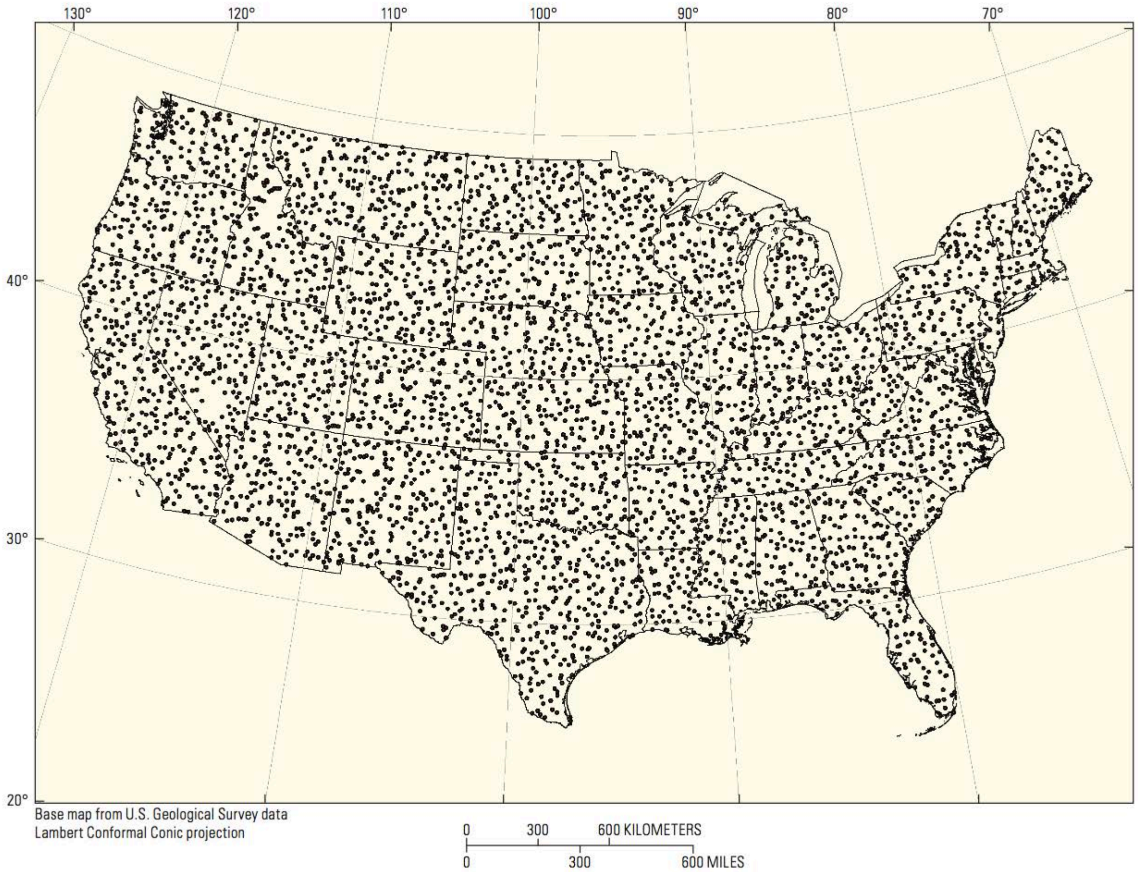
Appendix A1. Data Description

Figure A1.1 – Counties in Our Airborne Lead 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 airborne lead sample.

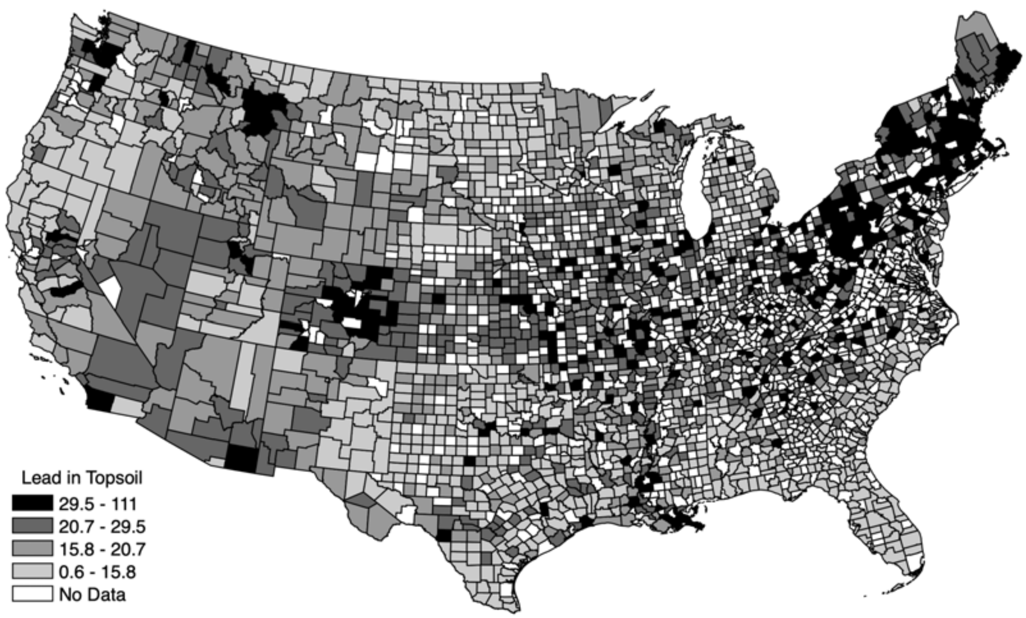
Figure A1.2 – Soil Sampling Sites



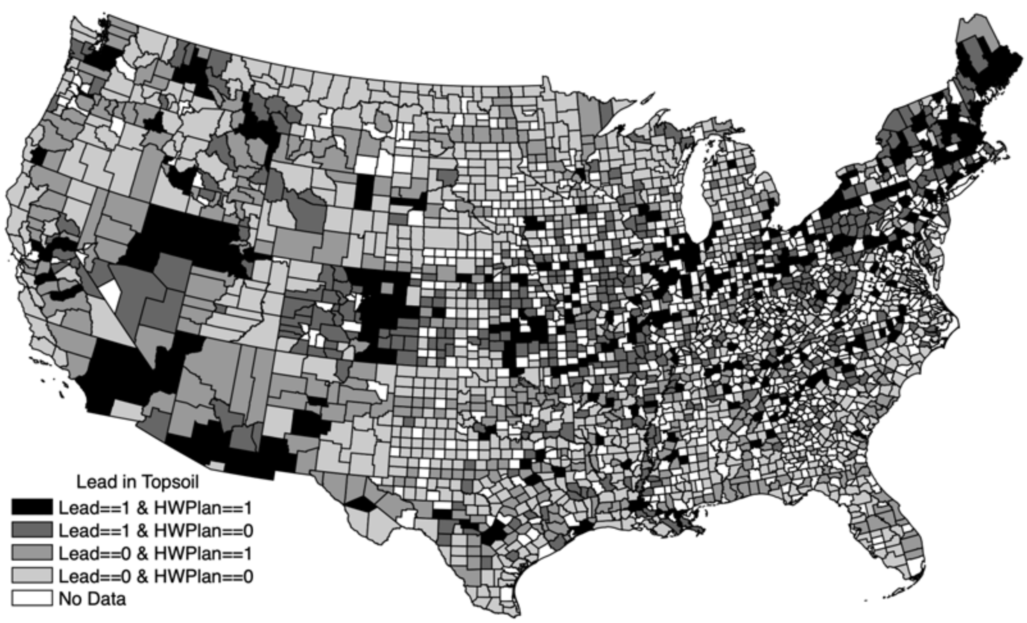
Notes: This map shows the location of 4,857 soil sampling sites in the conterminous United States. Source: Smith, D.B., Cannon, W.F., Woodruff, L.G., Solano, Federico, Kilburn, J.E., and Fey, D.L., 2013, Geochemical and mineralogical data for soils of the conterminous United States: U.S. Geological Survey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

Figure A1.3 – Lead in Topsoil in the 2000s

Panel A. Lead in Topsoil: mg/kg

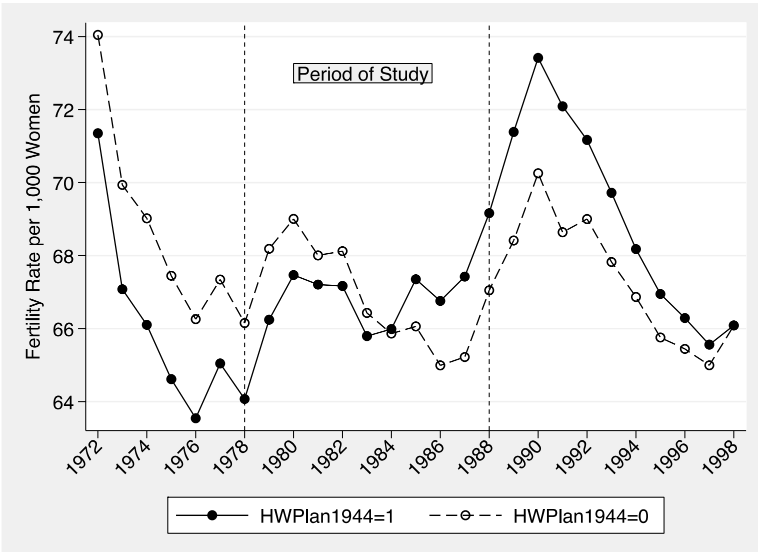


Panel B. Lead in Topsoil



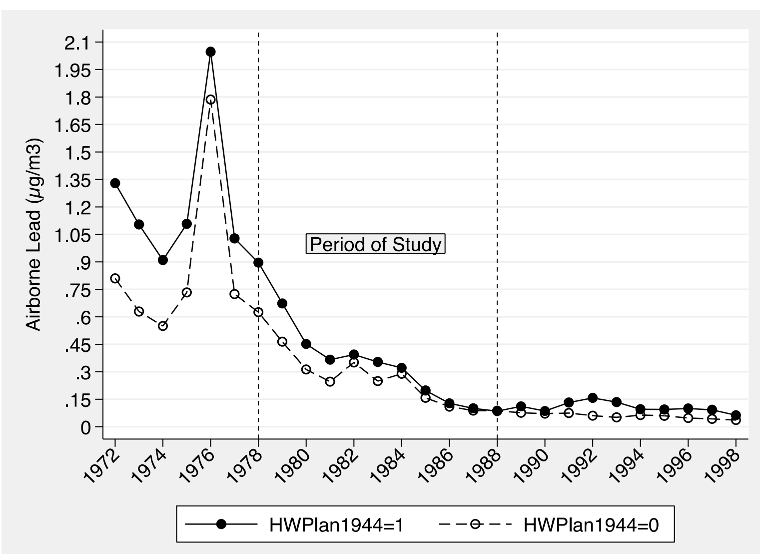
Notes: Panel A presents shows the lead concentration (mg/kg) in topsoil, at a depth of 0-5 cm. Data are taken from U.S. Geological Survey. Soils samples started to be collected for pilot studies from 2004 to 2007, but the main samples were collected by state with the last one collected in late 2010. Panel B 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 A1.4 – Trends in Annual Fertility Rates for 1972-1998



Notes: This figure plots annual general fertility rates for counties with and without highway as planned in the 1944 Interstate Highway System Map (HWPlan1944) during the period 1972-1998. General fertility rate is defined as total number of births per 1,000 females 15-44 years old. The series are weighted by number of women of childbearing age (15 to 44 years). The two short-dashed vertical lines indicate the period of our study – 1978-1988.

Figure A1.5 – Trends in Annual Airborne Lead Concentration for 1972-1998



Notes: This figure plots annual airborne lead concentration for counties with and without highway as planned in the 1944 Interstate Highway System Map (HWPlan1944) during the period 1972-1998. The data come from the EPA network of monitoring stations, and were obtained through a Freedom of Information Act (FOIA) request.

Table A1.1 – Additional Summary Statistics: 1978-1988 Airborne Lead Analysis

Variable	Mean	Std. Dev.
Panel A. Fertility Rates		
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
Panel B. Monthly Lead Statistics for the Panel Data over the period 1978-1988		
Lead in the East	0.311	0.351
Lead in the West	0.465	0.449

Notes: Panel A 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. Panel B shows the airborne lead concentration in the eastern and western counties.

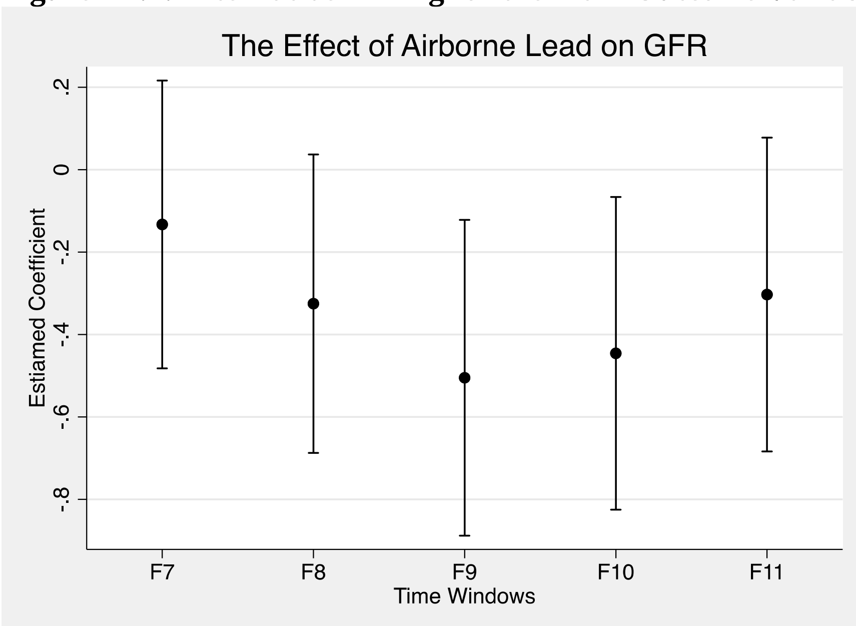
Table A1.2 – Summary Statistics: 2005 Topsoil Lead Analysis

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 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.

Appendix A2. Airborne Lead – Additional Analysis

Figure A2.1: Alternative Timing for the Main Outcome Variable



Notes: This figure plots the IV estimates and confidence intervals for the general fertility rate, measured seven (F7), eight (F8), nine (F9, preferred specification), ten (F10) and eleven (F11) months in the future. General fertility rate(GFR) is the total number of live births per 1,000 female population 15-44 years old. All specifications include the full set of controls: Economic Variables, Climate variables, Mother and Child Characteristics. Regressions are weighted by number of females 15-44 years old. Standard errors are clustered at the county level.

Table A2.1 – Airborne Lead and General Fertility Rate: 2SLS vs. LIML, and Eastern vs. Western U.S.

Variables	(1) All counties	(2) All counties	(3) Eastern U.S.	(4) Western U.S.
	IV (2SLS)	IV (LIML)	IV (2SLS)	IV (2SLS)
HW Plan 1944	-0.505***	-0.452***	-0.736**	-0.235
	(0.195)	(0.174)	(0.332)	(0.234)
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	18,453	4,864
First Stage F Stat	23.49	23.49	22.07	9.268

Notes: This table presents the IV results using instruments discussed in the identification section for the general fertility rate, measured nine months in the future. In columns 1 and 2 present the result for all counties, estimated by two-stage least squares estimator (2SLS) and continuously updated GMM estimator with centered moments (CUE). Column 3 and 4 present the result for the eastern counties, located to the east of 100th meridian and the western counties, located to the west of the 100th meridian 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 A2.2 – 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 A2.3 – 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 A2.4 – Airborne Lead vs. TSP and Fertility

Variables	(1) GFR IV	(2) GFR IV	(3) GFR IV	(4) GFR IV
Airborne Lead	-0.505***		-0.421	-0.456**
	(0.195)		(0.274)	(0.227)
TSP w/ Airborne Lead		-0.030		
		(0.018)		
TSP w/o Airborne Lead			-0.027	
			(0.044)	
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	23,218	23,218	15,745
First Stage F	23.49	2.326	0.270	30.94

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, column 3 the results of Lead and TSP without lead particulates (TSP w/o Airborne Lead), and column 4 the estimates of Airborne Lead but eliminating data for the years 1980-1982, which have been shown to affect TSP due to economic recessions (Chay and Greenstone 2003). 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 A2.5 – Airborne Lead and Fertility: Without Clean Air Act IV

Variables	(1) GFR IV	(2) GFR IV	(3) GFR IV
Airborne Lead	-0.505***	-0.385**	-0.836
	(0.195)	(0.178)	(0.658)
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	29.03	4.140

Notes: This table presents the IV estimates using all instruments discussed in the identification section in column 1 (our main specification), only instruments related to the phasedown of lead in gasoline, i.e. not including the instrument related to the CAA regulations in column 2, and only the instrument related to the CAA in column 3. 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 A2.6 – 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 A2.7– 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.

Table A2.8 – 1st Stage IV – Airborne Lead, Sulfur Dioxide, and Ambient Ozone on Instruments

	(1)	(2)	(3)
Variables	Airborne Lead	SO_2	Ozone
Attainment X CAANAS_TSP$_{1978}$	-0.071**	0.696	-0.000
	(0.035)	(0.471)	(0.001)
$LPD_{0.8gpg}$ *X HWPlan1944*	-0.092**	-1.482**	0.003
	(0.041)	(0.753)	(0.002)
$LPD_{0.5gplg}$ *X HWPlan1944*	-0.149**	-1.035	0.003
	(0.063)	(0.873)	(0.003)
$LPD_{0.8gpg}$	0.001	1.160	-0.004*
	(0.037)	(0.752)	(0.002)
$LPD_{0.5gplg}$	-0.042	0.442	-0.005
	(0.052)	(0.876)	(0.003)
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	15,647	13,695
R-squared	0.432	0.376	0.742
First Stage F	23.49	2.377	1.683

Notes: This table presents the first stage relationship between the instruments and airborne lead, sulfur dioxide (SO_2), and ambient ozone. 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.

Appendix A3: Topsoil Lead – Additional Analysis

Table A3.1 – 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 A3.2 – Lead in Topsoil and Fertility in Alternative Cross Sections in the 2000s

Variables	(1) GFR 2004 IV	(2) GFR 2005 IV	(3) GFR 2006 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 A3.3 – Lead in Topsoil and Fertility: Eastern vs. Western U.S. and High vs. Low Lead States

Variables	(1) GFR All Counties	(2) GFR East vs West	(3) GFR High vs Low Lead States
Lead	-7.762***		
	(2.816)		
Lead in the Eastern U.S.		-7.360*	
		(4.185)	
Lead in the Western U.S.		-8.142***	
		(2.371)	
Lead in Low Lead States			-4.387
			(2.915)
Lead in High Lead States			-9.667**
			(3.863)
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	2,096	2,096	2,091
First Stage F	12.13	4.150	6.073

Notes: This table shows the IV cross sectional effects of lead in topsoil on fertility for 2005. Columns 1 repeats the estimates from Table 8 specifications 10. Column 2 presents the effect of lead in the Eastern vs Western counties (counties to the east or to the west from the 100th meridian). Column 3 presents the effect of lead in high vs low lead states. 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 A3.4 – Lead in Topsoil and Completed Fertility – CPS 2000-2010

Panel A. Completed Fertility - OLS		
Variables	(1)	(2)
Topsoil Lead	-0.021	-0.058**
	(0.044)	(0.026)
R-squared	0.009	0.180
Panel B. First Stage - Topsoil Lead		
Variables	(3)	(4)
HWPlan1944	0.224**	0.165**
	(0.087)	(0.071)
R-squared	0.423	0.720
First Stage F Stat	6.649	5.459
Panel C. Completed Fertility - IV		
Variables	(5)	(6)
Topsoil Lead	-0.195	-0.175
	(0.170)	(0.254)
Year FE	x	x
State FE	x	x
Geographical Variables		x
Mother, Household, and County Characteristics		x
Observations	15,855	15,855

Notes: This table presents the OLS, first stage, and IV estimates using the instrument discussed in the identification section for completed fertility - the number of children a woman has ever had, excluding stillbirths, with weighted average of 1.89 in the sample. The sample is restricted to the female population 35-44 years old from the Current Population Survey (CPS) - Fertility Supplement for June 2000, 2002, 2004, 2006, 2008, and 2010. The number of observations in the table refers to the number of women whose county of residence matched the counties used for the the analysis of the effects of topsoil lead on the general fertility rate in 2005. Those were the 233 counties with FIPS available in the IPUMS-CPS - counties with 100,000 population or more. "Topsoil Lead" is an indicator variable for whether the topsoil lead concentration is above the national median. The instrument "HWPlan1944" is a dummy variable for whether a county was supposed to receive a highway based on the 1944 Interstate Highway System Plan. Geographical variables are average temperature, degree days below 10C, degree days above 29C, precipitation, and county-centroid latitude and longitude. Mother and Household Characteristics are indicators for education attainment (16 categories), age (10 age indicators, one for each age), marital status (7 categories), race (29 groups), hispanic origin (17 categories), and household income (originally coded into 63 categories).County Characteristics are the same as in the topsoil analysis, as listed in previous tables. Regressions are weighted by person weight provided by the CPS Fertility Supplement. 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.

Appendix A4: IV Diagnostics

Table A4.1 – 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 A4.2 – 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 5 and 10. Columns 3 and 4 repeat the estimates from Table 8, specifications 5 and 10 respectively.

Table A4.3 – Topsoil Analysis: 1st Stage IV for Alternative Specifications

Dependent Variables	Topsoil Lead	Commuting Time	Number of Physicians
Panel A. One Endogenous Variable			
HW Plan	0.104***		
	(0.030)		
AP F-Stat	12.13		
Panel B. Two Endogenous Variables			
HW Plan	0.104***	-0.022	
	(0.030)	(0.301)	
Hydropower Potential	-0.040	-1.552***	
	(0.134)	(0.434)	
AP F-Stat	12.84	12.33	
Panel C. Three Endogenous Variables			
HW Plan	0.101***	-0.043	6.020
	(0.030)	(0.302)	(12.861)
Hydropower Potential	-0.051	-1.623***	-2.443
	(0.132)	(0.431)	(11.480)
Hill-Burton Funds	0.002*	0.015***	0.934***
	(0.001)	(0.005)	(0.214)
AP F-Stat	4.35	10.64	7.12
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	2,096	2,096	2,096

Notes: This table presents the first stage relationship between the instruments and lead in topsoil, average commuting time, and number of physicians per 100,000 population. Panels A, B and C regressions are associated with the second stage in columns 1, 2 and 3 of Table A21 respectively. AP F-Stats are the Angrist-Pischke (2009) conditional first-stage F statistics. Topsoil Lead is an indicator variable for whether the topsoil lead concentration is above the national median. Average Commuting Time in 2000 comes from the U.S. Census 2000, and Number of Physicians per 100,000 population in 2004 comes from the County and City Data Book 2007. 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 A4.4 – Topsoil Analysis: IV Estimates for Alternative Specifications

Variables	(1)	(2)	(3)
Topsoil Lead	-7.762***	-7.687***	-8.140**
	(2.816)	(2.862)	(3.338)
Commuting Time		0.407	0.427
		(0.678)	(0.664)
Number of Physicians			0.006
per 100,000 Population			(0.018)
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	2,096	2,096	2,096
First Stage F Stat	12.13	3.547	1.151

Notes: This table shows the IV cross sectional effects of lead in topsoil on fertility for 2005. In column 1, only topsoil lead in instrumented. In column 2, topsoil lead and commuting time are instrumented. In column 3, topsoil lead, commuting time, and number of physicians per 100,000 population are instrumented. 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. Average Commuting Time in 2000 comes from the U.S. Census 2000, and Number of Physicians per 100,000 population in 2004 comes from the County and City Data Book 2007. 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.