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ABSTRACT

Pollution exposure early in life is detrimental to near-term health and an increasing body of evidence suggests that early childhood health influences health and human capital outcomes later in life. This paper reviews the economic research that brings these two literatures together. We begin with a conceptual model that highlights the core relationships across the lifecycle. We then review the literature concerned with such estimates, focusing particularly on identification strategies to mitigate concerns regarding endogenous exposure. The nascent empirical literature provides both direct and indirect evidence that early childhood exposure to pollution significantly impacts later life outcomes. We discuss the potential policy implications of these long-lasting effects, and conclude with a number of promising avenues for future research.

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I. Introduction

The protection of human health is a principal motivation for environmental regulation around the world. Children are particularly vulnerable to environmental exposures because their immune and other bodily systems are still developing and they often engage in behaviors that increase their exposure to toxic chemicals and organisms, e.g. they spend more time outside than adults (U.S. EPA 2013; Bateson & Schwartz 2007; Makri et al. 2004; Schwartz 2004). Rapid cell division and an intense phase of epigenetic programming make the prenatal and immediate postnatal period an especially sensitive one (Baccarelli & Bollati 2009; Gluckman et al. 2008; Holt 1998). As such, the protection of children has become a driving force behind many environmental regulations.[1]

The impacts of early life pollution exposure are of interest for non-health reasons as well. Early life health affects long-term outcomes including human capital accumulation, labor force participation and earnings (see Almond & Currie 2011 for a review of this literature). Thus, the marginal returns to regulations that protect children may be both large and rather diffuse in that they affect many outcomes.[2]

In addition to broadening the focus beyond health, economists have made two important methodological contributions to the study of pollution impacts on children. First, economists have developed a conceptual framework for considering the effects of pollution within the larger frame of health production and investments. The framework implies, for example, that a lifetime of investments may strengthen or attenuate the pure biologic insults experienced early in life. It also highlights that optimizing behavior, through residential sorting, can lead to non-random assignment of pollution. For example, as discussed further

[1] In the U.S., for example, Executive Order 13045 directs the EPA and other federal agencies to "ensure that its policies, programs, activities, and standards address disproportionate risks to children that result from environmental health risks or safety risks" (Clinton 1997).

[2] Large returns to early life interventions have been found in a number of settings outside of environmental health (Currie 2001; Heckman 2000, Schweinhart et al. 1993; 2005).

below, individuals with higher incomes are both less likely to raise their families in areas of poor environmental quality, and more likely to make greater investments in their children's health. Failing to account for the correlation of higher health investments with living in an area with better environmental quality will bias estimates of the effects of pollution.

Similarly, an optimizing framework leads to the consideration of avoidance behavior. Since the consequences of toxic exposures are costly, particularly to children, parents may engage in activities to prevent them. Avoidance behavior can muddy the measurement of biologic effects in epidemiologic research. Ignoring avoidance behavior can also lead to significant underestimation of the social welfare costs of pollution since a narrow focus on the costs of morbidity and mortality will exclude the costs of avoidance activities (Courant & Porter 1981; Harrington & Portney 1987; Bartik 1988).

A second, and related contribution in light of concerns regarding endogenous exposure to pollution, is the use of quasi-experimental techniques to develop causal estimates of the effects of early-life pollution. The shorter possible exposure period and more limited geographic mobility of children make it easier to use quasi-experimental methods to determine the effects of pollution on children relative to adults. Such causal inference has enabled the detection of effects at markedly low levels of pollution.

A third contribution of economists involves the explicit consideration of welfare and willingness-to-pay (WTP) for reductions in pollution. As discussed below, the data requirements for a complete WTP calculation are seldom met, but partial calculations may still be useful for policy.

This paper reviews the recent economic literature on the effects of early life exposure to pollution. We focus primarily on air pollution since it has received the most attention in the literature, largely due to greater data availability. The remainder of the paper is organized as follows. The next section describes the contribution of economics to our understanding of

the impacts of early life pollution exposure. We begin with a conceptual model, followed by a discussion of identification and welfare. Section III provides a structured review of the literature that organizes papers into common themes. Section IV offers some concluding remarks and suggestions for future research.

II. What Do Economists Bring to the Table?

1. Conceptual Model

In this section, we develop a simple three-period model that builds upon earlier work on human capital accumulation and investments (Grossman 1972; Cunha & Heckman 2007; Almond & Currie 2011) to highlight the salient features that link pollution and birth outcomes to health and human capital later in life.

Our framework divides life into three distinct stages: early childhood, late childhood, and adulthood. To fix ideas, one can view early childhood as beginning in utero and ending at age 5. Late childhood would comprise the school years, and adulthood can be viewed as the post-schooling period when people have typically entered the labor force. For simplicity, we model the human capital production function of a representative individual and abstract from the endogeneity of pollution exposure, though we return to this problem in the next section (Neidell 2009; Graff Zivin et al. 2011; Currie et al. 2011).[3]

Assume that early childhood human capital H_E is dependent on early childhood pollution exposure P_E and time-invariant family characteristics X, such as genetics.

$$H_E = f_E(P_E, X) \quad (1)$$

Late childhood human capital H_L depends on late childhood pollution exposure P_L and the human capital accumulated during early childhood. Importantly, families can make

[3] Individuals may differ in their susceptibility to pollution for a variety of reasons apart from the explicit differences by stage of life that we attend to here. This heterogeneity will affect the gradient between childhood and adult outcomes, but the basic insights from the model remain the same.

investments I_L in their child that influence the legacy of those early childhood outcomes. Those investments will depend upon realizations of human capital in the first stage of life.

$$H_L = f_L(I_L(H_E), P_L) \quad (2)$$

Finally, assume that adult outcomes H_A depend on both early and late childhood human capital. Given our focus on children, we ignore adult exposure to pollution and investments in human capital, such that adults in our model should be viewed as 'fully formed.' Human capital in adulthood is broadly construed to reflect the fact that pollution can affect cognitive attainment and earnings as well as health (Graff Zivin & Neidell 2013).

$$H_A = f_A(H_E, H_L) \quad (3)$$

Equations (1)-(3) imply that the impacts of early childhood pollution exposure on adult human capital will depend upon its short-run effects as well as the propagation of those effects through the rest of the life cycle. These pathways are easily shown by taking the total derivative of (3):

$$\frac{dH_A}{dP_E} = \frac{\partial f_A}{\partial H_E}\frac{\partial H_E}{\partial P_E} + \frac{\partial f_A}{\partial H_L}\frac{\partial H_L}{\partial P_E} \quad (4)$$

Note that P_E (or P_L) may also have a direct, latent effect on H_A, which does not act through changes in H_E or H_L. For the time being we ignore the partial derivatives of H_A with respect to P_E and P_L though we return to the question of latent effects below.

Our model of human capital accumulation can be used to illustrate several points regarding childhood exposure to pollution. As discussed above, it is reasonable to assume that the early childhood period is one of greater sensitivity to pollution. The nine months in utero is a critical period for physiological development and an increasing body of evidence suggests that fetal programming can be adversely impacted by toxic exposures (Almond & Currie 2011; Barker 1990; Bateson & Schwartz 2007). All else equal, this suggests that an equal dose of pollution will have a bigger effect (in absolute value) in early childhood:

$$\left|\frac{\partial H_E}{\partial P_E}\right| > \left|\frac{\partial H_L}{\partial P_L}\right| \quad \forall \; P_E = P_L. \tag{5}$$

In addition to greater contemporaneous health effects, early life exposures can result in latent health impacts. In particular, pollution may have epigenetic effects – permanent alterations in gene expression – that can negatively impact intellectual growth and maturity later in life (Petronis 2010). Someone with latent epigenetic damage might initially appear to be in perfect health so that it might be possible to observe the following:

$$\left|\frac{\partial H_E}{\partial P_E}\right| = 0 \quad and \quad \left|\frac{\partial H_A}{\partial P_E}\right| > 0. \tag{6}$$

The long potential latency period between exposure and the outcomes of interest also provides ample opportunity for effects to be amplified or dampened. Self-productivity and dynamic complementarities in health and learning, whereby capabilities beget capabilities in a multi-stage framework, suggest that early health shocks will be multiplied over the life cycle (Cunha & Heckman 2007). The early manifestation of health and cognitive deficits could induce parental (dis)investments in early childhood that will also impact later life outcomes. Whether parents compensate for poor endowments at birth by increasing investments in those children or reinforce poor endowments by directing their efforts toward children with better prospects is an open empirical question in the literature (Behrman et al. 1994; Datar et al. 2010). If we expand the last term of equation (4) above, the role of these investments can be made more explicit:

$$\frac{dH_A}{dP_E} = \frac{\partial f_A}{\partial H_E}\frac{\partial H_E}{\partial P_E} + \frac{\partial f_A}{\partial H_L}\left(\frac{\partial f_L}{\partial I_L}\frac{\partial I_L}{\partial H_L}\frac{\partial H_L}{\partial P_E}\right) \tag{7}$$

Assuming that the effects of pollution exposure are detrimental, self-productivity and dynamic complementarities imply that $\frac{\partial H_L}{\partial P_E}$ is large and negative – early deficits compound over the life cycle such that the impacts later can be quite large. Compensatory investments correspond to the case where $\frac{\partial I_L}{\partial H_L}$ is negative, while reinforcing ones imply that this term is positive.

The principal value of equation (7) is conceptual. Data limitations imply that all empirical investigations in this area will paint a partial picture of this total derivative. Nonetheless, the equation underscores the connections across a wide range of empirical literatures within economics, including the environmental, education, labor and health fields. This basic model also highlights the policy importance of the question addressed in this review. If the legacy effects of early pollution exposures are large, then even modest interventions to protect young children may have profound impacts on societal well-being and future economic growth. Of course, such benefits would have to be weighed against the costs of any regulatory efforts to protect children, and a proper welfare calculation should incorporate the costs borne by households seeking to avoid pollution and/or to compensate for its effects.

2. An Emphasis on Identification

While the conceptual model just described intentionally eschewed concerns about the endogeneity of pollution exposure, empirical economic studies on the effects of the environment on child health have not. Endogeneity can arise through two primary channels. The first is Tiebout sorting (Tiebout 1956), through which people "vote with their feet" by choosing residential locations based on area characteristics, such as pollution levels or attributes coincidentally correlated with pollution levels. A growing body of empirical evidence suggests that sorting based on environmental quality is indeed a major factor affecting residential location. For example, Banzhaf & Walsh (2008) find that high income families tend to move away from highly polluted areas, while Currie (2011), Currie et al., (2011), and Currie & Walker (2011) find that improving environmental quality in an area increases the share of pregnant women who are white and college-educated. As a result of this sorting, areas with higher levels of pollution may also have other unobserved

characteristics correlated with health, suggesting that omitted variable bias is likely to confound estimates.[4]

The second source of endogeneity arises from avoidance behavior. If individuals take actions to protect their children's health when pollution is high, these actions will lead to non-random assignment of ex post pollution exposure. These kinds of actions require knowledge of pollution levels, either through experiential changes in health or, as may be more likely for younger children, through publicly provided information. The dissemination of pollution information to the public is mandated in many large cities, and is often accompanied by recommended strategies for pollution avoidance, such as staying indoors or shifting activities to times of the day when pollution is expected to be lower.

Since avoidance behavior is an ex post decision– it occurs in response to realized pollution levels -- its omission from analysis does not introduce a bias per se in estimates, but rather affects the interpretation of estimated relationships. Estimates that account for avoidance behaviour uncover the direct biological effect of pollution on health ($\partial H_A/\partial P_E$). Estimates that do not account for avoidance measure a reduced form effect of pollution on health, which consists of the biological effect plus the degree to which avoidance behavior (A_B) is successful in averting detrimental health effects ($dH_A/dP_E = \partial H_A/\partial P_E + \partial H_A/\partial A_B$ $\partial A_B/\partial P_E$). Both estimates can be used to monetize the benefits from improvements in environmental quality, so the focus of estimation depends on the research question.

Economists have addressed endogeneity concerns with quasi-experimental techniques such as finding natural experiments that result in unexpected "shocks" to environmental quality. These shocks can be driven by government regulation (such as the Clean Air Acts in the United States), unexpected changes in industrial production (such as strikes and plant closings), or catastrophic events (such as temperature inversions or wildfires). Another

[4] We also note that pollution, rather than people, may "sort" whereby polluting industries locate in areas with lower land prices, which also tend to be areas with residents of lower socioeconomic status.

approach consists of exploiting high frequency variability in pollution over short periods of time in conjunction with local area fixed effects, under the assumption that sorting in response to environmental changes occurs more slowly than health changes. A final approach consists of within family designs, such as sibling comparisons, which hold fixed many unobserved characteristics common to children from the same family.

While each approach has its advantages, there are important limitations that must be recognized. For example, although an unexpected productivity shock can affect air pollution, it may also directly affect health through job losses or the loss of health insurance (von Wachter & Sullivan 2009). And the more time is allowed to elapse from the time of the shock, the greater the probability that residential sorting will complicate the picture. Natural experiments also do little to directly address ex post avoidance behaviour. Despite these limitations, we will show below that the weight of the evidence suggests that early life exposure to pollution has negative long term effects.

3. Welfare Calculations to Guide Policy

Environmental economics research often aims to develop measures of willingness-to-pay for reductions in pollution. Such estimates are necessary to inform environmental policy. While the theory underlying the computation of WTP is clear (Harrington & Portney 1987; Cropper & Freeman 1991), there are few studies that combine an emphasis on quasi-experimental identification strategies with WTP calculations. One likely explanation is the massive data requirements to compute a complete WTP – in principal, WTP must include measures of all outcomes affected, all types of avoidance behavior undertaken, and the disutility (such as pain and suffering) associated with any health effects.[5] As a result, economists often compute partial cost-benefit analyses, noting that the computed benefits

[5] See Deschênes et al. (2012) for an example of one of the most comprehensive estimates of WTP.

understate the complete WTP for a particular policy. It is also worth noting that, since economic studies are typically designed to test whether a null hypothesis can be rejected, the common practice is to employ conservative assumptions that bias estimated effects of the particular outcome of interest toward zero.[6] Hence reported magnitudes often provide only a lower bound on the magnitude of the effect. In the end, a policy recommendation is only clear if even these understated benefits exceed costs.

III. Literature Review

Tables 1 to 4 summarize the existing quasi-experimental research in economics on the effects of pollution on children's well-being. Tables 1 through 3 focus on air pollution, which is often the most reliably recorded measure of environmental quality. Table 4 summarizes the much smaller literature on water pollution. A general feature of this literature is that, while impacts are often attributed to a single pollutant, emissions of many pollutants tend to be highly correlated and may come from the same sources. For example, an analysis of the effect of carbon monoxide exposure on birth weight may really be measuring the effect of automobile exhaust, which includes particulate matter, nitrogen oxides, and other chemicals in addition to carbon monoxide. Even analyses based on multi-pollutant models rarely have measures of all relevant emissions. If all pollutants are emitted from the same source, this may not matter from a policy perspective but it will certainly limit generalizability across settings.

1. Long Term Effects of Air Pollution

Table 1 shows that relatively few studies make a direct connection between childhood exposure to pollution and long-term outcomes such as educational attainment and earnings.

[6] An example is sibling fixed effects estimates which are known to be biased towards zero in the presence of random measurement error.

The small number of studies is largely due to limitations in data availability: Data that allows the linkage of adult outcomes with childhood environmental quality is rare. In the absence of such data, some researchers have employed a cohort approach to exploit differences between cohorts of children born just before and after an environmental shock. This approach generally works best in the case of a large shock.

Almond et al. (2009) studied the fallout from the Chernobyl nuclear disaster using detailed Swedish administrative data. Although Sweden is more than 500 miles away from Chernobyl, weather conditions forced some of the plume of radioactive particles to pass over Sweden. Local variation in rainfall levels led to stark geographic variation in the levels of fallout throughout the country. By comparing cohorts in affected and unaffected areas, and cohorts in utero just prior to the disaster and during the disaster, they demonstrate that radiation exposure reduced overall grades by 2.5 percentage points and mathematics test scores by 6 percentage points despite the fact that the amounts of radiation involved were below thresholds widely considered, at the time, to be safe. They also found no immediate effects on health, as measured by birth outcomes and childhood hospitalizations, underscoring the latent nature of these effects.[7]

Black et al. (2013) conduct a similar analysis of the effect of radiation exposure in the 8th to 16th weeks of pregnancy due to fallout from nuclear tests. Using data from Norway, they first show that test frequency, proximity to the coast, and rainfall patterns influenced the deposition of fallout. They find that a one standard deviation increase in exposure decreased IQ scores by .025 of a standard deviation. Exposure also led to reductions in years of schooling and adult earnings.

Using a large dataset that follows Chilean children from birth, Bharadwaj et al. (2013) examine the relationship between air pollution exposure in each month of pregnancy and 4th

[7] It is notable that the radiation levels found in Sweden are quite comparable to those emitted by radon and used in medical radiation. However, policy levers for influencing exposure from such sources are quite different from typical environmental policy.

and 8th grade test scores. They find significant effects of exposure to carbon monoxide (and its correlates) and ozone in the 3rd and 4th months of pregnancy, a timing that is consistent with the results found in Black et al. (2013) and Almond et al. (2009).

Nilsson (2009) investigates the long-term impact of banning leaded gasoline in Sweden during the 1970s. In an innovative design, he used measures of lead from moss samples, to infer ambient lead levels in different areas of the country and is able to show a wide geographic dispersion of lead across space and over time. Linking the decline in ambient lead around the time of birth to later outcomes for the affected cohorts, his estimates imply that reducing lead levels from 10 to 5 micrograms per deciliter (the current regulatory standard in the U.S. is 15) increased high school graduation rates by 2.3% and earnings among young adults by 5.5%. The effects were larger for children of lower socioeconomic status.

Sanders (2012) builds on the work of Chay & Greenstone (2003b; discussed below) by asking whether cohorts affected by the reductions in U.S. pollution caused by the recession of the early 1980s scored better on high school tests. A drawback to his analysis is that he cannot identify where the mother resided when the children were born, so he is forced to assume that children were born in the place they attended high school. Despite this potential source of measurement error, he finds that a one standard deviation decrease in Total Suspended Particles around the time of birth increases high school test scores by 1.87 standard deviations.

Isen et al. (2013) are able to go further with a similar approach by using restricted access data on adult earnings that includes information on the actual county and date of birth of each worker. Their identification strategy follows Chay & Greenstone (2003a) in using the pollution reductions due to the passage of the 1970 U.S. Clean Air Act Amendments as a source of variation in pollution levels. Counties that were out of compliance with the new

CAA pollution thresholds were identified as non-compliant and were required to lower pollution, while counties with pollution levels just below the thresholds were not required to implement any changes. Comparing counties initially just below the threshold to those just above, they find that each 10 ug/m^3 decrease in Total Suspended Particles during pregnancy and early childhood resulted in a 1% increase in annual salaries. Of course, ambient levels of particulates have fallen greatly since the 1970s, so it is not clear that a similar decline in the U.S. today would have the same impact.

2. Air Pollution and Infant Health

Given the difficulty in making a direct connection between early life exposure to pollution and later outcomes, much of the literature focuses on the effects of pollution on fetal and infant health and then relies on the growing literature linking health at birth to long-term outcomes in order to make inferences about the likely long-term effects. The most commonly used measures of early childhood health are birth weight (especially low birth weight, defined as less than 2500 grams), prematurity (defined as gestation less than 37 weeks), and either infant mortality (death within the first year of life) or neonatal mortality (death within the first month of life). The literature focusing on the effects of pollution on infant health is summarized in Table 2. The studies in Table 2 are organized according to whether the country is a developed or a developing country, and whether the pollutant is a criterion air pollutant or another type of pollutant.

i. Developed countries

Chay & Greenstone (2003a, b) conducted two landmark studies on the effects of air pollution. The first study (Chay & Greenstone 2003a) pioneered the research design based on the Clean Air Acts discussed above and used in subsequent studies. Applying this design to county level data, they estimated that a one unit decline in particulates led to 5-8 fewer

infant deaths per 100,000 live births. Sanders & Stoecker (2011), using the same natural experiment, examine the effects of pollution on sex ratios at birth. Since male fetuses are thought to be more fragile than female fetuses, a decrease in the ratio of male live births to female live births is suggestive of an increase in fetal losses. Consistent with this hypothesis, they find that a reduction in pollution increases the fraction of male fetuses. The second Chay & Greenstone study (2003b) looked at the recession of 1982, which lowered pollution in areas that experienced larger declines in manufacturing (i.e.- the research design followed by Sanders 2012). These pollution reductions led to significant decreases in infant mortality.[8]

The levels of particulates studied by Chay and Greenstone are much higher than those prevalent today; for example, U.S. PM_{10} (particulate matter of 10 microns or less) levels fell by nearly 50 percent from 1980-2000. Moreover, the Chay and Greenstone studies are only able to examine the effects of particulates since other pollutants were not yet widely measured. In a similar inquiry, Currie & Neidell (2005) focus on a more recent time period when additional pollution measures are available. For identification they use high-frequency variation in pollution within zip codes over time. A disadvantage of this approach is that people living in persistently more polluted or higher variance areas may be systematically different from other people in ways that might correlate with their children's health. In order to control for these differences, Currie and Neidell include zip code fixed effects and zip code specific time trends and demonstrate that decreases in CO led to improvements in infant mortality.

In a related study, Currie et al. (2009b) used a large sample of infants born in New Jersey from 1989-2006 who were subjected to different levels of pollution in utero. They control for fixed elements of family background shared by siblings by including family fixed

[8] Arguably, Chay and Greenstone were inspired by a series of epidemiological studies investigating the health effects of the opening and closing of a steel mill in Utah in the 1980s (Pope 1989; Pope et al. 1992; Ransom and Pope 1995). Others have been inspired by these studies as well, for example Parker et al. (2008) returned to the same natural experiment and found that preterm births declined when the mill was closed but rebounded when it reopened.

effects. They also focused on a sample of mothers who lived near pollution monitors in order to improve their assignment of pollution exposure. They found that babies exposed in utero to higher levels of carbon monoxide suffered reduced birth weight and gestation length relative to their siblings, even though ambient CO levels were generally lower than current Environmental Protection Agency (EPA) standards. Their estimates imply that on average, moving from a high to low CO area would have a larger effect on infant health than having a pregnant woman reduce her smoking from ten cigarettes a day to zero.

Since many papers find negative health effects of CO, and CO comes mostly from cars, Currie & Walker (2011) exploited the introduction of electronic toll collection devices (E-ZPass) in New Jersey and Pennsylvania to directly examine the effect of automobile exhaust on infant health. Much of the pollution produced by automobiles occurs during idling and acceleration, so the introduction of E-ZPass greatly reduced auto emissions near toll plazas. For example, E-ZPass reduced CO by about 40% in the vicinity of toll plazas. Comparing mothers near toll plazas (<2 km) to those who lived along the same busy roadways but further away from toll plazas (2-10 km), they found that E-Zpass reduced the incidence of low birth weight and prematurity by about 10%. In a related paper, Knittel et al. (2011) examined the effect of traffic congestion in California using data on traffic jams that temporarily increased pollution levels. They also found significant effects of even relatively low levels of pollution on infant mortality rates.

Recently, the number of studies conducted outside of the U.S. has grown considerably. Using a design similar to Currie & Neidell (2005), Coneus & Spiess (2010) found large effects of CO on infant health in Germany. Luchinger (2010), also focusing on Germany, used the mandating of SO_2 scrubbers in power plants as a natural experiment. He found that reductions in SO_2 led to significant decreases in the rate of infant mortality. Janke et al. (2009) examine the relationship between localized pollution levels in Great Britain

between 1998 and 2005 and the deaths of children under 15.[9] They estimate that a reduction of 10 ug/m3 in PM_{10} is associated with 4 fewer deaths per 100,000.

ii. Developing countries

The impacts of pollution in developing countries are of independent interest since pollution levels are generally higher and infant health is often much worse than in more developed countries. Thus, the same health insults may have larger effects, and the data may also be used to test for potential non-linear effects of pollution. However, while data on pollution and health are often reliably recorded in more developed nations, such data may be more difficult to obtain in less developed countries. Jayachandran (2009) overcomes this obstacle by using satellite aerosol measures to track smoke from fires in Indonesia in 1997, and using data on "missing children" to infer infant mortality. She finds a reduction in cohort size for those exposed to the fires' smoke during the third trimester of pregnancy, and calculates that the fires resulted in a 20% increase in deaths among fetuses and children less than 3 years of age.

Foster et al. (2009) also use satellite measurements to approximate pollution levels throughout Mexico. Using participation in a voluntary pollution reduction program as an instrumental variable, they show that reductions in pollution improve infant mortality from respiratory causes. Also focused on Mexico, Arceo-Gomez et al. (2012) use thermal inversions, which trap pollution, as an instrumental variable, and find that CO has stronger per unit effects on infant mortality than in the U.S.

Cesur et al. (2013) examined the switch from coal to natural gas in Turkey and found that a one percentage point increase in subscriptions to natural gas was associated with a four percent decline in infant mortality. A notable feature of this study is that instead of focusing on the effect of a pollutant per se, they focus on a change in fuel delivery, which is perhaps

[9] We have included this in the infant health table since the vast majority of such deaths are for infants under 1 year of age.

more relevant from a policy perspective. Greenstone & Hanna (2011) use air pollution data from 140 Indian cities and find that air pollution regulation reduced pollution substantially. These regulations also led to a statistically insignificant decrease in infant mortality, though they note several data limitations that suggest their results should be interpreted with caution.

iii. Non-criteria pollutants

Most of the studies in Table 2 focus on so-called criteria pollutants, including ozone, particulate matter, carbon monoxide, nitrogen oxides, sulfur dioxide and lead, all of which are regulated under the Clean Air Acts in the U.S. Much less is known about other hazardous pollutants. Industrial plants in the U.S. emit approximately four billion pounds of toxic pollutants annually, including over 80,000 different chemical compounds (U.S. Gov. Account. Off. 2009). Regulation of these toxics is in its infancy and most have not undergone any form of toxicity testing (U.S. Cent. Dis. Control and Prev 2009). For example, it has been known for decades that mercury is highly toxic, yet the first regulation of mercury compounds in the United States - the Mercury and Airborne Toxics Standards - was unveiled in December 2011.

Two studies have used U.S. county-level data from the EPA's Toxic Release Inventory to document a correlation between higher emissions and infant death (Currie & Schmeider 2009; Agarwal et al. 2010). Currie et al. (2013a) further examined the effects of toxic emissions using openings and closures of more than 1,600 industrial plants that reported toxic emissions. By matching 1989-2003 data on 11 million individual birth records from five large states (Florida, Michigan, New Jersey, Pennsylvania, and Texas) with pollution monitor data, they first show that toxics can be detected up to a mile away from a plant, and that the "average" mother in these states lived within a mile of these plants. They then show that infants within a mile of a plant have a two percent higher incidence of low birth weight compared to infants one to two miles away, despite the fact that the two groups share equally

in the economic benefits of plant operation. While housing values were also reduced, this only occurred within a half mile of a plant, suggesting that some people at risk of poor health outcomes are unaware of the hazards.

Another paper that moves beyond the consideration of criterion air pollutants is Sneeringer (2009), who examines pollution due to large-scale livestock operations. Although these operations have generated concerns regarding the pollution of water sources, animal wastes are also associated with the production of particulate matter as well as the non-criteria pollutants hydrogen sulfide gas and ammonia, all of which can be harmful to the developing fetus. She finds that a doubling of livestock production in a county is associated with an increase in infant mortality of 7.4%. Although she cannot demonstrate a "first stage" effect of the operations on pollution, some evidence that the effect is primarily due to air pollution is obtained by examining causes of death (accidents and homicide vs. respiratory causes) and by comparing counties with high and low dependence on well water, which is more subject to contamination.

3. Air Pollution and the Wellbeing of Older children

Table 3 summarizes studies examining the effects of pollution on the health (Panel A) and cognitive outcomes (Panel B) of older children. Since there is no convenient summary measure of child health that is analogous to birth weight for infant health, most studies of child health focus on hospitalizations for respiratory infections or asthma. Respiratory ailments are a leading cause of hospitalizations among children, comparable in incidence only to injuries, which are unlikely to be influenced by pollution.[10]

Ransom & Pope (1995) produced one of the first quasi-experimental studies of this type, using the closure of a local steel mill as a natural experiment. They found that child

[10] As such, injuries can serve as a useful 'control' condition for studies examining hospitalizations.

hospitalizations for respiratory conditions fell when the mill was closed, and rebounded when the mill reopened. Since then a number of studies have been conducted making use of other clever natural experiments to identify the effects of pollution. Beatty & Shimshack (2011) look at mandatory reductions in school bus emissions; Lleras-Muney (2010) examines children in military households who are exogenously assigned to areas with different pollution levels based on the needs of the military; Lavaine & Neidell (2013) use strikes that shut down oil refineries in France; Yu (2011) studies a behavior modification experiment designed to reduce indoor air pollution from stoves; and Schlenker & Walker (2011) use changes in pollution at California airports due to delays at east coast hubs. All of these papers find that reductions in pollution significantly reduced child respiratory problems.

The papers by Neidell (2004; 2009) highlight the importance of avoidance behavior, which is an issue for the interpretation of all of the studies discussed thus far (including those focusing on infants). People take actions ranging from changes in daily activities to moving house in order to reduce exposures to harmful pollutants. If people act to lessen their exposure, then the potentially harmful effects of pollution may be understated by estimation procedures that do not take these actions into account. A growing body of evidence suggests changes in daily actions effectively reduce exposure to pollution, even when those actions are not directly in response to poor air quality. Both Neidell papers find evidence that the effects of pollution exposure are much greater than is generally estimated when precautionary actions are ignored. Neidell also stress that such behaviours must be taken into account when calculating the costs of pollution.

Panel B of Table 3 illustrates the fact that there are many fewer studies of the effects of pollution on non-health child outcomes such as schooling attainment or test scores. This reflects both limitations on the available data and conceptual difficulties in elucidating the way pollution can be expected to affect test scores. For example, since test scores reflect

cumulative knowledge, how should we account for the effects of cumulative exposure to pollution? In principal, the same issue applies to long-run health outcomes, but as discussed above, most of the research examining the effects of pollution on health outcomes has focused on relatively short-run effects (e.g. effects of in utero pollution on birth weight, or effects of pollution on hospitalizations for asthma).

One potential mechanism underlying an effect of pollution on test scores is through absence—if children are frequently absent from school because of high pollution levels, then this may interfere with their ability to learn. Currie et al. (2009a) find some evidence that higher pollution levels over six week attendance periods are associated with more student absences in Texas. Zweig et al. (2009) extend this analysis by using class-school-year level performance data to show that higher pollution levels decrease scores on annual achievement tests. To address concerns that differences in the student populations might be correlated with both pollution and lower test scores, they include school fixed effects as well as observable student and family characteristics in their analysis. Reyes (2011) does not have panel data, but shows a strong cross-sectional link between test scores in elementary schools in the 2000s and childhood lead levels in the same areas a decade earlier. Lavy et al. (2012) examine whether high pollution on the day of a high stakes test affects student performance. Using multiple test results for the same student and student fixed effects, they show that Israeli students earn lower scores when subjected to higher pollution on the day of the test.

4. Effects of Water Pollution

While the lion's share of studies on the effects of pollution on children is focused on air pollution, Table 4 provides a summary of the handful of studies that examine the effects

of water pollution.[11] One reason for the small number of studies is the primitive and fragmented state of water quality data relative to the data on air pollution. Whereas air quality monitoring in a given country is often undertaken by a single group or coalition of groups working together, such centralization is far less common for the monitoring of water quality. The scenario in the United States is not atypical, with the responsibility for monitoring water quality split between many programs, and the resulting information fragmented into many different incompatible databases. One database keeps track of permits for releasing chemicals into water bodies (the National Pollutant Discharge Information System); a second keeps track of toxic releases into the ground or surface water (the Toxic Release Inventory); a third records the results of mandatory periodic monitoring of public water systems (the Safe Drinking Water Information System); and a fourth samples water bodies for pollutants (the U.S. Geological Survey). Thus, it is extremely difficult to track a chemical released in one location to water ingested in another.

Currie et al. (2013b) examined the effects of chemical violations of drinking water quality standards in New Jersey from 1997 to 2007. Their data enabled the comparison of infants potentially exposed to contaminated drinking water in utero to siblings who were not. Using birth weight and gestation as outcomes, they found small effects of drinking water contamination for all infants, but large and statistically significant effects for infants born to less educated mothers. A potential explanation for this difference is that more educated mothers are more likely to be aware of the pollution and to take avoidance measures (Graff Zivin et al. 2011).

Troesken (2008) and Clay et al. (2010) look at the historic impact of lead from water pipes on infant health. In order to identify effects, both papers use the fact that in places where the water is more acidic, more lead leaches into drinking water from the pipes. The

[11] The Greenstone and Hanna paper mentioned earlier looked at the effects of water pollution regulation, but since they did not find any evidence of a first stage effect of regulation on pollution levels, it is not surprising that they found no effect of the regulation on health.

papers show that although the installation of public water systems with lead pipes reduced deaths from disease, in many locations they increased infant deaths due to lead poisoning.

The paper by Brainerd & Menon (2012) examines the impact of the runoff of agricultural chemicals into water supplies in India. The effects of the chemicals are identified using regional variations in crop cycles and rainfall. They find significant effects of this type of water pollution on infant mortality, child height-for-age and other measures. Similar to Currie et al. (2013b), they find larger effects among poorer households, which again is consistent with the idea that poorer households are less likely (or less able) to take measures to avoid pollution.

IV. Conclusions

The research reviewed in this survey was motivated by two broader literatures spanning several academic fields. The first suggests that events in early life have effects that reach into adulthood. The second demonstrates that pollution, and especially discrete episodes of intense pollution such as the "London Fog" of 1952, has significant effects on health. Putting these observations together led researchers to probe this relationship directly. Does early-life exposure to pollution have long-term consequences later in life? The studies reviewed here provide strong evidence that they can. Like all good social science research this realization leads to a further set of questions:

First, can we identify threshold levels of particular chemicals that are "safe" for fetuses and young children? There is a preponderance of evidence that high levels of pollution (either historically in developed countries, or currently in developing countries) are harmful. A particularly important question for policy is whether there is a safe level of these substances. A more subtle issue is that the thresholds may differ across groups. For example, children in developing countries may react more negatively to a given dose of

pollution if they are already weakened due to other health shocks. Conversely, in an environment where the selective pressures of a hostile environment imply that only the strongest survive, a given dose of pollution could have milder effects.

Second, can we identify factors that protect against or exacerbate the effects of exposure? As we have stressed above, the extent to which parents are able to avoid exposure has important implications for the interpretation of the estimated effects of pollution. Whether parents can affect long run outcomes by remediating or exacerbating these early effects is similarly important.

Third, can we provide more evidence about how the effects of early life exposure to pollutants affect not only health, but other important economic outcomes such as education, labor force participation and earnings? Our survey of the literature suggested that relatively little has been done in this regard, particularly those that directly examine the long-run impacts of pollution exposure in early life. Quantifying effects on these outcomes is important for policy analysis.

Given the potentially long-lasting consequences from early exposure to pollution, the marginal returns to pollution control may be particularly high for this vulnerable segment of the population. As economists extend their reach into this arena and shed light on these key questions, this will better inform policy makers who must make significant decisions regarding the different approaches to pollution control. Together, they comprise an exciting and important research agenda.

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Table 1: Studies of air pollution and long term outcomes

Paper / Country / Source of Variation	Methods	Data/Size	Outcomes
Almond et al. (2009) Sweden Chernobyl Disaster	OLS approach is used to measure outcomes of those exposed against a number of comparison groups. Additionally, a D-in-D approach was used to examine compensatory behavior effects on impacted children. Both approaches include a wide set of controls.	Outcomes (birth, health, school, & hospitalizations) data on Swedish birth cohorts from 1983-1988 are linked with radiation data collected from ground monitors and a country wide aerial survey of ground deposition in 1986. Analysis is at the child level. There are >500k observations used with the aerial exposure data, and ~170k when in situ measurements are examined.	Significant reductions of 2.5 percentile points for average grades, and 6% for math grades measured in secondary school for children most highly exposed to fallout in utero (ages 8-25 weeks). Impacts strongest among those likely to have faced higher exposure levels and to children of low income parents. No corresponding long-term health effects are found.
Bharadwaj et al. (2013) Chile Variation in ambient pollution during gestational development is used for identification	4th and 8th grade test outcomes are regressed on mean ambient pollutant levels in each of the 9 months of gestation and a large number of controls and fixed effects. Controls for monthly weather during gestation are included, as are mother demographic controls and community and gender fixed effects.	Test scores - in math, science, and language arts - for approximately 600k children are linked to monthly average pollution in the Santiago Metropolitan Region during each month of gestation. Pollution and weather data are taken from the Ministry of Environment and the NOAA summary of the day respectively, while test scores and child/family data are provided by the Chilean Health Ministry.	A 1 SD increase in Ozone levels during the 3rd month of pregnancy leads to 0.0025 and 0.00173 SD reductions in 4th grade math and language test scores respectively. Effects are broadly similar for 8th grade test performance.
Currie et al. (2013b) United States Differential in utero exposure to drinking water contamination violations between siblings is used for identification	A number of later life outcomes (IQ, height, years of education, high school completion and earnings at 35) are regressed on potential fallout exposure in municipality of mother's residence during weeks 8-16 of the pregnancy, as well as a number of parental and child controls, and municipality and month of birth fixed effects. Other specifications also include municipality trends, family fixed effects, and two measures of fallout included simultaneously.	Later life outcomes for ~400k individuals in the birth cohorts of 1956-1966 are linked to measurements from 13 fallout test stations to estimate monthly fallout levels (measured in the air and deposited) by municipality (for those within 20 km of a test station) while individuals were in utero.	1 SD increase in ground exposure is associated with a 0.025 SD decrease in IQ score, ~0.15 fewer years of education, and 0.1 to 0.25 log point reduction in earnings at age 30. Even wealthy families are unable to avoid such impacts. Largest in utero effects are found for exposures during weeks 8 to 16.
Isen et al. (2013) United States Differential changes in TSPs by county due to non-attainment status under the Clean Air Act Amendments of 1970	Non-attainment status of counties is assigned based on observed TSP levels, and is then used to instrument for a large change in TSP in counties identified as non-attainers. A difference-in-differences analysis is then run comparing changes in outcomes to those born in non-attainment vs. attainment counties before and after the 1971 implementation of the 1970 CAAAs. Regressions are weighted by # of workers.	Earnings records for 24 states from 1998-2007 - from the Longitudinal Employer Household Dynamics File - are merged with county and date of birth, and county level annual average and 2nd max observed TSP levels. In total, ~900k individuals are included in the analysis in 888 county/year observations.	A 1% increase in annual salaries of workers aged 29-31 is attributed to a 10μg/m3 unit decrease in TSP during pregnancy and early childhood. Most of this effect is due to increased workforce participation. The CAAA of 1970 lead to an average increase in lifetime earnings of $4,300 for the 1.5 million children born in non-attainment counties each year.

Table 1: Studies of air pollution and long term outcomes – Cont'd

Paper / Country / Source of Variation	Methods	Data/Size	Outcomes
Nilsson (2009) Sweden Geographic variation in reduction of lead levels due to phase out of leaded gasoline	OLS regressions are estimated for many outcome variables, regressing the outcome on lead exposure, an exceedingly rich set of parental, child, and municipality specific characteristics, and finally fixed effects for year of birth and municipality of birth. Conditional on the municipality fixed effects parental outcomes are not predictive of a child's lead exposure.	Ambient lead levels for 1,000 locations around Sweden in 1975, 1980, and 1985 from moss samples are aggregated to provide municipality-level estimates of lead exposure. This data is linked to socio-economic and outcome variables for children born in the 3 years preceding each of the lead samples. Outcomes examined include high school GPA and test scores, high school completion and educational attainment, labor market earnings and teenage motherhood. Sample sizes range from ~250k to ~800k individuals.	A significant and non-linear relationship is shown between municipality air lead levels in early childhood and young adult outcomes. Significant improvements in young adult outcomes were found for the reduction in air lead levels obtained between 1972 and 1984 in Sweden, but no significant effects of further reductions were found below estimated blood-lead levels of 5μg/dL. Study also finds that low-SES children are affected more for any given amount of lead exposure, and that this effect is not solely due to residential segregation.
Reyes (2007) United States State specific reduction in lead exposure due to 1970 Clean Air Act removal of Lead from gasoline	The implied first stage is supported with OLS regressions showing that gasoline lead and air lead are good predictors of child blood lead. The main specification is a state-level regression of logged per capita crime rates (violent, property, and murders are run separately) for the years of 1985-2002 on effective lead exposure (estimated from gasoline lead levels during ages 0-3 of the average age of arrested cohorts), state dummies, and a large number of additional covariates that might be thought to impact crime rates.	Creates state-year Lead exposure estimates from EPA monitor data and measures of Lead per gallon of gasoline by state and year from DOE and private annual reports. Exposure estimates are linked to crime and National Health Survey data by state and year. The 918 observations include 50 states plus D.C. for 1985-2002, and are weighted by population in the analysis.	A significant relationship between lead exposure in childhood, and violent crime rates later in life is demonstrated with an estimate of 0.8 for the elasticity of violent crime to childhood lead exposure. ~56% of the drop in violent crime observed in the U.S. in the 1990s can be attributed to reductions in lead exposure during the 1970s. The effects are focused on violent crimes.
Sanders (2012) United States Early 1980s Recession and related drops in manufacturing employment	OLS and 2SLS link changes in year of birth average TSP at the county level and changes in average performance on a 10th grade standardized tests at the school level. TSP measures are used both directly, and also instrumented using county-level employment changes in manufacturing. School-level and year-of-birth-by-year-of-test fixed effects are included as well as controls for school-level student characteristics, county-level weather, and economic/demographic characteristics in year of birth and year of test. In the IV specification where manufacturing jobs are used to instrument for TSP, county-level income is also instrumented using national crude oil prices.	TSP measures from EPA monitors are aggregated to the county-year level for 1979-1985, and merged with weather data from the Global Surface Summary. Employment, income, population, and density data are added from the Regional Information System, and test scores for 1994-2002 10th grade cohorts are provided from the Texas Education Agency. Sample sizes are ~100k students per year born in 1979-1985 at 416 schools in 30 counties.	OLS regressions suggest that a 1 SD reduction in TSP during the year of birth is associated with a 2% of a SD increase in 10th grade test scores. The IV estimates yield a 6% of a SD increase in test scores (and a 3% increase in county passing rates) from a 1 SD reduction in TSPs.

Table 2: Studies of air pollution, fetal health, and infant mortality

Paper / Country / Source of Variation	Methods	Data/Size	Outcomes
Arceo-Gomez et al. (2012) Mexico Week-to-week meteorological covariation with cyclical air pollution changes is used for identification	Weekly levels of pollution and infant death by municipality in Mexico City are analyzed using municipality fixed effects. Main results are IV using # of days of inversion layer per week to instrument for air pollution. An additional inversion is associated with 3.5% increase in PM and 5.4% increase in CO.	For the period from 1997-2006, weekly average levels of pollution, infant and neonatal mortality, and number of inversions are calculated for each of Mexico City's 56 Municipalities. Pollution values are interpolated from observations at 10-26 stations (depending on availability) and inversions are ID'd in Ministry of the Environment data.	1ppb more CO leads to .0032 more infant deaths per 100,000 births, and 1 extra μg/m3 results in 0.24 more infant deaths per 100,000 births. PM_{10} effects are similar while the CO impacts are larger.
Agarwal et al. (2010) United States Variation in chemical releases is utilized for identification	A WLS approach regressing county demeaned outcome variables on concentrations of toxic releases, time fixed effects, and controls for parental and county level covariates.	Annual Toxic Release Inventory (TRI) data on toxic chemical releases by manufacturing site are aggregated to the county level and merged with county level infant fetal mortality rates in the United States for 1989 to 2002. >40,000 county/year observations , of which ~4000 have air pollution data allowing controls for ambient PM_{10} and Ozone levels.	Reductions of annual toxic chemical releases are estimated to have lead to approximately 11,694 saved infant lives over the study period, which the authors estimate (using a $1.8M < VSL <$8.7M) provided a cost savings of $21B to $101B.
Currie et al. (2013b) United States Differential in utero exposure to drinking water contamination violations between siblings is used for identification	Difference-in-difference is used to link changes in TSP levels to infant health outcomes, comparing changes in infant mortality between non-attainment counties and others. Additionally, the analysis uses non-attainment status as an instrumental variable for TSP declines from 1971 to 1972, and a regression discontinuity comparison is made of counties just above and below the non-attainment threshold.	County-level data on infant health, air pollution, and other characteristics for the period from 1969-1974. Data comes from the National Mortality and Natality Detail Files, the EPA, the Bureau of Economics Analysis, and the Regional Economics Information System. A panel of 501 counties is created for the analysis.	The majority of TSP reductions occurred in non--attainment counties. A 1% reduction in ambient average TSPs in a county led to a 0.5% fall in the infant mortality rate in the county.
Chay and Greenstone (2003b) United States 1981-82 recession and resulting differential reductions in TSPs between counties	First differences are used to identify effects from cross-county, intra-state variation in pollution reductions due to the recession taking into account a rich set of covariates. Counties with "large" and "medium" changes in TSPs are also compared separately to counties with "small" changes to investigate non-linearity of health impacts from TSPs.	Data from the Census, Bureau of Economic Analysis, National Mortality Detail Files, and National Natality Detail Files are merged and aggregated to the county level. Observations were then matched with EPA monitor data which provided approximated 1200 county-years of data between 1978-1984.	One percent reduction in TSP levels is associated with a 0.35 percent reduction in infant mortality at the county level. Nationwide, this suggests that the recession lead to ~2500 fewer infant deaths during the years of 1980-1982. Health effects are non-linear in TSP exposure.

Table 2: Studies of air pollution, fetal health, and infant mortality – Cont'd

Paper / Country / Source of Variation	Methods	Data/Size	Outcomes
Coneus and Spiess (2010) Germany Cross time and location variation in pollutant levels used for identification	Mother Fixed Effects models with year-zip code effects as well as limited sets of covariates are estimated for a number of health outcomes for both infants and 2-3 year olds ."Indoor air pollution" proxied for by cigarette use. Models are estimated for pollution at birth, during pregnancy, and for latent values during pregnancy and longer term exposure variables for the older children. Outcome variables include a number of physical developmental measures and illness indicators. Observation level is child/quarter.	Data from the German Socio-Economic Panel (SOEP) on socio-economic conditions and health of newborns and 2-3 year olds in the birth cohorts from 2002-2007 is merged with data on total-pregnancy, trimester-specific, at-birth, and first-year-of-life pollution levels from observations of the 5 pollutants of interest from Germany's Federal Environment Agency. Cohort sizes are ~1100 newborns and ~700 2-3 year olds per year.	CO has negative impacts on birth and health outcomes (esp. in 3rd trimester). High exposure to CO leads to a 289g lower birthweight. Marginally significant results for Ozone and high levels of NO_2 and SO_2 through pregnancy. In utero exposure to PM_{10} is not found to have negative impacts. Ozone exposure at a young age is correlated with negative health outcomes - such as a 0.70 % increase in bronchitis with a one unit increase in the 3-year average O_3 level - as is exposure to PM_{10} (although less robustly), while no clear relationships are found between early-life CO, SO_2, or NO_2 exposure and the health outcomes studied.
Currie et al. (2011) United States Superfund site cleanup	Difference-in-Differences analysis comparing the change in birth outcomes before and after Superfund site cleanup for mothers within 2 km of the site to mothers between 2 and 5 km of the site. A broad set of mother and child covariates are included and site-level or zip-code fixed effects are also included in some specifications. Additional analyses are run for a subset of the most contaminated Superfund sites.	Florida, Michigan, New Jersey, Pennsylvania, and Texas births between 1989 and 2003 with mother addresses within 5 km of a Superfund site that was cleaned up. 154 sites are included in the analysis providing ~600k mothers in the sample, of which ~92k lived within 2 km of a cleaned up site.	Following clean ups, significant reductions (from 20-25%) in congenital anomalies to mothers living within 2 km of a site are observed. Also, when only a subsample of the most contaminated sites is used, significant (4.5 deaths per 1,000 live births) reductions in infant death are found across specifications, authors note this result seems too large and may be due partly to sorting.
Currie and Neidell (2005) United States Inter-temporal variation in pollution and infant health are used to identify effects	Pollution levels are assigned to zip codes by weighting monitor averages for monitors within 20 miles with the inverse of the monitor's distance to the zip code center. A discrete-time hazard model is estimated with a linear spline in duration and pollution exposure measures for all 3 pollutants at 1, 2, 4, 8, 12, 20, and 32 weeks of life. Infant death is also regressed on these pollution measures as well as average measures of pollution in each trimester, gestational age, birth weight, demographic controls, and zip code/month fixed effects. OLS models which include large numbers of covariates, are estimated for fetal death and low-birth-weight outcomes.	California EPA monitor data is used to create weekly ZIP code averages of ambient pollution levels which are merged with weather data from the National Climatic Data Center, and health data on births from pregnancies that reach 26 weeks gestation from the California Birth Cohort files for 1989-2000. In total, 4,593,001 children are in the sample. Each week of life is treated as a separate observation yielding ~250 million observations for analysis.	A 1 unit reduction in CO leads to 2.89 fewer deaths per 1000 live births, leading to ~991 fewer infant deaths in CA attributable to the drop in CO over the 1990s. Results are robust in regional and age-specific subsamples, as well as to the omission of prenatal exposure measures, and broader temporal baskets. Leads and lags analyses also suggest harvesting is not significant. Authors do not find compelling evidence of pre-natal exposure effects.

Table 2: Studies of air pollution, fetal health, and infant mortality – Cont'd

Paper / Country / Source of Variation	Methods	Data/Size	Outcomes
Currie et al. (2009b) United States Changes in pollution levels are relied upon for identification	OLS estimations of average exposure to the three pollutants of interest during the 3 trimesters of pregnancy are made controlling for weather, mother's characteristics (including whether and how much the mother smoked), and child gender. Similar models are also estimated with monitor/quarter fixed effects and mother fixed effects. An OLS hazard model is estimated for probability of infant death in the weeks after birth with similar controls to the above, plus birth weight classifications and a linear spline in weeks since birth. Analysis is also done separately for children with smoking mothers.	1989-2003 New Jersey Department of Health data on births and deaths for infants of mothers with addresses w/in 10 km of a pollution monitoring station are merged with observed pollution levels from the nearest station. There are 628,874 observations in the baseline sample, 283,393 in the mother fixed-effects sample, and 61,996 children in the smoking mothers sample.	Negative impacts of 3rd trimester exposure to CO are found across specifications (with a one unit increase in CO during the 3rd trimester leading to an average birth weight reduction of 16.65g). Results are inconsistent and less significant for PM_{10} and O_3. The negative effects of CO exposure continue after birth in the infant sample with a 1 ppm decline in avg. CO levels in the first 2 weeks after birth leading to 0.18 fewer deaths per 1000 live births. The negative impacts of CO are found even at low levels of ambient CO.
Currie and Schmeider (2009) United States Inter-year, within county variation of toxic releases is used for identification	Effects of toxic chemical releases (weighted by county area) into the air are assessed on birth weights, gestational ages, and infant mortality. Individual regressions are run for each outcome variable against All Toxic releases, chemicals id'd as affecting development, and those not, VOCs, heavy metals, and a number of individual toxics. A broad set of county-level controls are employed including county and year fixed effects. Similar analyses are also done comparing fugitive to stack toxic emissions.	~5200 county/year observations are created with Birth and Infant health data for births in the first 3 months of the year from the Vital Statistics Natality data. This is merged with the prior year's EPA Toxic Release Inventory data as well as a rich set of county level demographic and socioeconomic controls. The California Office of Environmental Health Hazard Assessment's list of known developmental toxicants is used in some specifications to ID toxicants of interest.	Significant, but small-magnitude, negative effects are found for releases of a number of toxics on gestation, birth weights, and probability of infant death. Reductions in the emissions of toluene, lead, and cadmium account for ~4% of the reduction in infant mortality that occurred in the late 1980s and 1990s. Fugitive emissions have larger effects. Results are much stronger for toxics thought to have developmental effects.
Currie and Walker (2011) United States Introduction of Congestion Reducing Automated Toll Payment Systems	A difference-in-differences approach is used comparing changes in birth outcomes (low-birth weight and prematurity) of mothers living w/in 2 km of a converted toll plaza to changes in birth outcomes of mothers living between 2 km and 10 km of a toll station and within 3 km of a major freeway. Similar pre-trends are demonstrated between treatment and control groups. Regressions control for mother's race, age, and education level, multiple births, and child's gender. Plaza, year, and month fixed effects are also included.	Location and date of opening of E-ZPass toll plaza conversions is linked to Vital Statistics Natality records for mothers living near toll plazas in New Jersey and Pennsylvania for the years of 1994-2003 and 1997-2002 respectively. The sample consists of mothers living within 10 km of 98 toll plazas yielding ~30k birth observations before and after conversion in the treatment group, and >150k observations before and after conversion in the control group.	Significant reduction in prematurity and low birth weight births of 8.6% and 9.3% respectively are associated with the conversion of toll plazas to the EZ-Pass systems. Authors show no significant differential shift in housing prices near converted toll stations, suggesting that sorting isn't occurring in the short term. Results are robust for non-smokers, smaller "treatment" and "control" areas, and to mother fixed effects. Effects are much stronger among African-American mothers.

Table 2: Studies of air pollution, fetal health, and infant mortality – Cont'd

Paper / Country / Source of Variation	Methods	Data/Size	Outcomes
Foster et al. (2009) Mexico Certification of businesses under Mexico's Clean Industry Certificate program	Estimated air quality and infant health outcomes are separately regressed onto a variable that captures the fraction of firms within a municipality that have been certified by a given month. Municipality and month-year fixed effects, and both time varying municipality controls and the square of a number of time invariant municipality characteristics are also included. There are only 94 auditors that can grant certification, and distance to these auditors is used as an instrument for certification.	Daily air quality estimates for all of Mexico are created from Aerosol Optical Depth (AOD) measurements in the MODIS satellite data. AOD estimates are aggregated to the monthly-municipality level, and merged with estimated temperature and dew-point controls, infant mortality data, firm and employment data, and Clean Industry Certification awards. 1,706 municipalities are the focus of the analysis over the period from 2000-2006, yielding ~32k observations.	Authors estimate that certification of all firms in a municipality would lead to a 3.6% improvement in AOD and a 16% reduction in respiratory related infant mortality. These results are combined to suggest that a 1% increase in AOD leads to a 4.4% increase in infant mortality due to respiratory ailments.
Greenstone and Hanna (2011) India Implementation of pollution control policies	Pollutant levels (and later infant mortality rates) are regressed on a vector of dummies for years when each policy was in force, city and year fixed effects, and consumption and literacy controls. 3 additional specifications are run to test for whether yearly average pollution levels (estimated in the first specification) are affected by policy implementations.	1987-2007 air pollution data from a total of 140 cities and 1986-2005 river water monitor data for 162 rivers from India's Central Pollution Control Board is merged with a city-year dataset on pollution regulations, and city-year infant mortality and socio-economic data.	Air pollution regulations reduced average ambient levels of particulates (by 19%), SO_2 (by 69%), and NO_2 (by an insignificant 15%), but led to statistically insignificant improvements in infant mortality. The water pollution regulations investigated showed no statistically significant effects on pollution or health.
Janke et al. (2009) United Kingdom Inter-temporal pollutant level variation used for identification	Various mortality rates are regressed on annual levels of the 4 pollutants, a moderate number of time-varying local authority covariates, a time trend, region specific time trends, and a local authority fixed effect.	Pollution monitor data for 1998-2005 from a number of sources is aggregated to annual averages at "local authority" level, and then linked to mortality data at the authority/year level over the same period. ~2300 authority/year observations are used in the analysis.	A 10 μg/m3 increase in PM_{10} is associated with an increase in death rate of 4 per 100,000 among those under age 15 (on a mean mortality rate of 44 per 100,000). Other pollutants are not found to have significant impacts on child mortality.
Jayachandran (2009) Indonesia 1997 wildfires on the islands of Sumatra and Kalimantan	Regress of the natural log of district/month cohort sizes on measures of smoke at (the month of), before (the 3 months prior to), and after (the 3 months subsequent to) birth as well as birth month/year and sub-district fixed effects. Dates of analysis were chosen to avoid fertility effects the fires might have had.	2000 Indonesian Census data, with analysis by birth-month-cohorts for December 1996 to May 1998 for 3,751 Indonesian sub-districts. There are ~67k children in these ~700 cohorts. The median monthly values of daily air pollution is proxied by aerosol measures from the Earth Probe Total Ozone Mapping Spectrometer mapped onto sub-districts.	Pollution from fires led to a 1.2% decrease in cohort size among children in the third trimester of pregnancy during the 5 month period of the fires. This implies 15,600 fetal, infant, and child deaths are attributable to the fires, a 20% overall increase in under-3 mortality. Results are more pronounced among boys, and among lower income households.

Table 2: Studies of air pollution, fetal health, and infant mortality – Cont'd

Paper / Country / Source of Variation	Methods	Data/Size	Outcomes
Knittel et al. (2011) United States Weekly variation in ambient pollution (instrumented) and infant mortality is exploited for identification	Strong links between traffic congestion and pollution are demonstrated. The three pollutants of interest are instrumented using traffic congestion interactions with weather conditions. The main specification is a discrete time hazard model estimated as a linear probability model using person-week observations which controls for age in weeks with a flexible spline. Analysis is done separately for the 1989-2000 and 2002-2007 periods in order to assess whether lower pollution levels have different health effects.	1989-2000 and 2002-2007 ambient air pollutant levels, weather conditions, and traffic densities are merged and aggregated to the zip code-week level for much of Central and Southern California. Infants are assigned to a zip-code and are tracked weekly through the first 52 weeks of life, yielding a sample of ~150 million infant/weeks during the early time period and ~75 million observations in the later period.	A one unit reduction in PM_{10} leads to 18 fewer infant deaths per 100,000 live births. There is ittle evidence of stable impacts from CO or Ozone.
Lüchinger (2010) Germany Mandated installation of SO_2 scrubbers on power plants	Difference-in-Differences comparison of the treatment - installation of a sulfur scrubber on a power plant - is made across treatment and control groups made up of counties which are downwind and upwind of power plants. The frequency of days downwind from a plant in a given year is used to weight the "treatment" group. In addition to wind direction, treatment levels for a county are determined by scrubber installation, plant size, and plant distance from each county.	1985-2003 Infant mortality data is linked to annual monitor-level mean SO_2 levels and aggregated to the county level. Power plant characteristics and scrubber installation data is available for all 303 fossil fuel plants with capacity >100 megawatts during the time period of interest, and monitor collected wind data is linked to each plant. ~7500 county-year observations are used for the main analysis.	Instrumenting for pollution changes leads to higher estimates of the effects of SO_2 on infant mortality than OLS. The author finds an elasticity of 0.08-0.13, which suggests that the reduction of SO_2 observed over the study period has led to 895-1528 fewer infant deaths annually in Germany.1/3 of the infant mortality effects of higher SO_2 exposure are realized in the first day after birth, and 50-80% of the effects during the first month outside the womb.
Sanders and Stoecker (2011) United States 1970 Clean Air Act Amendments (CAAAs)	Regression discontinuity at the time of CAAAs implementation is implemented via a County-level, first difference model with state fixed effects, which is estimated with the change in pollution from 1970 to 1972 instrumented by county estimated nonattainment status. The outcome examined is the ratio of male to female live births; male fetuses are more susceptible to in utero insults. Thus increased shares of male live births suggest fewer fetal deaths. A large number of county-level covariates are included as controls, including TSP level in 1970.	Birth data from the National Center for Health Statistics Vital Statistics Micro-data is merged with EPA measures of ambient TSPs and aggregated to the county-year level. This yields 281 counties with full desired data, representing 50% of live births. First difference is calculated on changes from 1970 to 1972.	Children are more sensitive to exposure to TSPs in utero than post birth. Overall it is estimated that a 1 unit increase in annual average TSP ambient pollution leads to a 0.088 point change in the probability of a birth being male. This suggests that the CAAAs lead to a 3.1% change in probability of a male birth, and an estimated 21,000 to 134,000 avoided fetal deaths in affected counties (which is 2 to 13% of total births).

Table 2: Studies of air pollution, fetal health, and infant mortality – Cont'd

Paper / Country / Source of Variation	Methods	Data/Size	Outcomes
Sneeringer (2009) United States Identification arises from spatial variation in livestock operations due to farm consolidations	Unit counts of livestock are used to proxy for pollution from livestock farming. An OLS regression run for health outcomes on # of livestock in a county and a large number of time-varying county covariates capturing: demographics, population and housing characteristics, weather controls, industrial concentrations, Clean Water Act permits, and other attributes. Year, county, and state fixed effects are also included in the model.	Livestock-by-county information is taken from a proprietary source based on NRC data from the 1982, 1987, 1992, and 1997 Agricultural Censuses, and merged with Restricted-use birth and death records from the National Center for Health Statistics for 1980-1999. Additional county-level controls are taken from a variety of other sources. Ultimately, 9,223 county-5-year-period observations are used, based on ~75M total births.	123 more deaths of infants <1 year old and 100 more deaths of infants <28 days old per 100,000 live births result from an increase of 100,000 animal units in a county. The average annual unit increase from 1982 to 1997 (for counties with increases) was 35%, suggesting a 2.8% increase in infant mortality in these counties, or a total of 3,500 additional infant deaths in the U.S. over the time period. Effects are connected to air rather than water pollution through a number of findings.

Table 3 - Panel A: Studies of air pollution and child health

Paper / Country / Source of Variation	Methods	Data/Size	Outcomes
Beatty and Shimshack (2011) United States School bus emissions reductions	Authors first use a 2 period D-in-D specification where changes in health outcomes (from 2002 to 2006) in districts that had significantly retrofitted their bus fleets by 2006 are compared to health outcomes in districts that hadn't yet begun retrofits. The second specification is a month by month D-in-D (with month, year, and district dummies) comparing before and after periods (variously defined by a school reaching a number of different retrofit thresholds). All specifications control for a small number of district and weather covariates. Economic and weather controls as well as county and state/year fixed effects are also included in the regressions.	Washington State data on bus retrofit program adoption (state funded) from 53 school districts (with ~4000 total buses) is linked to hospital discharge data for 1996-2006 and Census demographic data. Then everything is aggregated to the School District-month level with a total of ~5830 observations for analysis.	Preferred estimates demonstrate that school districts that adopt emissions reducing retrofits on their school bus fleets experience 23% fewer bronchitis and asthma cases, and 37% fewer children's pneumonia cases per month. Results are attributed to within bus exposure to bus emissions.
Lavaine and Neidell (2013) France Temporary shutdown (due to strikes) of oil refineries	Pollution exposure of admitted patients is estimated, and then census tract respiratory hospital admissions are regressed on this exposure measure weather controls and tract, month, and year fixed effects. Since exposure is endogenous, it is instrumented using an indicator for whether the census tract is close to a refining facility affected by strikes, and whether the month is October 2010 (when the strikes were in force).	Respiratory hospitalizations data from the French National Hospital Discharge Database is merged with pollution, weather, and socioeconomic data. After dropping tracts and refineries for which key pieces of data are missing, 3,100 French census tracts are left with data for 2007-2010.	Authors find that SO_2 levels well below current quality standards lead to significant health impacts, especially among the at-risk populations of the elderly and the young. A one month, 1 μg/m3 decrease in SO_2 concentrations leads to a 5 gram increase in avg. birthweights and a 0.18 day increase in gestational age. Impacts appear to be strongest during the third trimester.

Table 3 - Panel A: Studies of air pollution and child health – Cont'd

Paper / Country / Source of Variation	Methods	Data/Size	Outcomes
Currie et al. (2013b) United States Differential in utero exposure to drinking water contamination violations between siblings is used for identification	Uses exogenous location assignments of army personnel and the uniform nature of housing/services across Army bases to identify contemporaneous effects of 5 pollutants on child hospitalizations. A linear probability model is estimated for whether a child was hospitalized in a given year based on levels of the 5 pollutants, weather controls, child characteristics, base fixed effects and base/year characteristics, and father's rank/occupation/year fixed effects.	Annual Individual level data on all enlisted men stationed in the Continental U.S. from 1988-1998, and hospitalization data (including condition) for all their wives and children, is linked (via Kriging methods) to annual EPA and weather data. This provides 159,275 annual observations of children 0-5 years old and 44,663 of children under age 1.	No impacts are found for children age 0-1 year old. For children 2-5 years old, increased probabilities of respiratory hospitalization are associated with higher levels of O_3 in all samples, and CO also contributes significantly for children of families that didn't move in a given year. A one SD increase in O_3 levels leads to an 8-25% increase in the likelihood of respiratory hospitalization among children ages 2-5, implying an elasticity of 0.5 to 1.5.
Neidell (2009) United States Smog Alerts	Assesses whether behaviors change when an Ozone Alert occurs using a regression discontinuity approach, regressing log of attendance at the outdoor attractions on an indicator for a local Ozone, a function in forecast ozone levels, controls for weather and other air pollutants, and indicators for holidays, summer schedule, and day of week. A similar regression is run with the outcome variable of asthma hospitalizations (by age), and also includes interactions of lagged ozone forecasts and levels, as well as indicators for Ozone alerts.	Daily attendance data for two outdoor attractions (the LA Zoo & Griffith Observatory) for 1989-1997 is merged with hospital discharge data, weather data, and data on both predicted and actual ozone levels in 10 Air Monitoring Zones in the Los Angeles area.	People respond to public information about pollution by spending less time outside. Ignoring avoidance behavior understates the negative impacts of pollutants (specifically Ozone) on health outcomes of the young and elderly. A 0.01 ppm increase in the 5-day Ozone levels increases child hospital admissions by 1.09%, but when smog alerts are controlled for, this jumps to a 2.88% increase in such child hospital admissions.
Neidell (2004) United States Intra-zip code variation in seasonal air pollution levels is used for identification	Zip code-month ER admissions for asthma are regressed on contemporaneous measures of four air pollutants, the number of air quality episodes (a proxy for avoidance behavior), a number of covariates (including weather), and dummy variables for each zip code- year and year-month. Model is estimated separately for each of 5 age groups in the 1-18 age range.	Zip code level data for California is aggregated for hospital discharges due to asthma for ages 1-18, weather monitors, and air pollution monitors for the period of 1992-1998. Demographic, home values, and Ozone alerts data is also used. This provides ~50,000 zip code-month observations for analysis.	CO has e a significant effect on asthma for kids 1-18. If 1998 levels of CO were at their 1992 levels, 5-14% more hospital admissions due to asthma would have been expected. Avoidance behavior significantly reduces the negative effects of air pollution. Negative air pollution effects are larger among children of lower socio-economic status.
Ransom and Pope (1995) United States Temporary closure of steel mill in Utah	A difference-in-differences approach comparing logged health outcomes in a valley with a (intermittently shut down) steel mill to logged health outcomes in a nearby valley (with no mill) is used with negative binomial regression models. Regressions include seasonal controls, but few other covariates.	Data on local counts of daily deaths and hospital admissions (including reason for admission) for individuals living in two distinct valleys in Utah (the Utah and Cache Valleys) is linked to data on the temporary 13-month closure of a large steel mill (due to a labor dispute) in 1986 and 1987.	Hospital admissions for respiratory ailments increase significantly when the mill was open (relative to the control). Admissions due to bronchitis and asthma nearly doubled among preschoolers in the treatment valley when the mill was open vs. closed (compared to almost no change in the control valley), and resulted in an ~ 60 additional hospital admissions per year in this age group.

Table 3 - Panel A: Studies of air pollution and child health – Cont'd

Paper / Country / Source of Variation	Methods	Data/Size	Outcomes
Reyes (2012) United States Differential rates of declines in leaded fuel usage between states are used for identification	The relationship between blood lead and effective grams of lead in purchased gasoline is determined via a simple OLS regression using the NHANES II data (and a number of individual controls), and the resulting estimates are used to predict (by state, age, year of birth, and a number of other individual characteristics) blood lead levels at age 0-3 for those surveyed in the NLSY. Childhood and young adult outcomes are then regressed (using OLS, probit, ordered probit, or censored tobit depending on the outcome) on this estimated value of blood lead and a vector of individual demographics, as well as dummies for mother's age and birth cohorts.	Individual outcome data on ~10k young adults from the NLSY 79 and NLSY 97 surveys is linked to state-month estimates of effective grams of lead per gallon of purchased gasoline (for the time period when the child was 0-3 years of age), and census data. Additionally, 1976-1980 blood level data from 2,322 children under age 6 from the NHANES II is linked to the grams of lead per gallon measure by state.	Large negative impacts of early childhood lead exposure are found on outcomes including childhood behavioral problems, teenage aggression and pregnancy, and young adult criminal behaviors. The elasticities between these behaviors and lead exposure range from 0.2 to 1.0.
Schlenker and Walker (2011) United States Airport delays at East Coast hubs	Examine effect of pollution from airports on ER visits and hospitalizations for respiratory and heart ailments. Instrument for pollution levels in zip codes near airports with delays at East Coast hub airports (which lead to delays and increased taxiing, and thus increased pollution at the California airports that are the focus of this study). Additionally, wind variation (interacted with East Coast taxiing congestion) is used as an additional instrument for pollution in zip codes near major California airports.	Daily data on air pollution levels, weather, hospital admissions, and ER visits for zip codes surrounding California's 12 largest airports is linked to Department of Transportation data on taxiing time at these airports and 3 major eastern hubs. Zip code direction from nearest airport and wind direction data is also included. Main sample is ~180k day-zip code observations from 2005-2007.	Increased taxiing leads to significant increases in ground-level air pollution near airports. A 1 SD increase in taxiing time at LAX increases CO levels near the airport by 0.32 SDs and 0.23 SDs 10 km from the airport. A 1 ppb increase in CO leads to 0.8 additional daily hospital visits per 10 million children under 5 year due to asthma and 5.5 additional hospital visits among due to all respiratory ailments. The elderly and the young to be more sensitive, but impacts of CO are found across all ages. Significant effects are not found for NO_2 or O_3.
Yu (2011) China Intervention assignment	A number of D-in-D models are estimated. Due to apparent non-random sample selection, assigned treatment and control groups are not the preferred specification. Author employs propensity score matching following Abadie et al. (2001) to better construct matched treatment and control groups. The matching variables are validated following Imbens (2010) and checked using false treatments.	1050 children <5 years of age in rural Chinese households were examined 6 times before and 8 times after the intervention, which was implemented on 3 groups of households. The first received subsidized stoves and a behavioral intervention, the second, only a behavioral intervention, and the third served as a control.	Both interventions were effective in reducing acute incidence of both upper (by 9-23%) and lower (by 1 to 3%) respiratory infections among small children, though the additional intervention of stove subsidization was not found to have significantly better outcomes among children.

Table 3 - Panel B: Studies of air pollution and children's schooling and cognition

Paper / Country / Source of Variation	Methods	Data/Size	Outcomes
Currie et al. (2009a) United States Changes in counts of binned pollution levels used for identification	A triple differences model is employed, holding school, year, and 6-week attendance period characteristics constant to examine the effects of shifts in the # of days in 5 levels bins on attendance for each of the 4 pollutants of interest. School demographic & age characteristics, as well as precipitation and temperatures are controlled for.	1996-2001 Administrative data from schools within 10 miles of a pollution monitoring station from the 39 largest school districts in Texas is merged with ambient pollution data from these monitors. The attendance data from the 1,512 schools is in 6 week blocks at the school level, so hourly pollution data is aggregated to that granularity, resulting in >12million student-attendance period-year observations.	CO levels below the current EPA Air Quality Standards lead to increases in school absences. Specifically, the reduction in high-CO days during the period of the study led to a 0.8 percentage point (on a 3.58% base) reduction in absences, with large impacts for vulnerable populations such as asthmatics. No statistically significant relationship is found between more days with high PM_{10} or Ozone and increased absences.
Lavy et al. (2012) Israel Natural variation of pollution on test days is used for identification	Fixed effects regressions are run of student test scores on contemporaneous weather and pollution variables, with results presented for student, school, and city level fixed effects models. Controls for student and parental characteristics and month and test level fixed effects are also included.	~300k (for $PM_{2.5}$) and ~150k (for other pollutants) test scores from the years of 2000-2002 are matched to contemporaneous pollution and weather conditions. Test scores are from the Bagrut (A high school graduation requirement for academic track). Pollution data is from 139 stations across Israel, assigned to students based on city of test and monitor locations w/in 2.5 km of the city limits.	Higher levels of both $PM_{2.5}$ and CO are associated with lower scores. A $PM_{2.5}$ Air Quality Index (AQI) >100 associated with ~2.5 points less (out of 100) and a CO AQI>100 associated with ~9.5 fewer points scored. This effect is homogeneous for CO, but more intense among groups with higher rates of asthma for $PM_{2.5}$.
Reyes (2011) United States Identification comes from within-school, inter-temporal variation of blood lead levels	Cohort average test scores are regressed on a measure of blood lead (either levels or indicator of # of children over certain thresholds), a broad set of community, district, and school specific controls, and year fixed effects. An OLS regression weighted by cohort size is the main estimation method.	A panel of school-level cohort-year data on 3rd and 4th graders from >1,000 public schools in Mass. between 2000-2009 is created through the aggregation of individual-level standardized test scores and blood level measurements. Additional school and community level controls are gathered from state and federal data sources. ~18k cohort-year observations are used in the analysis.	Blood lead level data from the 1990s coupled with test performance data from the 2000s is used to demonstrate the strong cross-sectional link between childhood blood lead levels and test scores in elementary schools. However, such links are not robust to the inclusion of significant covariates. The lead reduction levels observed over the time period reduced the share of children scoring unsatisfactory on standardized tests by 1-2 percentage points.
Zweig et al. (2009) United States Identification comes from inter-temporal variation of pollution and test scores within cities	Average class test scores by subject are regressed on a number of measures of contemporaneous pollution, controls for time variant average student, family, and school characteristics, city unemployment levels, and school fixed effects. A specification with year fixed effects is also estimated.	Individual, survey data from three cohorts of students from the Children's Health Study (CHS) in 88 Southern Californian schools is aggregated to the class-school-year level and merged with publicly available data on schools, communities, and test scores. These 216 observations are linked to contemporaneous yearly average measures of air pollution for monitors placed by CHS.	A 10% decrease in the ambient levels of PM_{10}, $PM_{2.5}$, and NO_2 led to increased scores on standardized math tests of 0.15%, 0.34%, and 0.18% respectively. Only $PM_{2.5}$ levels are found to contribute significantly to reading scores, with a 10% reduction in the annual average $PM_{2.5}$ level associated with a 0.21% increase in reading scores. Annual Ozone levels are not found to contribute significantly to reading or math scores.

Table 4: Studies of water pollution

Paper / Country / Source of Variation	Methods	Data/Size	Outcomes
Brainerd and Menon (2012) India Temporal and Regional Variation in fertilizer use, leading to differential exposure (via water) to young children of different ages and regions	Statewide measures of waterborne agricultural pollutants in the month of conception are regressed on health outcomes. Levels of non-agricultural water pollutants, a wide range of mother, father, household, and state of residence characteristics are controlled for. Interacted regional and month/year of conception fixed effects are also included. Preferred specification utilizes month/region planting seasons as instrumental variables for the presence of agricultural pollutants.	Estimated State/Month-level water quality date for 1978-2005 is merged with 3 rounds of the Indian National Family Health Survey (1992, 1998, & 2005), yielding in utero pollutant exposure estimates and health outcomes (as well as demographic controls) for ~400k births.	The instrument is validated by demonstrating that average fertilizer levels in water are higher in planting months. A 10% increase in the avg. agro-chemical levels in the water during the month of conception is associated with a 3.52% increase in infant mortality and a 6.65% increase in neonatal mortality. A 10% increase in agro-chemical water pollutants in the month of conception leads to a 0.26 standard deviation reduction in age-five z scores.
Clay et al. (2010) United States Cross city variation from water chemistry and utilization of lead service pipes	An examination of infant mortality and worker productivity using OLS regressions on water pH and interactions of water pH with service pipe materials. A rich set of city characteristic (including water and milk quality and women's suffrage), regional fixed effects, and climactic controls are utilized, and possible selection into pipe choice is addressed by repeating the analysis among lead-pipe-only cities.	City-level mortality, population, and demographic characteristics for 1900, 1910, and 1920 are merged with service pipe and water chemistry data by city from The Manual of American Waterworks, 1897 and The Water Encyclopedia respectively. Ultimately ~200 cities are in the data for each of the 3 years analyzed. Wage estimates by city in 1899 1904, 1909, & 1914 are from the Census of Manufacturing.	In 1900, an all-lead-service-pipe city (~11% of the U.S. population) could reduce infant mortality by 12 to 14% with a drinking water pH reduction from 6.7 to 7.5, (i.e. moving from the 25th percentile to the 50th), ~25% of the decline in infant mortality in these cities from 1900-1920 is attributable to decreased lead exposure. Suggestive evidence is shown that wages were lower in cities with higher lead exposure and higher infant mortality.
Currie et al. (2013b) United States Differential in utero exposure to drinking water contamination violations between siblings is used for identification	Mother fixed effect model is estimated comparing sibling birth outcomes (birth weight & prematurity) from the same mother while controlling for bins of mother's age, mother's race, education level, marital status, and risk factors, as well as child gender, weather controls, and year*month of birth fixed effects. Also estimated are models analyzing characteristics of mothers who move in response to contamination information, and IV models with instrument constructed using mother's initial residence.	1997-2007 Birth outcomes from natality records are merged with records on drinking water contamination violations, temperature and precipitation data, and drinking water service areas for the same time period. Births from multi-child families identified as being part of a water service area are used, yielding 529,565 observations.	It is found that the children of less educated women are much more susceptible to contamination of drinking water in utero, with a 14.55% increased likelihood of low birth weight and a 10.3% increased chance of a premature birth associated with living in a district with contaminated water during the pregnancy.

Table 4: Studies of water pollution – Cont'd

Paper / Country / Source of Variation	Methods	Data/Size	Outcomes
Troesken (2008) United States Differences in lead pipe usage, age of pipes and water chemistry across municipalities is used for identification	Cross sectional regressions of 1900 infant mortality and still-birth rates on an indicator for city usage of lead service pipes as well as a moderate number of city covariates including measures of population, infectious disease environment, and public health infrastructures. City observations are weighted by population. A number of specifications are assessed to try and control for correlation between avoidance of lead pipe usage and a city's unobserved "health consciousness".	Lead service pipe usage for 74 Massachusetts towns in 1900 is merged with age & cause specific death rates, population, water chemistry info, and the share of water mains <10 years old. For 20 of these towns, measured levels of lead in drinking water are also known.	Elimination of lead from drinking water contributed significantly to falling rates of infant mortality in the twentieth century. This paper estimates that the usage of lead service pipes increased infant mortality rates by 25-50%, and that high-acidity water and new lead pipes contributed to even higher effects.
Zhang (2012) China Rollout of treated water in rural villages	Individual health indicators (illness incidence in last month, weight/height, and height measures) are regressed on a village-month level indicator for water from a water treatment plant, a moderate set of individual and household covariates, and region and year fixed effects.	Health and water source data is taken from China Health and Nutrition Survey data from 7 survey waves on 4500 rural households from 152 villages from 1989-2006, and is linked to data (by village) on when water from a treatment plant was available in the town. A town is defined as having plant water when a significant jump in the share of households claiming water plant as their source of water is observed.	Treated water leads to an increase in the weight to height ratio of children (avg. age of whom is 8.9 years) of 0.446kg/m and an increase in height of 0.962cm on average. Lower incidence of recent illness is not detected among children, although the incidence of illness among adults is estimated to decrease by 11% with the introduction of a water plant.