Shale Gas Development and Infant Health: Evidence from Pennsylvania

Elaine L. Hill*

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Abstract

This research exploits the introduction of shale gas wells in Pennsylvania in response to growing controversy around the drilling method of hydraulic fracturing. Using detailed location data on maternal address and GIS coordinates of gas wells, this study examines singleton births to mothers residing close to a shale gas well from 2003-2010 in Pennsylvania. The introduction of drilling increased low birth weight and decreased term birth weight on average among mothers living within 2.5 km of a well compared to mothers living within 2.5 km of a future well. Adverse effects were also detected using measures such as small for gestational age and APGAR scores, while no effects on gestation periods were found. These results are robust to other measures of infant health, many changes in specification and falsification tests. These results do not differ across water source (i.e. public piped water vs. ground well water) and suggest that the main mechanism is air pollution from localized economic activity. These findings suggest that shale gas development poses significant risks to human health and have policy implications for regulation of shale gas development.

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*Hill: University of Rochester School of Medicine & Dentistry, 265 Crittenden Blvd Rochester, NY 14642, elaine_hill@urmc.rochester.edu. I am grateful to the Cornell Population Center for their generous financial support. Thank you to Amy Farrell of Pennsylvania Department of Health for facilitating access to the data. Gratitude to David Sahn, Jordan Matsudaira, John Cawley, Alison Buttenheim, Joanna Upton, Julia Berazneva, Kira Villa, David Goldsmith, Nick Sanders, Reed Walker, Matt Neidell, Seth Berrin Shonkoff, Doug Almond, Chris Timmins, Lucija Muehlenbachs, Alan Krupnick and seminar participants at Cornell University, Columbia University, University of Pittsburgh, University of Maryland College Park, Resources For the Future, PAA 2012, and ISEE 2014 for invaluable comments. A previous version of this paper was circulated as "Unconventional Natural Gas Development and Infant Health: Evidence from Pennsylvania."

1 Introduction

The United States (US) holds large unconventional gas reserves in relatively impermeable media such as coal beds, shale, and tight gas sands, which together with Canada account for virtually all commercial shale gas produced in the world (IEA, 2012).[1] New technologies, such as hydraulic fracturing and directional drilling, have made it economically and practically feasible to extract natural gas from these previously inaccessible geological formations.[2] In 2010, unconventional gas production was nearly 60% of total gas production in the US (IEA, 2012). Natural gas from the Marcellus formation, particularly in Pennsylvania, currently accounts for the majority of this production (Rahm et al., 2013).[3]

The expansion of shale gas development in the US has brought with it a national debate that seemingly lacks a consensus over its economic, environmental, health and social implications. Shale gas has been promoted as a low-cost source of electricity, residential and commercial energy, industrial feed stocks, and even as transportation fuel. Natural gas provides an attractive source of energy because it emits fewer pollutants (e.g., carbon dioxide, sulfur dioxide, nitrogen oxides, carbon monoxide and particulate matter) when burned than other fossil-fuel energy sources per unit of heat produced. As mentioned above, it also comes predominantly from reliable domestic sources and has resulted in many landowners receiving high resource rents for the hydrocarbons beneath their land.[4] There is growing evidence that natural gas development creates jobs and generates income for local residents in the short run (Weber, 2011; Marchand, 2012). Other studies have shown that housing prices for those homes on public water increase in close proximity to

[1]The International Energy Agency (IEA) defines unconventional gas as sources of gas trapped in impermeable rock deep underground.

[2]Hydraulic fracturing (popularly known as "fracking" or "fracing") stimulates the well using a combination of large quantities of water ("high-volume"), fracturing chemicals ("slick water") and sand that are injected underground at high pressure. This process fractures the rock and causes the resource to be released.

[3]Pennsylvania experienced very rapid development of shale gas, with 4,272 shale gas wells drilled from 2007-2010 (PADEP, 2010).

[4]Upon signing their mineral rights to a gas company, landowners may receive hundreds or even thousands of dollars per acre as a bonus payment, and then a per unit (mcf) royalty of gas extracted.

drilling in Pennsylvania and New York, but that perceived risks of ground water contamination reduces housing prices for homes that use well water (Muehlenbachs et al., 2014).[5] The benefits of domestically sourced natural gas have been at the forefront of a public debate, even mentioned by President Obama in his 2012 and 2013 State of the Union Addresses as an initiative of his administration. In addition to its economic benefits, many claim that a move to natural gas development (and away from petroleum-based energy) will support U.S. energy independence and national security.

The focus of the other side of this debate, however, is the potential environmental impacts – and subsequent public health implications– of shale gas development. Shale gas development is currently exempted from the Safe Drinking Water Act, Clean Air Act, and Clean Water Act regulations. Serious environmental and health concerns have nonetheless emerged regarding drilling activity (COGCC & Commission, 2009). The opposition to shale gas development cites recent studies reporting methane leakage (Howarth et al., 2011; Hultman et al., 2011), local air pollution (Litovitz et al., 2013; Colborn et al., 2012; Witter et al., 2013), water pollution (Olmstead et al., 2013; N. Warner et al., 2012; DiGiulio et al., 2011; Osborn et al., 2011; EPA, 2004; DEP, 2009; Lyverse & Unthank, 1988), and increased truck traffic (Considine et al., 2011; ALL Consulting, 2010). Inferring from the environmental concerns, a few recent studies have assessed the potential health effects of unconventional methods using case studies, health impact assessments and toxicology to show that there are likely to be short and long term negative health effects (Bamberger & Oswald, 2012; L. McKenzie et al., 2012; Colborn et al., 2011).[6] While the public health literature has suggested that human health might be affected by exposures to shale gas development,

[5] Gopalakrishnan & Klaiber (in press) found reduced housing prices associated with the introduction of shale gas development in Washington County, PA; the effects fell disproportionately on rural homes that rely on ground water.

[6] These studies do not measure actual health effects, but use other methods to infer the potential for harm to human health. Shale gas development brings with it complex chemicals used in the "fracturing fluid," causing public health concerns of ground water contamination. These chemicals are small in proportion to the quantity of fresh water, but are associated with many negative health effects if ingested or inhaled, such as cancers, nervous system impairment and impaired lung function. See Colborn et al. (2011) regarding health effects of fracturing chemicals; see L. McKenzie et al. (2012) for a review of studies investigating the effects of inhalation exposure.

and there have been numerous anecdotal accounts and suspicions, this is the first study to date rigorously linking shale gas development to human health outcomes.[7]

This paper takes a step toward addressing the gap in the literature by using data that contains the longitude and latitude of all shale gas wells, the street address (geocoded) of all new mothers, and data on whether the mother's address falls within public water service areas to estimate the impacts on infant health of shale gas development. To define a treatment variable, I exploit both the timing of drilling activity (using the "spud date," or the date the drilling rig begins to drill a well) and the exact locations of well heads relative to residences. I then use as a comparison group mothers who live in proximity to future wells, as designated by well permits. The exact locations of both wells and mothers' residences allow me to exploit variation in the effect of gas drilling within small, relatively homogenous socio-economic groups, and the timing of the start of drilling allows me to confirm the absence of substantive pre-existing differences. Through this method, I am able to provide the first robust estimates of the impact of maternal exposure to shale gas development on birth outcomes.[8]

The main results suggest both statistically and economically significant effects on infant health. I find that shale gas development increased the incidence of low birth weight and small for gestational age in the vicinity of a shale gas well by 25 percent and 18 percent, respectively. Furthermore, term birth weight and birth weight were decreased by 49.6 grams (1.5 percent) and 46.6 grams (1.4 percent), on average, respectively and the prevalence of APGAR scores less than 8

[7]There have been a wide range of claims and anecdotal evidence of negative effects on human and animal health, including a wide range of health-related symptoms. For example, Lisak (2013) has compiled a list of 1384 people and families (as of June 2013) who believe they have been harmed by shale gas production in the US. Each person/family listed is associated with details regarding the type of gas facility, the location, the believed exposure (air, water, etc.) and symptoms as well as any media reports related to the individual/family. Other examples include many local media reports and the "Drilling Down" series by Ian Urbina of the New York Times which examines the risks of shale gas development (Urbina, 2011). More recently, researchers from the University of Pittsburgh documented self-reported health impacts and health stressors perceived from shale gas development in Pennsylvania (Ferrar et al., 2013).

[8]Concurrent to this work, Hill (2013) provides the first estimates of the impacts of more general oil and gas development on infant health and finds adverse birth outcomes in Colorado.

increased by 26 percent. No changes in gestation or premature birth were detected. The difference-in-differences research design, which relies on the common trends assumption, is tested by examining the observable characteristics of the mothers in these two groups before and after development. The research design is robust to a range of specifications. I also test whether these results vary by water source, given the concerns around shale gas development and ground water contamination. The results do not differ across water source (i.e. public piped water vs. ground well water) and suggest that the mechanism could be air pollution from increased localized economic activity.

2 Background

2.1 A Brief Shale Gas Overview for Pennsylvania

In Pennsylvania, shale gas development involves both vertical and horizontal wells drilled primarily into the Marcellus Shale, but more recently, the Utica Shale. The drilling process includes a technique to stimulate the wells called hydraulic fracturing. Hydraulic fracturing is a process that uses water to fracture the rock or shale beneath the ground. On average, in Pennsylvania, it involves injecting 3-4 million gallons of water mixed with sand and fracturing chemicals into the well and using pressure to fracture the shale about 7,000 ft below the surface (ALL Consulting, 2009). Shale plays are heterogeneous and so the distance drilled and quantity of water required differs across varied geological formations.

The entire process of completing a natural gas well takes, on average, 3-4 months to finish.[9] During the first month, diesel trucks bring in materials required for the drilling process, averaging 1500-2000 truck trips per well completion in Pennsylvania (ALL Consulting, 2010). During the first 30 days after well completion, it is estimated that approximately 30-70% of the water used during the drilling process returns to the surface (called flowback) and is collected in ground level water impoundments and then taken to be treated at a waste water facility (ALL Consulting, 2009).

[9] Due to improved drilling technology, this time to completion was greatly reduced in 2011 to approximately 1 month.

Most wells are drilled on private property that has been leased to oil and gas companies.[10] There are a growing number of wells being drilled on public BLM lands, due to the push for more domestically sourced natural gas. After the land is leased by the mineral owner, a company applies for a permit to drill on that property. The state government approves permits and once a company has a permit, the drilling often commences quickly thereafter. There are many layers of decision-making independent of the mineral owner that determine exactly which leases become permits and which permits become a well. This research uses only those locations that are permitted by the state to reduce selection bias in the estimates that follow.

2.2 Shale Gas Development As A Potential Pollution Source

Preliminary evidence indicates that shale gas development may produce waste that could contaminate the air, aquifers, waterways, and ecosystems that surround drilling sites or areas where water treatment facilities treat the waste water from the drilling process. However, there is little consensus about the likelihood of contamination, mechanisms or how widespread it might be.

For water pollution, faulty well casings or surface spills and accidents are considered the least controversial pathways (Osborn et al., 2011; Jackson et al., 2013; EPA, 2004; DEP, 2009; Lyverse & Unthank, 1988).[11] A few recent studies have suggested impacts of the treatment and release of waste water on surface water quality (Olmstead et al., 2013; N. R. Warner et al., 2013).

Despite less attention in the media, air pollution is gaining more recent attention by researchers. All stages of shale gas development have the potential to produce hazardous air pollution emissions (EPA, 2000, 2010, 2011; Kargbo et al., 2010; Schmidt, 2011). Air pollution has become a more immediate concern following some recent studies in Colorado that discovered higher levels of volatile organic compounds (VOCs), methane and other hydrocarbons near drilling sites (L. McKenzie et al., 2012; Colborn et al., 2012; Gilman et al., 2013; Pétron et al., 2012). Other emissions associated

[10]To date, there are no estimates in Pennsylvania of how many properties are “split estate”- the condition where surface owners do not own the mineral rights.

[11]With virtually no pre-drilling samples of water wells near drilling sites, most studies are not considered conclusive.

with combustion include particulate matter, polycyclic aromatic hydrocarbons, sulfur oxides and nitrogen oxides (Colborn et al., 2012; EPA, 2008).

In addition to the potential air pollution from the drilling process itself, traffic is often cited as a potential cause of increased ambient air pollution (Considine et al., 2011). According to a report to the New York Department of Environmental Conservation (NY DEC), the estimated quantity of traffic necessary for well completion is anywhere from 1,500 to over 2,000 truck trips (ALL Consulting, 2010). This traffic is necessary to haul in and out drilling fluids, sand and drilling equipment. Volatile organic compounds (VOCs), which include BTEX and other hydrocarbons, and fugitive methane gas mix with nitrogen oxides (NO_x) from truck exhaust and produce ground-level ozone (Gilman et al., 2013).

2.3 Pollution and Infant Health Literature

There is a growing literature within health economics that addresses the most common air pollutants utilizing quasi-experimental designs and rich controls for potential confounders to identify the infant health effects of ambient air pollution.[12] For example, Currie & Walker (2011) estimate that reductions in air pollution from E-Z Pass result in reductions of LBW between 8.5-11.3 percent and Currie et al. (2009) find that a one unit change in the mean level of carbon monoxide increases the risk of LBW by 8 percent. For comparison, Currie et al. (2009) find that mother's smoking in utero increases LBW by 0.18 percentage points or a 2% increase in the overall prevalence of LBW in New Jersey during their study period. Zahran et al. (2012) utilize the natural experiment of benzene content in gasoline from 1996 to 1999 in the US and found exposure to benzene reduces birth weight by 16.5 g and increases the odds of a very low birth weight event by a multiplicative factor. Lavaine & Neidell (2013) use the natural experiment of a strike that effected oil refineries in France to explore the temporary reductions in SO_2 and find that the reductions increased birth weight by 75 grams, on average (2.3 percent increase) and reduced low birth weight by 2 percentage points

[12] See Currie, Zivin, et al. (2013) for a review of the economics literature on short and long term impacts of early life exposure to pollution. Also, see the Appendix for a more detailed literature review of the recent studies.

for residences within 8 km of the air pollution monitor.

Most of the studies to date that address potential health impacts of shale gas development measure pollutants at drilling sites or in drilling fluids and then identify the health implications based upon expected exposure to these chemicals. For example, Colborn et al. (2011) find that more than 75% of the chemicals could affect the skin, eyes, and other sensory organs, and the respiratory and gastrointestinal systems. Chronic exposure is particularly concerning because approximately 40-50% could affect the brain/nervous system, immune and cardiovascular systems, and the kidneys; 37% could affect the endocrine system; and 25% could cause cancer and mutations. These may have long-term health effects that are not immediately expressed after a well is completed. Another study that attempts to predict the health risk of natural gas development performed an Health Impact Assessment (HIA) in Colorado (L. McKenzie et al., 2012). They determined that the cancer risks within 1/2 mile of a well are 10 in a million and 6 in a million for those residences greater than 1/2 mile from a well. Benzene was the major contributor to the risk. L. M. McKenzie et al. (2014), a study published concurrently to this work, estimated that the prevalence of congenital heard defects (CHDs) increased and neural tube defects prevalence was associated with the highest tertile of exposure compared with the absence of any gas wells within a 10-mile radius in Colorado. Exposure was negatively associated with preterm birth and positively associated with fetal growth, although the magnitude of association was small.

Although there have been a few correlational studies, to my knowledge, this is the first study to estimate the causal relationship between shale gas development and health using population data.

3 Data

My analysis is based upon a data set acquired from the Pennsylvania Department of Environmental Protection (PA DEP) that contains GIS information for all of the wells drilled in the state of Pennsylvania since 2000 and define whether it is a Marcellus shale well. In total, the analysis uses 2,459 natural gas wells completed between 2006 and 2010. For the analysis that follows, the

spud date (date when the drilling rig begins drilling the well) is used as the temporal identification of treatment. In addition to the existing gas well data, this study also makes use of the permit data on the PA DEP website. This allows for the identification of permits that do not become a well during the sample time frame. This information is used to define a potential control group for those infants born to residences close to existing gas wells. The assumption being that these residences are a potential counterfactual group: those who have the potential to live close to a gas well in the future, but have not yet had a well drilled as of the timing of the data collection.

My second source of data comes from restricted-access vital statistics natality and mortality data from Pennsylvania for the years 2003 to 2010. The restricted-access version of these birth certificate records contain residential addresses geocoded to latitude and longitude and unique identifiers for the mother, father and infant. This precision is essential to my identification strategy because the consequences of drilling are highly localized (Sage Environmental Consulting, 2011; Muehlenbachs et al., 2014). The vital statistics contain important maternal characteristics such as race, education, age, marital status, WIC status, insurance type, and whether the mother smoked during her pregnancy. In the empirical analysis that follow, I control explicitly for these, as well as month of birth, year of birth, the interaction, and gender of the child.[13] I exclude multiple births in all analyses because plural births are more likely to have poor health at birth independent of exposures to environmental pollution.

I focus on low birth weight (LBW) and term birth weight as the primary outcomes of interest. Low birth weight, defined as birth weight less than 2500 grams, is commonly used as a key indicator of infant health and has been shown to predict adult health and well-being.[14] I also present the

[13] I also test whether drilling activity has affected these characteristics directly by changing fertility and/or the composition of families living near shale gas development and I find few economically significant changes.

[14] Oreopoulos et al. (2008) use twin and sibling fixed effects models on data from Manitoba, Canada that follows births through 18 years of age to show that birth weight (and other infant health measures) has a significant effect on both mortality within one year and mortality up to age 17. They also find that birth weight is a strong predictor of educational and labor force outcomes, such as high school completion and welfare take-up and length. These findings are similar to those of Black et al. (2007) who use data from Norway and find that birth weight has a significant effect on earnings, education, height and IQ at age 18. Johnson & Schoeni (2011) use national data from

continuous measure of term birth weight, defined as birth weight for infants who reach full term at 37 weeks gestation. Other birth outcomes that I examine include the continuous measure of birth weight, gestation (measured in weeks), premature birth (defined as gestation length less than 37 weeks), small for gestational age (SGA; defined as 10th percentile of weight distribution for the gestational week of birth), congenital anomalies, and infant mortality (death in the first year).[15] Another potential measure of health at birth is the 5 minute American Pediatric Gross Assessment Record (APGAR) score.[16] I use an indicator for whether the APGAR score is less than 8 to predict an increase in the need for respiratory support. Each of these outcomes has been previously examined in both the epidemiological and economics literature (e.g., Currie & Neidell (2005); Currie et al. (2011); Mattison et al. (2003); Glinianaia et al. (2004); Knittel et al. (2011); Currie et al. (2009); Currie & Walker (2011); Currie, Davis, et al. (2013)). Following Currie, Davis, et al. (2013), I also construct a single standardized measure to address examining multiple outcomes and multiple hypothesis tests (Kling et al., 2007).[17]

The third data source utilized in this research is a shape file containing the boundaries of public water service areas (PWSA) provided by the Pennsylvania Geospatial Data Clearinghouse (PADEP, 2013). Using a geospatial merge, I link the mother address to the service area boundaries and then define whether the mother's residence uses piped public water or private (ground)

the US and find that low birth weight increases the probability of dropping out of high school by one-third, lowers labor force participation by 5 percentage points, and reduces earnings by almost 15 percent. More recently, Figlio et al. (2013) use linked birth and schooling records in Florida and find that birth weight has a significant impact on schooling outcomes for twin births.

[15]Small for gestational age (SGA) is used to determine the immediate health care needs of the infant and is used increasingly to predict long-term adverse health outcomes and potential exposure to environmental pollution (Callaghan & Dietz, 2010). This paper uses the World Health Organization weight percentiles calculator (WHO, 2011) which follows the calculations recommended by Mikolajczyk et al. (2011).

[16]The physician rates the infant a 0, 1, or 2 on each of 5 dimensions (heart rate, breathing effort, muscle tone, reflex initiability, and color), and then sum the scores, giving an APGAR score of 0-10, where 10 is best. This discrete measure is highly correlated (when the score is low) with the need for respiration support at birth (Almond et al., 2005).

[17]I first convert each birth measure so that an increase is "adverse" and then standardize the measure to a mean of zero and standard deviation of 1. I then construct the summary measure by taking the mean over the standardized outcomes, weighting them equally.

well water. Additionally, I define distance from the boundary of the PWSA to explore birth outcomes amongst residences very close to the boundary to reduce confounding relationships linked to different drinking water sources (Muehlenbachs et al., 2014).

Table 1 provides summary statistics for the universe of births in Pennsylvania from 2003-2010. The first column reports characteristics of all births and the second column reports characteristics of births for mothers' residences within 2.5 km of where a shale gas well has been drilled or will be drilled. The localized data I use in this analysis is actually quite similar to the characteristics of the rest of the state.[18] Column (3) provides a decomposition of birth weight of residences within 2.5 km of a well to gauge the importance of the various observable mother characteristics. The regression also includes month of birth, year of birth, and county of birth dummies to account for any secular time trend. These control variables are included in all my subsequent regression analysis, but, for simplicity, I do no report these coefficients in the tables below.

Table 2 provides summary statistics for the primary difference-in-difference (DD) analysis sample to assess how selective my main estimation sample is. In the analysis that follows, the sample is restricted to those mothers' residences within 2.5 km of a gas well or permit (future well) and I compare residences before and after drilling. The cross-sectional differences in sample means for characteristics of birth and mother's demographic characteristics are reported in Table 2. Most of the statistically significant differences between these two samples are arguably not very economically important. Mothers with infants born after drilling are less likely to be over the age of 35, more likely to receive WIC, and more likely to receive Medicaid, on average. However, Table 3 suggests no changes in these economic variables after shale gas development.[19]

[18]Mothers who live close to shale gas development are less African American and Hispanic, slightly better off in terms of health outcomes, younger, better educated and more likely to be married at the time of birth compared with the state average. The mothers in the analysis sample are also more likely to smoke than the average for the state.

[19]An examination of fertility over time suggests a consistent number of births within 2.5 km of the well head. Muehlenbachs et al. (2014) do not find any changes in neighborhood composition using Census data at the tract level from 2000-2012 in Pennsylvania.

4 Empirical Strategy

Since air or water pollution are not randomly assigned, studies that attempt to compare health outcomes for populations exposed to pollution may not adequately control for confounding determinants of health. In the absence of a randomized trial, I exploit the variation over time in the introduction of shale gas wells in Pennsylvania during 2003-2010. Combining gas well data and vital statistics allows the comparison of infant health outcomes of those living near a gas well and those living there before drilling began. Rather than compare aggregated areas, I know specific locations where shale gas drilling has taken place and the dates of when drilling began. The specific location data allow me to compare health at birth within very small areas in which mothers are likely to be more homogeneous in observable and unobservable characteristics than in normal aggregate comparisons.

Relying on cross-sectional variation alone, however, would be problematic if mother characteristics vary within the small radius of interest that are unobservable to the researcher. If, for example, the location of gas drilling occurs where the neighborhoods are already economically distressed, then the variation in health outcomes may reflect socio-economic status, as opposed to living in close proximity to shale gas development. I therefore examine localized health at birth outcomes shortly before and after shale gas drilling. There is little guidance in the literature about how near a household must be to a gas well for exposure to affect birth outcomes. Currie, Davis, et al. (2013) characterize this relationship empirically using low birth weight and find that toxic emissions from toxic plants travel at least 1 mile.[20] I use 2.5 km as the primary distance of interest for the main specifications that follow. In Appendix Table A2, I report different distances from the well head for the definition of treatment. I detect increases in low birth weight and decreases in term birth weight up to 3.5 km from the well head, an important contribution of this paper and of

[20]There are some other clues in the current literature regarding shale gas development: L. McKenzie et al. (2012) predict health effects more than a half mile from the well head, Colborn et al. (2012) detect air pollution at high levels at 1.1 km of the well head, and using ambient air pollution modeling, Sage Environmental Consulting (2011) recommend distances from schools and hospitals of more than a mile from the well head.

significant independent interest to the policy debate around shale gas development.

4.1 Graphical Evidence

If living close to a drilled well has a negative impact on infant health at birth, we should see average prevalence of low birth weight for mother's residences in close proximity to wells increase subsequent to when drilling begins. Moreover, we should observe larger impacts for homes closest to drilling activity. Figure 1 shows the low birth weight (LBW) gradient of distance to closest well before and after drilling. LBW prevalence is on average higher for those residences close to drilled wells, compared with those who are close to permitted wells. This persists out to almost 5 km. The notion that the reduction in birth weight within 2.5 km of a well reflects the causal impact of drilling activity would be supported if the decline coincides with when drilling begins and does not reflect a preexisting downward trend in birth weights. Figure 3 shows the LBW gradient of time with respect to when drilling begins. This gradient is measured for births 500 days before and after drilling for residences within 5 km of a well. If the low birth weight increase showed in Figure 1 reflected a preexisting trend, we would see a consistent upward trend over this time period prior to when drilling begins. Instead, I find a fairly sharp increase in low birth weight coincident with the spud date (defined as time=0) for residences within 2.5 km of a shale gas well. In contrast, the average low birth weight for residences at greater distances (but less than 5 km) from a well did not increase after drilling began. It is therefore plausible that the two groups would have had a similar trend in low birth weight prevalence over time in the absence of shale gas development.

In contrast, Figure 2 shows the premature birth gradient of distance to closest well before and after drilling. Here, we do not see a clear trend in premature birth over distance (this result is confirmed in the regression analyses that follow; there is no effect of drilling on premature birth within 2.5 km of a well). Figure 4 shows the trend in premature birth. Again, as was suggested by Figure 2, there does not appear to be a clear relationship between drilling and premature birth.

4.2 Methods

I proceed by estimating models informed by the graphical evidence to estimate the effects of proximity to gas wells on infant health. First, I perform specification checks and test the assumptions for the difference-in-difference estimator to be valid. These models check that the observable characteristics of the mothers are the same across both affected and comparison groups and take the following form:

$$MChar_{ict} = \delta_0 + \delta_1 Close_{ict} + \delta_2 Post_{ict} + \delta_3 Close_{ict} * Post_{ict} + \gamma_t + \chi_c + \varepsilon_{ict} \quad (1)$$

where $MChar_{ict}$ are indicators for mother i's observable characteristics during month-year t in county c. These indicators include education, age, race and ethnicity, mobility, and maternal smoking. $[Close]_{ict}$ is an indicator equal to one if the mother's residence is close (2.5 km) to a current or future drilled well. $[Post]_{ict}$ is an indicator equal to one if the well has been drilled prior to the pregnancy. The coefficient of interest is on the interaction between $[Close]_{ict}$ and $[Post]_{ict}$. γ_t are indicators for the year, month and year*month to allow for systematic trends. χ_c are indicators for each mother's county of residence . Standard errors are clustered at the county. Any systematic changes in maternal characteristics following the introduction of shale gas development would require taking this selection into account when assessing the effects of development on health outcomes.

My baseline model is a difference-in-difference model –in which mothers exposed within 2.5 km from a well head before drilling are used as a control for those exposed after drilling began– to estimate the impact of exposure to shale gas development on birth outcomes. Thus, the counterfactual change in infant health for mother's residences close to a shale gas well is estimated using births prior to drilling at the same distance from the well head. These models take the following form:

$$Outcome_{ict} = \delta_0 + \delta_1 Close_{ict} + \delta_2 Post_{ict} + \delta_3 Close_{ict} * Post_{ict} + \delta_4 X_{ict} + \gamma_t + \chi_c + \varepsilon_{ict} \quad (2)$$

where $Outcome_{ict}$ is either low birth weight, prematurity and other measures of health at birth for each infant i born in year-month t in county c. The estimated impact of shale gas drilling on infant health is given by the coefficient δ_3 and is the difference-in-differences estimator. The vector X_{ict} contains mother and child characteristics including indicators for whether the mother is African American, Hispanic, four mother education categories (less than high school (left out category), high school, some college, and college or more), mother age categories (teen mom (left out category), 19-24, 25-34 and 35+), indicators for smoking during pregnancy, an indicator for receipt of Women, Infants, and Children (WIC), three health care payment method categories (Medicaid, private insurance, and self-pay), mother's marital status and an indicator for sex of the child. Indicators for missing data for each of these variables were also included.

The main model, equation (2), is estimated using a comparison group that is restricted to those infants born to residences within the specified distance of a permit or future gas well. This identification strategy assumes that infants born within a similar distance to a permit that is a potential future well would face similar ex ante conditions as those born close to a permit that did become a well during the sample. Infants born to mothers who reside close to potential wells are likely to be the most similar comparison group when it comes to family, geological formation and community characteristics. The decision for which permits become a well is arguably exogenous to the families in these locations. This should account for both observable characteristics, as well as unobservable characteristics, such as economic factors that promote gas drilling in a community and the unobserved geology of the shale underneath these communities.

Ground water contamination from the process of hydraulic fracturing has received the most media attention as a pathway for adverse public health effects. Following Muehlenbachs et al. (2014), I test whether there are heterogeneous effects of shale gas development by water source.

The full model takes the form:

$$
\begin{aligned}
Outcome_{ict} = \delta_0 + \delta_1 Close_{ict} + \delta_2 Post_{ict} + \delta_3 PWSA_{ict} + \delta_4 Close_{ict} * Post_{ict} \\
+\delta_5 Close_{ict} * PWSA_{ict} + \delta_6 PWSA_{ict} * Post_{ict} + \delta_7 Close_{ict} * Post_{ict} * PWSA_{ict} \\
+\delta_8 X_{ict} + \gamma_t + \chi_c + \varepsilon_{ict}
\end{aligned} \tag{3}
$$

where $Outcome_{ict}$ are the same infant health measures as in equation (2). The controls X_{ict} are also the same. $PWSA_{ict}$ is an indicator equal to one if the maternal residence receives public water from a public water service area (PWSA). δ_7 is the triple-difference estimator of the impact of proximity to a well after drilling for homes that receive public water.

5 Estimation Results

5.1 Differences in Characteristics of Mothers Close to a Well

I formally test whether there are any preexisting trends in adverse birth outcomes or characteristics in these communities prior to drilling. In Table 3: Panel A, I compare those within 2.5 km to those 2.5-5 km from a future gas well and find little evidence of any preexisting differences in either health at birth or mother characteristics that would be indicative of worse health trends in these communities prior to drilling. Although there are some statistically significant differences, these communities boast heavier babies. Mothers who live within 2.5 km from a permit appear to have less education than those who live 2.5-5 km from a permit and they are also more likely to be born in Pennsylvania. Despite these significant differences, there doesn't appear to be any systematic adverse health trend prior to drilling that would threaten the conclusions that follow.

To further test the validity of my research design, I estimate equation (1) and use the difference-in-difference estimator to see if there are any changes in mother characteristics after drilling began. In Table 3: Panel B, only one maternal characteristic shows a significant change with drilling: mothers observed after drilling are more educated than those observed prior to drilling. Increased

college completions amongst mothers would suggest improvements in infant health in these communities, rather than adverse health effects. However, this does suggest some selection and so I include these and other controls in all the subsequent results.[21]

5.2 The Impact of Shale Gas Development on Birth Outcomes

Table 4 shows the results from estimating equation (2) on low and term birth weight. Distance to a (future) well is held fixed at 2.5 km for these models. Each coefficient represents an estimate of δ_3 –my difference-in-difference estimator– from a separate regression. Columns (1) and (3) show a model that controls only for month and year of birth, month*year and county fixed effects. Adding controls for observable characteristics of the mother should only reduce the sampling variance while leaving the coefficient estimates qualitatively unchanged. Columns (2) and (4) add maternal characteristics and show that controlling for maternal characteristics has little effect on the estimated coefficients. I find a statistically significant increase in low birth weight of 1.36 percentage points and a reduction in term birth weight of 49.58 grams, on average. Thus, mothers who give birth after drilling are more likely to have reduced weight babies. This difference is suggestive of an overall increase in low birth weight of 25 percent (base of 5.5 percent) and a decrease in term birth weight of 1.5 percent (base of 3418 grams), on average.[22] The results are qualitatively similar when I estimate equation (2) for other distances up to 4 km from a gas well or permit (See Appendix Table A2).

Table 5 presents similar estimates to Table 4 for changes in birth weight, 5 minute APGAR scores less than 8, gestation (weeks), premature birth, small for gestational age (SGA), congenital anomaly and infant death. As before, each column presents estimates from a separate regression,

[21]The time frame of interest is during the onset of the Great Recession. It may indicate that the opportunity cost of going to college, or becoming a mother, has reduced and so more educated mothers are having children. Other research has linked recessions to improved infant health outcomes, so it is unlikely to be the driver of impacts reported in the next section (Chay & Greenstone, 2003; Dehejia & Lleras-Muney, 2004).

[22]Overall prevalence is calculated as follows: 0.0136/0.055=24.7 percent low birth weight and 49.6/3418 = 1.5 percent reduction in term birth weight.

comparing outcomes before and after drilling at 2.5 km from a well head. I present results with maternal controls due to there being little appreciable difference for the models without these controls (results available upon request). Looking across all health at birth measures, these estimates are consistent with shale gas development being detrimental to infant health. The introduction of shale gas development reduced birth weight by 46.6 grams (1.4 percent reduction), which is consistent with the findings for term birth weight. Five minute APGAR scores were also affected by drilling; drilling increased scores less than 8 by 2.51 percentage points or an overall increase of 26 percent. Small for gestational age (SGA), a strong indicator of intrauterine growth restriction (IUGR), increased by 1.81 percentage points or an increase of 18 percent from the mean. Perhaps surprisingly, given that low birth weight is often correlated with premature birth, gestation and premature birth show no difference with the introduction of shale gas development. Congenital anomaly and infant death are not individually statistically significant from zero, but these outcomes are quite rare and differences are not likely to be detected with the size of my sample.[23]

Following Currie, Davis, et al. (2013), I address the issue of precision using a summary index measure of infant health.[24] A drilled shale gas well has a small and statistically significant effect on the summary index, increasing the probability of an adverse health at birth outcome by 0.026 standard deviations. This result is consistent with the finding that living within 1 mile of an operating toxic plant increased the probability of a poor health outcome by 0.016-0.017 standard deviations (Currie, Davis, et al., 2013).

5.3 The Impact of Shale Gas on Birth Outcomes by Water Source

Piped water is regulated by the Clean Drinking Water Act and monitored by the EPA, whereas ground water is the responsibility of the residential owner to test for contaminants.[25] Table 6

[23]Currie & Neidell (2005) and Currie et al. (2009) used samples greater than 125,000 to detect changes in infant mortality.

[24]I first convert each birth measure so that an increase is "adverse" and then standardize the measure to a mean of zero and standard deviation of 1. I then construct the summary measure by taking the mean over the standardized outcomes, weighting them equally.

[25]Water testing can be costly and prohibitive for some families.

presents the results for equation (3).[26] This formally tests whether there are differences in the infant health outcomes detected in the main results between different drinking water sources (δ_7 on the interaction $D_i^{2.5km} * Post_i * PWSA_i$). For example, for low birth weight, ground water homes had an increase in low birth weight of 0.425 percentage points and public piped water homes had an increase in low birth weight of 0.556 percentage points post-drilling within 2.5 km of a well. Similarly, public water homes had reduced term birth weight of 32.11 grams, while ground water homes had reduced term birth weight of 19.69 grams, on average. Despite some differences in magnitude, the differences between the estimates are not statistically significant and suggest that the exposure mechanism is likely air pollution or increased economic activity in these communities (e.g. increased noise, stress from community change).[27]

5.4 Robustness Checks

Table 7 shows estimates of maternal mobility for the sample of mothers who have multiple singleton births and those who have ever resided within 2.5 km of a well or future well during 2003-2010. The first column predicts the likelihood that a mother moved (changed residential location) between pregnancies. The coefficient suggests that moving increased by 2.2 percentage points after drilling, although this is not statistically significant. The next six columns report the birth outcomes for the mothers who moved and the mothers who do not move. Despite some

[26] I report the coefficients required to calculate two effects: the effect of shale gas development for ground water homes versus piped public water homes 2.5 km of a well post-drilling. Full results available upon request.

[27] Appendix Table A4 provides the cross-sectional demographic characteristics for the analysis sample on ground versus piped water. Those on piped water are more likely to have worse birth outcomes in the cross-section, which may be due to proximity to urban/semi-urban locations. Following Muehlenbachs et al. (2014), I also test whether there are differences within a tight bandwidth of 1 km on either side of the public water boundary. This assumes that ground water sourced homes near the boundary are more similar to piped homes in observable and unobservable characteristics than those on ground water farther from the boundary. This subsample confirms that there are no differences in shale gas impacts across water sources (Muehlenbachs et al. (2014) found differences only in the subsample for housing prices). Estimation of equation (2) with the sub sample within 1 km on either side of the public water boundary yields similar results as those reported in Table 4. Results available upon request.

potential increased mobility of these mothers, the results are qualitatively similar for those who stay as those who move and indicate that the main results are not driven by maternal mobility.

Table 8 contains estimates of robustness checks for four measures of infant health: low birth weight, term birth weight, birth weight and small for gestational age. Each coefficient represents an estimate of δ_3 from a separate regression for various subgroups and additional controls. The first panel shows the effect of restricting the sample to infants born within 2 years (before and after) of the spud date for the closest well. This specification is designed to address any possible concerns about unequal prior and post observation periods for each location or concerns about unobserved and differential sorting in the mothers living close to drilled versus permitted wells. The point estimates are somewhat smaller, but qualitatively similar to the estimates in Tables 4 and 5. Table 8: Panel B shows the results using the sample of births from 2008 to 2010, when most of the shale gas development took place during the sample frame. This point estimate is slightly larger for low birth weight (LBW) and small for gestational age (SGA) indicating a 1.89 and a 2.51 percentage point increase in LBW and SGA, respectively. Also a slightly larger point estimate, column (3) suggests that birth weight is reduced by 54.8 grams on average and is statistically significant. Column (2) suggests a reduction in term birth weight of 31.5 grams, but is no longer statistically significant. Panel C reports the results from adding the continuous distance to the closest well, as well as the number of wells drilled within 5 km of the maternal residence. Again, the point estimates are very similar to those reported in Tables 4 and 5.

An important issue to explore is whether the effects of exposure to shale gas drilling are the same for different subgroups of the population. Some groups, such as high school dropouts, African American mothers and smokers, may face differential risks from similar levels of pollution exposure. To assess any heterogeneous impacts of shale gas development across different demographic groups, the next three panels of Table 8 highlight estimates from these important subgroups. The sample of African American mothers is very small, making up just 3% of the sample, but the coefficient estimates suggest larger impacts albeit not statistically significant. Currie et al. (2009) and Currie & Walker (2011) found larger effects of pollution for mothers who were smok-

ing. Within 2.5 km of a drilled or future well, the sample of smokers has a point estimate of 1.94, however, smokers in the population are more likely to have low birth weight babies at baseline and so this does not suggest a differential effect on the incidence of low birth weight for smokers. And the coefficient is not statistically significant (p-value=0.16). However, term birth weight is reduced by 62.3 grams and is statistically significant and suggests a larger effect on average term birth weight for infants born to smokers (1.9 percent reduction). The effects for high school dropouts are much larger (Panel F) and suggest that maternal exposure to shale gas development for high school dropouts increases low birth weight by 4.8 percentage points, reduces term birth weight by almost 80 grams, and reduces continuous birth weight by over 100 grams, on average. This result may be indicative of less avoidance behaviors amongst the least educated mothers surrounding drilling locations. Additional subgroup analyses are presented in Appendix Section A.

Another difference-in-difference model commonly used in the environmental health literature is to compare observed health close to a pollution source versus slightly further away. The most recent of these studies is (Currie & Walker, 2011); the authors compared mothers within 2 km of a toll plaza to mothers who are 2-10 km from a toll plaza, before and after the adoption of E-Z Pass in Pennsylvania and New Jersey.[28] In Appendix Table A1, I present results utilizing a similar model as a robustness check for using permitted/future wells as the comparison group. Here, the difference-in-difference model compares residences close to a well (within 2.5 km) and residences a little further away (2.5-15km), before and after drilling. The point estimates are somewhat smaller, but still suggestive of a statistically significant increase in low birth weight and decrease in term birth weight, on average. Using 2.5-15 km as the comparison group provides a lower-bound estimate; shale gas development increases the overall prevalence of low birth weight by 12.5 percent and reduces term birth weight by 0.6 percent, on average.[29]

[28](Hill, 2013) also uses this research design to explore the impacts of oil and gas development in Colorado, comparing 1 km to 1-5 km away from the well head, before and after drilling.

[29]Depending on the scale of shale gas development, it is possible that other aspects of drilling activity will influence infant health within 15 km of a well and could explain these smaller estimates. For example, communities with shale gas development are exposed to increased truck traffic, pipelines, water storage, compressor stations and general increased localized economic ac-

5.5 Falsification Tests

My analysis shows little evidence of any preexisting differences in communities located close to drilled wells relative to communities close to permits or future wells. It is theoretically possible that the increase in low birth weight after drilling is driven by differential trends in fertility or migration post-drilling amongst mothers who do not have multiple births during the sample. I investigate this possibility by estimating equation (2) using permit dates to define exposure, instead of spud dates. I also create a placebo test using a random date for the closest well. In these specifications, I find no evidence of a spurious effect, although the coefficient on term birth weight suggests that there may be a reduction in average term birth weights after the permit date but this result is fairly small and not statistically significant (Table 9, column (5)).[30]

6 Discussion

There are five main findings in this paper. First, my results suggest that shale gas development can have adverse effects on the health of people living nearby, namely that of prenatal infants. Babies born of mothers who lived within 2.5 km of a gas well during pregnancy had lower birth weights on average after drilling than prior to drilling. Shale gas development increased the incidence of low birth weight and small for gestational age in the vicinity of a shale gas well by 25 percent and 18 percent, respectively. Furthermore, term birth weight and birth weight were decreased by 49.6 grams (1.5 percent) and 46.6 grams (1.4 percent) on average, respectively, and the prevalence of APGAR scores less than 8 increased by 26 percent. Utilizing a health index, I find that drilling increased the probability of an adverse health at birth outcome by 0.026 standard deviations of the index. While these impacts are remarkably large, they are biologically plausible given the correlations between air pollution (or maternal stress) and birth outcomes found in previous studies. For example, Zahran et al. (2012) found exposure to benzene reduced birth weight by

tivity. These community level effects are less likely to influence the estimates in the main results of the paper that use permitted/future wells as the comparison group.

[30] In some cases, land clearing and well pad preparation will take place after permit date.

16.5 grams and increased the odds of a very low birth weight event by a multiplicative factor, and Slama et al. (2009) found that exposure to benzene reduced birth weight by 77 grams. For context, Almond et al. (2005) found that smoking reduces a child's birth weight by about 202 grams. Given the wealth of studies that identify a causal link between birth weights and long-run outcomes, these impacts are likely to persist throughout these children's lives.

Second, while there is some weakly suggestive evidence that mothers may be more likely to move after drilling, there does not appear to be any evidence that higher SES mothers are systematically more likely to move in response to drilling activity. I cannot rule out moving as a form of avoidance behavior, which could mask the costs of drilling to communities where it occurs if those most affected move away. Additionally, I do not find differential effects for those who stay versus those who move, which provides evidence that the research design is robust to changes in maternal mobility in response to drilling activity.

Third, effects of gas drilling are larger for lower SES children. There is prior evidence that in some cases this is explained by the fact that lower SES women take fewer measures to avoid pollution. I do not, however, detect heterogeneous responses as measured by moving. As previously mentioned, early shocks to a child's health can persist for many years, hence if poorer families are unable to mitigate the risks of drilling activity their children's health development is likely to suffer, which is reflected in literature that finds pollution to be one potential mechanism by which SES affects health (Neidell, 2004).

Fourth, using public water service areas to define maternal residences that receive piped public water versus maternal residences that use well (ground) water, I do not find differences in adverse birth outcomes between these two groups. This is suggestive evidence that the mechanism is not through the exposure pathway of water.[31]

Fifth, though exact mechanisms are difficult to ascertain with the data currently available, the increase in small for gestational age and low birth weight without a symmetric increase in pre-

[31]This does not rule out ground or surface water contamination caused by shale gas development; it, however, indicates that changes in reproductive health in these communities after shale gas development is driven by something other than water source.

mature birth indicates that infants born to mothers exposed to drilling are coming to full term, but are small. Thus, exposures to drilling activity are suggestive of intrauterine growth restriction ($<$10th percentile of birth weight for gestational age), which has not been definitively linked in the literature to particulates, but instead indicative of high levels of polycyclic aromatic hydrocarbons (Glinianaia et al., 2004; Bobak, 2000; Sram et al., 2005). Low birth weight, in contrast, has been linked to many of the measured air pollutants associated with gas drilling and is indicative of exposures to benzene, particulates, SO_2, NO_x, and VOCs (amongst others). These results suggest that requiring air pollution monitoring of drilling sites could assist researchers and public health officials in efforts to ascertain exposure pathways for residents living nearby and inform policies to mitigate any risks that are likely to be very localized.

Sixth, stress causes low birth weight primarily through premature birth. Therefore, the increase in low birth weight without the subsequent increase in premature birth suggests that stress is not the primary mechanism.

6.0.1 Cost Estimates

While the economic benefits of shale gas development are quantifiable, the public health benefits may be more difficult to assess. Improvements in public health that stem from electricity sourced from natural gas instead of coal are likely to be substantial, but not uniformly distributed. This paper provides evidence that maternal exposure within at least 1.5 miles of shale gas extraction is detrimental to fetal development. A recent report from the Institute of Medicine estimates that the cost to society of low birth weight and premature infants is $51,600 per infant for the first year of health care costs (in 2005 dollars, Behrman & Butler (2007)). A different estimate in the same year found that each preterm/low birth weight baby incurs an average of $15,100 additional hospital costs in the first year of life (Russell et al., 2007). I use this lower bound for the following cost calculations. Each low birth weight infant is fifty percent more likely to require special education services and each special education child costs the state of Pennsylvania $10,404 in 2007 (Chaikind & Corman, 1991; Augenblick et al., 2007). Following Currie, Davis, et al. (2013), I

use $76,800 as an estimate of the discounted life time wages lost from low birth weight status.[32] Combining hospital costs attributable to low birth weight ($15,100 in additional hospital costs), estimates for special education services ($5,200) and decreased earnings ($76,800), an arguably conservative estimate is $96,500 in added cost for each low birth weight child.[33]

Due to shale gas development occurring only recently in Pennsylvania, the number of infants observed close to existing wells before birth is quite small, or just under 2,500 infants. This translates to a cost of $4.1 million and accounts mostly for infants born after gas development in 2010. As a back-of-the envelope estimate, even if we assume that only the same number of infants were exposed in 2011, this translates to a cost of $8.2 million associated with 2 years of shale gas development in Pennsylvania. This is all the more likely to be a lower bound given that 2,618 additional wells were drilled in 2011 (PADEP, 2010). Using the 2010 sample of permits as an example, 21,646 infants were born within 2.5 km of a permit or existing well. The estimates in this paper suggest that, if all of these permits were drilled prior to birth, we would expect to see 310 additional low birth weight infants, an increase that could be valued at $29.9 million.[34]

A recent assessment by The Wall Street Journal estimates that over 15 million Americans live within 1 mile of an oil or gas well drilled since 2000 in 11 of the 33 states where drilling is taking place (Gold & McGinty, 2013). Using a rough estimate that half of those people are women and forty percent of them are ages 18-44, there are more than 2.8 million American women with a well within a mile of their homes (Howden & Meyer, 2010). Using the current fertility rate of 64 per 1000 women in this age group nationally (Martin et al., 2012), there are over $170,000$ pregnant women within 1 mile of a well in these states. Using the estimates in this paper as a benchmark, oil and gas development in these communities could amount to over $2,000$ additional low birth weight infants each year. This amounts to a cost of more than $230 million each year in the 11 states assessed by Gold & McGinty (2013).

[32] See Currie, Davis, et al. (2013) for more details regarding this calculation.

[33] This figure excludes medical bills after the first year, parental lost earnings and other costs and is, hence, a lower bound estimate of costs.

[34] In contrast, each shale gas well costs a producer between $2-3 million to drill and with 2,459 gas wells in this analysis, that amounts to $4.9 billion in production costs (Hefley et al., 2011).

7 Conclusions

My study seeks to understand and quantify the impacts of shale gas development on infant health. The chemicals used during drilling, cleaning drill rigs and hydraulic fracturing are linked to birth defects, cancer and reduced lung function, but there is little guidance from the scientific literature about the magnitude, time horizon or likelihood of these effects. Additionally, recent studies have shown an increase in air pollution associated with drilling, but little research has been done to assess how far these air pollutants can travel.

As a first step, I assembled a unique data set with the latitude and longitude of new mothers' residences and the locations of shale gas wells and permits in Pennsylvania. I examine the impacts of living in close proximity to shale gas development on low birth weight, term birth weight and other measures of infant health. This study is the first to examine health outcomes directly linked to shale gas development.

These results suggest that shale gas wells are associated with reduced average birth weight among infants born to mothers living within a 2.5 km radius from a shale gas well; this implies a monetized cost of $4.1 million. The impacts associated with shale gas studied in this paper are large but not implausible given the estimates found in the literature for air pollution impacts on low birth weight and term birth weight. I also find statistically significant increases in small for gestational age, the prevalence of five minute APGAR scores less than eight and decreases in birth weight on average. The strength of this approach is in exploiting a natural experiment that controls for unobservable characteristics and the results are robust across a variety of specifications, providing evidence on the credibility of the research design.

It is clear from these results that policies intended to mitigate the risks of shale gas development can have significant health benefits. I find detectable effects of shale gas development on low birth weight and term birth weight more than 3.5 km from the well head (more than 2 miles or over 11,000 ft). This finding is of significant independent interest and an important contribution of this paper. Current required set back distances (distance between well head and nearby residences, hospitals and schools) range from 300 ft to 800 ft across the 33 states where shale gas development

is taking place. With detectable infant health effects up to 2 miles away, these set back distances may be deemed insufficient to protect human health. The impacts of shale gas development estimated in this paper are independent of drinking water source and suggest that the mechanism by which shale gas development adversely affects reproductive health is through the pathway of air pollution. This finding also adds impetus for regulators to increase regulations that reduce air pollution emissions from drilling operations and for industry actors to increase voluntary action to reduce air pollution emissions.

While the research design does not allow for causal claims regarding the precise mechanisms of the effects of shale gas development on infant health, related research informs us that there are many potential pathways of exposure. These findings then confirm that these pathways, and the nature and magnitude of their impacts, merit further investigation. In order to mitigate the potential risks, we need more guidance from scientific studies to show how far air emissions from gas operations are transported and/or the likelihood of surface and ground water contamination. Additionally, since I have focused on only the infant health effects of shale gas development, the total health effects of drilling exposure are likely to be much greater. Further research on the longer term health impacts of shale gas development on all members of our society –as well as the probable mechanisms and how best to mitigate them– is warranted.

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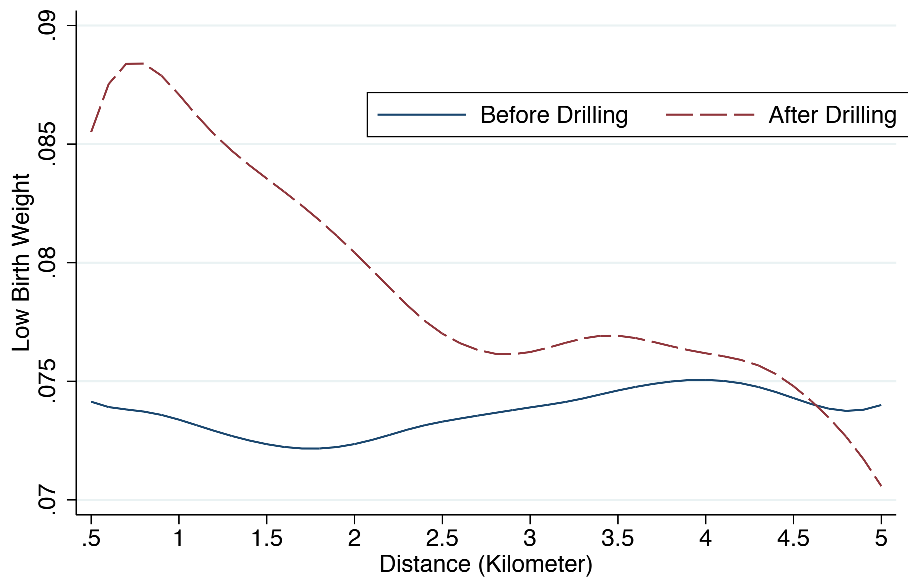
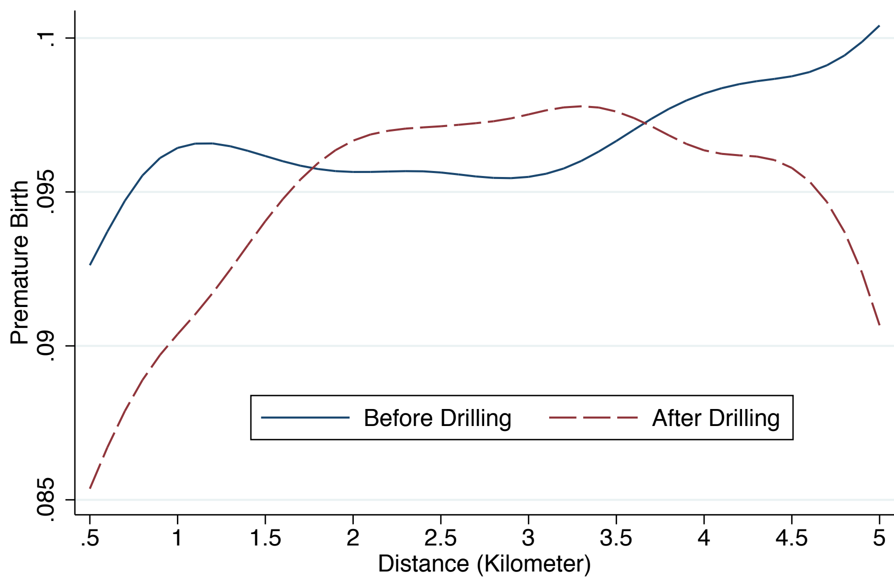


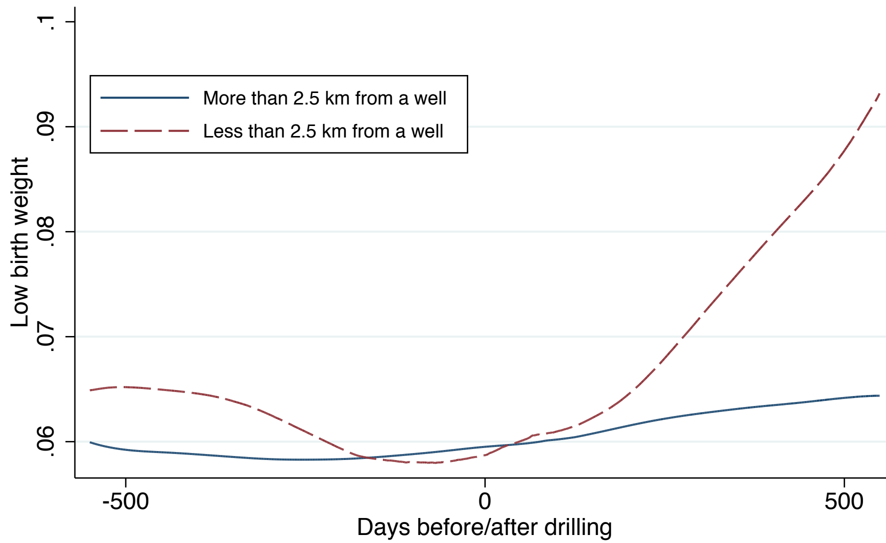
Results from a local polynomial regressions (bandwidth=0.1 km) of low birth weight on distance from closest well's future/current location. Source: Author calculations from Pennsylvania Department of Health Vital Statistics.

Figure 1: Low Birth Weight Gradient of Distance from Closest Shale Gas Well



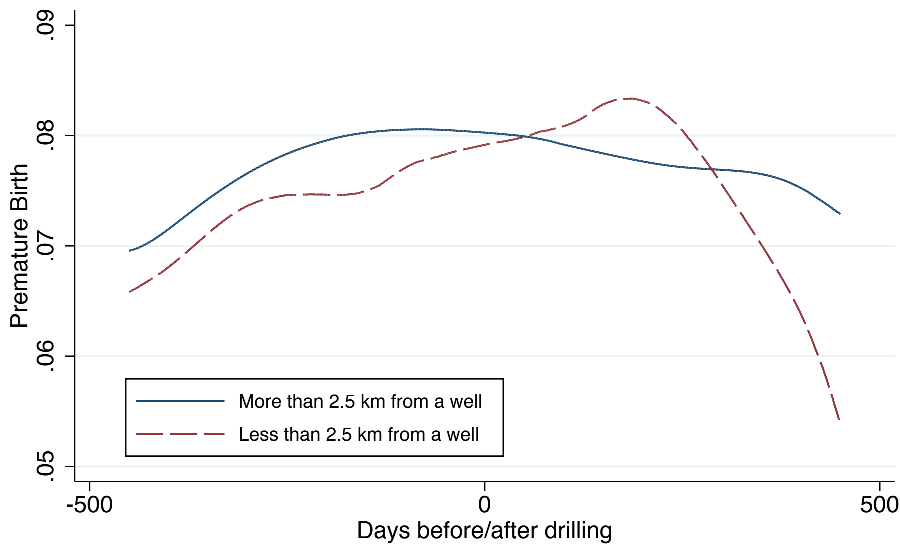
Results from a local polynomial regressions (bandwidth=0.1 km) of premature birth on distance from closest well's future/current location. Source: Author calculations from Pennsylvania Department of Health Vital Statistics.

Figure 2: Prematurity Gradient of Distance from Closest Shale Gas Well



Results from a local polynomial regression (bandwidth=90) of low birth weight on days before/after spud date. Observations within 5 km of a well. Source: Author calculations from Pennsylvania Department of Health Vital Statistics.

Figure 3: Low Birth Weight Trends Before and After Drilling



Results from a local polynomial regression (bandwidth=90) of premature birth on days before/after spud date. Observations within 5 km of a well. Source: Author calculations from Pennsylvania Department of Health Vital Statistics.

Figure 4: Prematurity Trends Before and After Drilling

Table 1: Characteristics of Births in Pennsylvania, 2003-2010

	All Births	Residences within 2.5 km of well	
	Mean	Mean	Marginal effect in birth weight regression
Characteristics of birth			
Birth weight (grams)	3285.361	3309.93	
Term birth weight (grams)	3396.84	3404.62	
Gestation in weeks	38.554	38.567	
Premature	0.102	0.092	
Low birth weight (LBW)	0.083	0.071	
Small for gestational age (SGA)	0.116	0.107	
Female	0.49	0.49	
Mother's Characteristics			
Drop Out	0.162	0.111	
High School	0.269	0.295	36.03***
			(12.74)
Some college	0.26	0.299	55.18***
			(12.42)
College plus	0.302	0.291	75.53***
			(17.71)
Teen Mom	0.056	0.047	
Mom Aged 19-24	0.262	0.266	-14.41
			(17.78)
Mom Aged 25-34	0.529	0.548	-3.928
			(16.35)
Mom Aged 35 and older	0.153	0.139	-0.0640
			(19.34)
Mom Black	0.157	0.025	-117.9***
			(12.29)
Mom Hispanic	0.091	0.011	70.44
			(52.58)
Married at time of birth	0.578	0.635	56.98***
			(9.674)
Mom Smoked While Pregnant	0.225	0.298	-161.1***
			(6.783)
Received WIC	0.384	0.399	20.19**
			(7.724)
Medicaid	0.27	0.323	-44.76**
			(21.42)
Sample Size	1116978	22257	19582
R^2			0.053

Source: Author calculations from Pennsylvania Department of Health Vital Statistics. * p<0.10, ** p<0.05, *** p<0.01

Table 2: Summary Statistics For Difference-in-Difference Sample

	Sample Means within 2.5 km		T-Stat of
	Before	After	Difference
Characteristics of Birth			
Birthweight	3343.234	3310.302	2.70**
Term Birth Weight	3418.39	3383.15	3.30***
Gestation Length	38.676	38.658	0.43
Premature	0.077	0.078	-0.12
Low birth weight (LBW)	0.055	0.063	-1.52
Small for gestational age (SGA)	0.098	0.106	-1.25
APGAR 5 minute	8.884	8.88	0.33
Mother's Demographic Characteristics			
Dropout	0.112	0.119	-1.0
High School	0.297	0.287	0.97
Some college	0.299	0.293	0.69
College plus	0.289	0.299	-1.08
Teen Mom	0.048	0.049	-0.3
Mom Aged 19-24	0.267	0.274	-0.66
Mom Aged 25-34	0.545	0.56	-1.35
Mom Aged 35 and older	0.14	0.117	3.08**
Black	0.025	0.024	0.07
Hispanic	0.011	0.01	0.58
Smoked during pregnancy	0.299	0.3	-0.12
Married	0.633	0.626	0.67
WIC	0.395	0.426	-2.92**
Medicaid	0.32	0.375	-5.43***
Private Insurance	0.569	0.55	1.81
Sample Size	19246	2364	

Source: Author calculations from Pennsylvania Department of Health Vital Statistics. * p<0.10, ** p<0.05, *** p<0.01

Table 3: Pre- and Post- Drilling Differences in Average Mother Characteristics of Births Close to Well Locations

	(1)	(2)	(3)	(4)	(5)	(6)
	Education (years)	Teen Mom	Dropout	Black	Smoked	Born in PA
	Panel A: Pre-drilling differences in mother characteristiscs					
Within 2.5 km of well	-0.290***	0.00261	0.0067	-0.00735	0.00959	0.0301***
	(0.0903)	(0.00337)	(0.00998)	(0.00607)	(0.0104)	(0.00862)
Sample Size	43426	43582	43582	43582	43582	43582
R^2	0.063	0.009	0.028	0.016	0.024	0.018
	Panel B: Differences in characteristiscs for analysis sample using DD estimator					
Within 2.5 km * post-drilling	0.310***	0.000550	-0.0132	0.00343	0.00277	-0.0222
	(0.0944)	(0.00666)	(0.0118)	(0.00308)	(0.0196)	(0.0163)
Sample Size	21581	21646	21646	21646	21646	21646
R^2	0.066	0.012	0.039	0.016	0.026	0.020

Notes: Each coefficient is from a different regression. Pre-drilling (post-drilling) refers to births that occur before (after) the spud date of the closest well. Standard errors are clustered at the mother's residence county. All regressions include indicators for month and year of birth, birth*year and residence county indicators. Source: Author calculations from Pennsylvania Department of Health Vital Statistics. Significance: * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

Table 4: Impact of Well Location on Low and Term Birth Weight

	(1)	(2)	(3)	(4)
	Low Birth Weight		Term Birth Weight	
Within 2.5 km of well	-0.000790	-0.00178	18.2	24.01
	(0.00272)	(0.00320)	(18.53)	(15.56)
Post-drilling	-0.0101	-0.00824	6.088	23.79**
	(0.00879)	(0.00873)	(10.75)	(9.352)
Within 2.5 km * post-drilling	0.0144**	0.0136**	-47.82***	-49.58***
	(0.00537)	(0.00511)	(15.12)	(14.04)
Sample Size	21610	21610	19978	19978
R^2	0.008	0.021	0.013	0.075
Maternal Characteristics	no	yes	no	yes

Notes: Each coefficient is from a different regression. The sample is limited to singleton births. All regressions include indicators for month and year of birth, month*year, residence county indicators, an indicator for drilling before birth (defined by closest well), an indicator for residence within 2.5 km of a well or future well and the interaction of interest of Post-Drilling * Within 2.5km. Maternal characteristics include mother black, mother Hispanic, mother education (hs, some college, college), mother age (19-24,25-34, 35+), female child, WIC, smoking during pregnancy, marital status and payment type (private insurance, medicaid, self-pay, other). Indicators for missing data for these variables are also included. Standard errors are in parentheses and clustered at the mother's residence county. Source: Author calculations from Pennsylvania Department of Health Vital Statistics. Signifance: * p<0.10, ** p<0.05, *** p<0.01.

Table 5: Difference-in-Difference Estimates of the Effect of Drilling on Health at Birth by Proximity

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Birth Weight	APGAR < 8	Gestation	Premature	SGA	Congenital Anomaly	Infant Death	Summary Index
Within 2.5 km * post-drilling	-46.62***	0.0251**	-0.0771	-0.000343	0.0181**	-0.00193	-0.00075	0.0264**
	(12.52)	(0.0101)	(0.0513)	(0.00681)	(0.00764)	(0.00189)	(0.00143)	(0.0101)
Sample Size	21610	21646	21204	21204	21524	21646	21646	21646
R^2	0.061	0.029	0.021	0.012	0.040	0.008	0.042	0.045

Notes: Each coefficient is from a different regression. The sample is limited to singleton births. All regressions include indicators for month and year of birth, month*year, residence county indicators, an indicator for drilling before birth (defined by closest well), an indicator for residence within 2.5 km of a well or future well and the interaction of interest reported above. Maternal characteristics include mother black, mother Hispanic, mother education (hs, some college, college), mother age (19-24,25-34, 35+), female child, WIC, smoking during pregnancy, marital status and payment type (private insurance, medicaid, self-pay, other). Indicators for missing data for these variables are also included. Standard errors are in parentheses and clustered at the mother's residence county. Source: Author calculations from Pennsylvania Department of Health Vital Statistics. Significance: * p<0.10, ** p<0.05, *** p<0.01.

Table 6: The Effect of Shale Gas Extraction on Birth Outcomes by Water Source

	(1)	(2)	(3)	(4)	(5)
	LBW	TBW	Summary Index	Premature	SGA
Post	-0.00357	60.42**	-0.0255	0.0290***	-0.0217
	(0.00909)	(29.20)	(0.0350)	(0.00874)	(0.0199)
Within 2.5 km * post	0.00782	-80.11**	0.110**	-0.0202**	0.0308*
	(0.0118)	(30.79)	(0.0450)	(0.00946)	(0.0179)
PWSA * post	-0.00573	-44.74*	0.0131	-0.0278***	0.00245
	(0.00546)	(26.48)	(0.0561)	(0.00577)	(0.0153)
PWSA * within 2.5 km * post	0.00704	32.32	-0.0541	0.0249	-0.0160
	(0.0161)	(33.29)	(0.0657)	(0.0154)	(0.0196)
Sample Size	21,610	19,978	21646	21,204	21,524
R^2	0.021	0.075	0.047	0.013	0.040

Notes: Each column is a different regression. The full model is a triple difference, with important coefficients reported above. PWSA is an indicator equal to one if the mother's residence recieves piped public water. Standard errors are clustered at the mother's residence county. All regressions include indicators for month and year of birth, birth*year and residence county indicators. See Table 4 for description of maternal characteristics included. LBW= low birth weight; TWB= term birth weight; SGA= small for gestational age. Source: Author calculations from Pennsylvania Department of Health Vital Statistics. Significance: * p<0.10, ** p<0.05, *** p<0.01.

Table 7: The Effect of Shale Gas Extraction on Birth Outcomes by Maternal Mobility

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
		Non-Movers			Movers		
	Moved	LBW	TBW	Summary Index	LBW	TBW	Summary Index
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Within 2.5 km * post	0.022	0.0117	-59.11**	.0812**	0.00951	-59.24	0.148***
	(0.0139)	(0.0123)	(22.59)	(0.0321)	(0.0165)	(38.36)	(0.0557)
Sample Size	16008	11860	10975	11879	4121	3814	4129
R^2	0.196	0.035	0.094	0.063	0.06	0.13	0.087

Notes: See Table 4 for description of included covariates. Each column is a different regression. The sample in these regressions is made up of mothers with multiple births and therefore multiple recorded residencial addresses. Movers (Non-Movers) are those that changed (did not change) residential address during 2003-2010 across multiple observed pregnancies. Source: Author calculations from Pennsylvania Department of Health Vital Statistics. Note: LBW= low birth weight; TWB= term birth weight. Significance: * p<0.10, ** p<0.05, *** p<0.01.

Table 8: Robustness Checks, Shale Gas Development on Birth Measures

	(1) Low Birth Weight	(2) Term Birth Weight	(3) Birth Weight	(4) Small for Gestational Age
Panel A: +/- 2 years				
Within 2.5 km * post	0.0133	-39.0261	-38.8751	0.0198
	(0.008)*	(20.857)*	(19.827)*	(0.009)**
R^2	0.013	0.069	0.052	0.038
Observations	12930	11964	12930	12919
Panel B: All observations 2008-2010				
Within 2.5 km * post	0.0189	-31.4895	-54.8326	0.0251
	(0.011)*	(24.001)	(24.471)**	(0.013)*
R^2	0.016	0.068	0.054	0.047
Observations	7189	6674	7189	7180
Panel C: Number of wells and continuous distance				
Within 2.5 km * post	0.0132	-49.8154	-46.3336	0.0176
	(0.005)**	(14.379)***	(13.184)***	(0.008)**
R^2	0.021	0.076	0.061	0.040
Observations	21524	19898	21524	21439
Panel D: African American only				
Within 2.5 km * post	-0.0224	-81.6538	-18.0341	-0.0432
	(0.099)	(82.052)	(99.389)	(0.046)
R^2	0.107	0.144	0.112	0.158
Observations	531	482	531	531
Panel E: Smokers only				
Within 2.5 km * post	0.0194	-62.2487	-46.5296	0.0080
	(0.014)	(34.525)*	(39.532)	(0.026)
R^2	0.023	0.051	0.047	0.028
Observations	6465	5903	6465	6436
Panel F: High school dropouts only				
Within 2.5 km * post	0.0478	-79.9855	-104.6243	0.0169
	(0.028)*	(46.064)*	(58.259)*	(0.033)
R^2	0.040	0.105	0.089	0.058
Observations	2434	2221	2434	2428

Notes: See Table 4. Each panel is a separate regression. All regressions include controls for maternal characteristics, county fixed effects and time trends. Source: Author calculations from Pennsylvania Department of Health Vital Statistics. Significance: + p<0.15, * p<0.10, ** p<0.05, *** p<0.01.

Table 9: Falsification Tests on Impact of Well Location

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Baseline Estimates			Permit Date			Random date		
	LBW (1)	TBW (2)	Premature (3)	LBW (4)	TBW (5)	Premature (6)	LBW (7)	TBW (8)	Premature (9)
Within 2.5 km * post	0.0136**	-49.58***	-0.000343	-0.000106	-5.03	-0.00149	0.00103	-1.152	-0.00654
	(0.00511)	(14.04)	(0.00681)	(0.00682)	(12.382)	(0.00897)	(0.00303)	(11.5)	(.00789)
Sample Size	21610	19978	21204	19246	17795	18854	21610	19978	21204
R^2	0.021	0.075	0.012	0.009	0.013	0.009	0.021	0.075	0.012

Notes: See Table 4. Each panel is a separate regression. All regressions include controls for maternal characteristics and time trends and county fixed effects. Columns (1), (2) and (3) are the baseline estimates from Tables 4 and 5. Columns (4) - (6) use permit date to define "treatment" and the coefficient reported is the interaction between an indicator for whether the permit was within 2.5 km from the mother's residence and whether the birth occured after (post) the permit date. Columns (7)-(9) use a random date to define post birth. Source: Author calculations from Pennsylvania Department of Health Vital Statistics. LBW= low birth weight; TWB= term birth weight. Significance: * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

Appendices

A Additional Robustness Checks

Appendix Table A3 contains estimates for white mothers only, non-smokers only, mothers aged 19-35 only, mothers born in Pennsylvania only, and estimates for two different designations of drilling intensity (top producing and top drilled counties). For whites, non-smokers and mothers aged 19-35 years, the results are all consistent with the main findings. Using mothers born in Pennsylvania as a proxy for migration, I present results for this group in Panel D and find similar results. Of course, this does not account for migration within Pennsylvania, but 80 percent of the mothers in communities where drilling took place were born in Pennsylvania, compared to 60 percent of mothers in the rest of the state. Finally, my identification strategy uses spud date to define exposure, but shale gas development involves more than individual gas wells. The majority of pollution emitted comes from compressor stations, which are used during the production period that follows drilling. Panels E and F of Appendix Table A3 allow for comparison between the top 10 producing counties and the top 10 counties with the most wells drilled during my sample. These estimates are slightly larger than the effects estimated in Tables 4 and 5 suggesting that as drilling and production intensifies, the impacts estimated in this paper may be a lower bound.

Table A1: Impact of Well Location on Low and Term Birth Weight within 15 km

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Pre-drilling				Pre- and post- drilling			
	Low Birth Weight		Term Birth Weight		Low Birth Weight		Term Birth Weight	
Within 2.5 km of well	-0.00319*	-0.00247	11.04*	12.29*	-0.00401**	-0.00335**	-4.14	3.951
	(0.00178)	(0.00203)	(6.328)	(5.033)	(0.00169)	(0.00157)	(4.774)	(2.975)
Post-drilling					-0.000143	-0.00202	12.04**	13.45***
					(0.00143)	(0.00162)	(5.715)	(4.816)
Within 2.5 km * post-drilling					0.00688*	0.00652*	-22.07*	-23.34**
					(0.00373)	(0.00338)	(11.13)	(10.01)
Sample Size	144127	141127	129781	129781	183314	183314	168673	168673
R^2	0.002	0.021	0.008	0.073	0.002	0.020	0.007	0.073
Maternal Characteristics	no	yes	no	yes	no	yes	no	yes

Notes: Each coefficient is from a different regression. Pre-drilling(post-drilling) refers to births that occur before (after) the spud date of well within 2.5 km. The sample is limited to singleton births and residences within 15 km of a gas well or permit. All regressions include indicators for month and year of birth, month*year, residence county indicators, an indicator for drilling before birth (defined by closest well), an indicator for specified distance from a well or future well/permit and the interaction of interest reported above. Maternal characteristics include mother black, mother Hispanic, mother education (hs, some college, college), mother age (19-24,25-34, 35+), female child, WIC, smoking during pregnancy, marital status and payment type (private insurance, medicaid, self-pay, other). Standard errors are in parentheses and clustered at the mother's residence county. Source: Author calculations from Pennsylvania Department of Health Vital Statistics. Significance: * $p<0.10$, ** $p<0.05$, *** $p<0.01$

Table A2: The Effect of Shale Gas Extraction on Birth Weight by Distance

	(1) 0-1 km	(2) 0-1.5 km	(3) 0-2 km	(4) 0-2.5 km	(5) 0-3 km	(6) 0-3.5 km
Panel A: Low Birth Weight						
Nearby * post-drilling	0.00742	0.00821	0.0127**	0.0136**	0.0115**	0.00912**
	(0.0169)	(0.0102)	(0.00512)	(0.00511)	(0.00510)	(0.00391)
Sample Size	3796	8200	14113	21610	28865	36393
R^2	0.052	0.030	0.023	0.021	0.019	0.019
Panel B: Term Birth Weight						
Nearby * post-drilling	25.47	-8.326	-38.05*	-49.58***	-30.84**	-29.69**
	(37.01)	(18.87)	(21.49)	(14.04)	(14.20)	(12.59)
Sample Size	3504	7561	13028	19978	26637	33572
R^2	0.123	0.092	0.077	0.075	0.078	0.077

Notes: See Table 4. Each panel is a separate regression. All regressions include controls for maternal characteristics, county fixed effects, and time trends. "Nearby" is defined by the distance in the column headings. Source: Author calculations from Pennsylvania Department of Health Vital Statistics. Significance: * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

Table A3: Robustness Checks, Shale Gas Development on Birth Measures

	(1) Low Birth Weight	(2) Term Birth Weight	(3) Birth Weight	(4) Small for Gestational Age
Panel A: White mothers only				
<2.5 km gas well * Post-drilling	0.0162	-53.3692	-51.5537	0.0202
	(0.005)***	(13.467)***	(12.262)***	(0.009)**
R^2	0.017	0.072	0.057	0.036
Observations	20892	19321	20892	20808
	0.0124			
Panel B: Non-smokers only				
<2.5 km gas well * Post-drilling	0.0124	-47.7803	-49.8992	0.0229
	(0.005)**	(18.577)**	(20.266)**	(0.011)**
R^2	0.012	0.036	0.028	0.016
Observations	15145	14075	15145	15088
Panel C: Mothers aged 19-35 only				
<2.5 km gas well * Post-drilling	0.0184	-70.7524	-67.4247	0.0195
	(0.007)**	(12.282)***	(13.193)***	(0.009)**
R^2	0.017	0.072	0.058	0.036
Observations	17605	16295	17605	17538
Panel D: Mother born in PA only				
<2.5 km gas well * Post-drilling	0.0132	-53.5205	-40.0122	0.0185
	(0.005)***	(17.299)***	(16.914)**	(0.009)*
R^2	0.018	0.076	0.060	0.038
Observations	17491	16163	17491	17424
Panel E: Top 10 producing counties only				
<2.5 km gas well * Post-drilling	0.0165	-50.3268	-43.6648	0.0138
	(0.007)**	(13.436)***	(9.748)***	(0.008)+
R^2	0.021	0.074	0.060	0.037
Observations	15052	13911	15052	15001
Panel F: Top 10 counties with the most drilled wells only				
<2.5 km gas well * Post-drilling	0.0188	-43.6077	-37.3565	0.0154
	(0.004)***	(13.837)**	(12.803)**	(0.009)+
R^2	0.018	0.067	0.052	0.037
Observations	13208	12214	13208	13156
	0.0124			

Notes: See Table 4 for description of included covariates. Each panel is a separate regression. All regressions include controls for maternal characteristics, county fixed effects and time trends. Source: Author calculations from Pennsylvania Department of Health Vital Statistics. Significance: + p<0.15, * p<0.10, ** p<0.05, *** p<0.01

Table A4: Summary Statistics For Difference-in-Difference Sample by Water Source

	Sample Means within 2.5 km		T-Stat of
	Ground Water	Public Water	Difference
Characteristics of Birth			
Birthweight	3360.94	3332.85	3.15**
Term Birth Weight	3425.33	3411.07	1.84
Gestation Length	38.76	38.65	3.69***
Premature	0.048	0.059	-3.06**
Low birth weight (LBW)	0.068	0.08	-2.84**
Small for gestational age (SGA)	0.093	0.101	-1.68
APGAR 5 minute	8.892	8.881	0.96
Mother's Demographic Characteristics			
Dropout	0.124	0.109	3.01**
High School	0.297	0.295	0.19
Some college	0.308	0.296	1.73
College plus	0.268	0.297	-3.94***
Teen Mom	0.039	0.05	-3.28**
Mom Aged 19-24	0.25	0.274	-3.28**
Mom Aged 25-34	0.566	0.541	3.23**
Mom Aged 35 and older	0.144	0.135	1.61
Black	0.006	0.031	-10.04***
Hispanic	0.008	0.012	-2.56*
Smoked during pregnancy	0.26	0.311	-7.06***
Married	0.698	0.612	10.84***
WIC	0.358	0.411	-6.71***
Medicaid	0.272	0.343	-9.59***
Private Insurance	0.611	0.553	7.38***
Sample Size	5218	16392	

Source: Author calculations from Pennsylvania Department of Health Vital Statistics. * $p<0.10$, ** $p<0.05$, *** $p<0.01$