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Shale Gas Development and Infant Health: Evidence from Pennsylvania

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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 2.5 km of a well compared to mothers 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 mechanism is air pollution or stress 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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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, 2010a).

[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; 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, and there

[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 McKenzie et al. (2012) for a review of studies investigating the effects of inhalation exposure.

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 is air pollution or stress from localized economic activity.

2 Background

2.1 Shale Gas Overview

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).[11] Despite less attention in the media, air pollution is gaining more recent attention by researchers; sources of air pollution are expected with combustion activities, methane flaring and truck traffic (Witter et al., 2013; EPA, 2011).

2.2.1 Ground and Surface Water Contamination

Much of the concern identified in the media around unconventional drilling methods, and specifically the method of hydraulic fracturing, relates to potential human exposure due to ground water contamination (Urbina, 2011). According to a Congressional report, between 2005 and 2009, the 14 oil and gas service companies reportedly used more than 2,500 hydraulic fracturing products

[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.

containing 750 chemicals and other components (Energy Commerce Committee, 2011). Of these 2,500 products, 650 contained 29 chemicals that are either 1) known or possible human carcinogens 2) regulated under the Safe Drinking Water Act for their risks to human health or 3) listed as hazardous air pollutants under the Clean Air Act. The most widely used chemical was methanol, a known hazardous air pollutant. The BTEX compounds –benzene, toluene, ethylbenzene and xylene– appeared in 60 of the hydraulic fracturing products used between 2005 and 2009. BTEX compounds are known human carcinogens. The gas companies reportedly injected 11.4 million gallons of products containing at least one BTEX chemical over the five year period reported. These chemicals are used in small proportion (0.5-2%) to the quantity of fresh water used in the drilling process and so skepticism exists regarding how susceptible aquifers are to contamination (ALL Consulting, 2009). A report by the US Environmental Protection Agency showed that if BTEX was used, then the concentration of BTEX at the point of injection would be 45-4,400 ppb for benzene, 120-31,000 ppb for toluene, 120-8,700 ppb for ethylbenzene and 330-26,000 ppb for xylene (EPA, 2004). And with chemicals like benzene considered hazardous to human health at 5 ppb (0.005mg/L), these concentrations are considered very high, but the report concluded that the risk to groundwater sources was minimal due to mitigation techniques of dilution, dispersion and degradation (EPA, 2004).

In the current literature, the two least controversial pathways of ground water contamination are faulty well casings or from abandoned wells nearby (Osborn et al., 2011; Jackson et al., 2013; EPA, 2004; DEP, 2009; Lyverse & Unthank, 1988).[12] More controversial sources of ground water contamination are pathways between the shale formation and the aquifer, or if the drilling process occurs too close to a drinking water aquifer (N. Warner et al., 2012; DiGiulio et al., 2011). Migration of brine is theoretically possible, given certain assumptions, but the likelihood remains debated in the literature (Myers, 2012; Saiers & Barth, 2012).

[12] The PA DEP estimated that it only had records for 141,000 of 325,000 oil and gas wells drilled historically in the state, leaving the status and location unknown for approximately 184,000 abandoned wells (PADEP, 2000). The likelihood of abandoned wells being conduits of groundwater contamination in Pennsylvania remains unknown at this time.

To date, there are only a few studies addressing ground water contamination concerns. One EPA study found that wells near drilling sites had elevated levels of methane, hydrocarbons associated with the shale play, and solvents used in the drilling process in wells tested near Pavilion, Wyoming (DiGiulio et al., 2011).[13] Another recent study, using a sample of 60 water wells in Northeastern, PA, found that drinking-water wells within a 1 km radius of a well head had methane concentrations 17 times higher than wells outside of the 1 km radius, with no measurable contamination of brine or fracturing fluids (Osborn et al., 2011).[14] The authors sampled an additional 81 water wells to enhance their previous findings and found methane in water wells 82 percent of the time, with concentrations 6 times higher for homes less than 1 km from a shale gas well (Jackson et al., 2013).[15] The simplest explanations for their observations were faulty or inadequate steel casings and imperfections in the cement sealing. The Pennsylvania Department of Environmental Protection (PA DEP) issued 90 violations in 2010 and 119 violations in 2011 for faulty casing and cementing. Potential human health effects from drinking water contaminated with methane are not well understood.

Although surface water is more likely to be affected by drilling activity, from land-clearing, flow back water, and surface spills, few studies to date have assessed the risks associated with the treatment of flow back water (Krupnick et al., 2013). Olmstead et al. (2013) conducted a large-scale examination of the extent to which shale gas development affects surface water quality in Pennsylvania and determined that the treatment and release of waste water from shale gas wells increased prevalence of downstream concentrations of chloride. Total suspended solids (TSS) were increased by the presence of shale gas wells in the watershed, but the mechanism was indeterminate and perhaps related to spills, land-clearing or another un-known source of TSS related to the

[13]Due to mounting criticism regarding the report and the interpretation of its findings, USGS has released quality control well data with no interpretation and Pavilion, Wyoming is part of the large EPA study currently underway (Wright et al., 2012; EPA, 2012).

[14]The authors indicate that the presence of the well itself may be the conduit for methane migration, not necessarily the process of hydraulic fracturing.

[15]The authors also studied ethane and propane, two hydrocarbons that are only associated with gas extraction activities, and found that ethane was 23 times higher for homes less than 1 km from a gas well.

density of wells. Another recent study found elevated levels of radioactivity, salts and metals in river water and sediments at a site where treated water from oil and gas operations is discharged into a western Pennsylvania creek (N. R. Warner et al., 2013). The potential implications of these findings on surface drinking water sources have yet to be assessed.

2.2.2 Air Pollution

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 (McKenzie et al., 2012; Colborn et al., 2012; Gilman et al., 2013; Pétron et al., 2012). Other emissions associated with combustion include particulate matter, polycyclic aromatic hydrocarbons, sulfur oxides and nitrogen oxides (Colborn et al., 2012; EPA, 2008).

Air emissions inventories for many of the older shale plays are available, such as the Barnett Shale in Texas and the Denver-Julesburg Basin in Colorado (Armendariz, 2009; Bar-Ilan et al., 2008; CODPHE, 2009; Sage Environmental Consulting, 2011). Air emissions inventories indicate that the majority of emissions are of pollutants with low toxicities (e.g. methane, ethane, propane and butane), but several pollutants with high toxicities are also being emitted during the drilling process (i.e. benzene, acrolein and formaldehyde). The majority of air pollution detected is attributed to on-going production activities and compressor stations, suggesting that the air emissions persist beyond the introduction of drilling activities (Armendariz, 2009; Bar-Ilan et al., 2008; Pétron et al., 2012). For example, CODPHE (2009) indicates that ambient benzene and VOC levels increased by 38% and 40%, respectively, from 1996 and 2007 and are likely related to the large increase in shale gas development in Garfield County, Colorado. A study of Texas drilling rigs found that the total amount of combined organic compounds emitted for the year 2008 was 82,251 tons/year for all drilling activity that year.[16] However, a fairly comprehensive study in Fort Worth,

[16]This figure combines measurements for CO, NO_x, PM_{10}, SO_2 and VOCs (Eastern Re-

Texas found that, despite detecting increased hazardous air pollutants associated with drilling, the 600 foot setback distance within the city for the average exposure was protective of human health according to the air dispersion modeling performed (Sage Environmental Consulting, 2011). The authors recommended a longer-term monitoring program with greater scope to confirm their findings from air dispersion modeling.

Studies of air pollution in Pennsylvania are suggestive of increased emissions associated with shale gas development, but have produced inconsistent results. For example, the Pennsylvania Department of Environmental Protection (PA DEP) has conducted three short-term (1 week) air pollution studies in three regions of the state but found little evidence of air pollution concentrations that would likely trigger air-related health issues associated with Marcellus Shale drilling activities (PADEP, 2010b, 2011b,a). But the air emissions inventory for the unconventional natural gas industry, conducted for the year 2011, indicates modest emissions of CO, NO_x, PM_{10}, SO_x and VOCs (PADEP, 2013a). These results were verified by a recent RAND study that used the PA DEP data and other sources to estimate the emissions from shale gas in Pennsylvania (Litovitz et al., 2013). The most significant pollutants, according to the authors, were NO_x and VOCs, which were equivalent to or larger than some of the largest single emitters in the state and the low-end estimates of nitrogen oxide emissions were 20-40 times higher than the level that would be defined as a "major" emissions source. During the same time period, due to the conversion of electricity from coal to natural gas in the state, the overall pollution for all the criteria pollutants measured decreased substantially and more than outweighed the new pollution related to shale gas development. These data, however, indicate a more nuanced picture of air emissions from drilling activities and show that shale gas development is now a significant source of air pollution in rural counties with few other point-sources of pollution. For example, the 2,600 tons and 2,440 tons of shale-related NO_x emitted in Bradford County and Susquehanna County, respectively in 2011 make up one-third of the statewide shale-related NO_x of 16,500 tons (PADEP, 2013c). These levels surpass the single-largest industrial source of NO_x pollution in the 11-county northeast region, a

search Group, 2009).

coal-fired power plant in Northampton County that emitted 2,000 tons in 2011 (Legere, 2013).

An important recent study, Colborn et al. (2012), measured air pollution continuously for one year near a well pad that was located in a sensitive area that required the operator to abide by best management practices designed to minimize impacts. Despite a closed-loop system used to pipe fracturing fluids to the pad and immediately capture the flow back fluids and pipe them to another facility for treatment, the study still measured non-methane hydrocarbons throughout the drilling and production phases. The authors also detected polycyclic aromatic hydrocarbons (PAHs) at greater concentrations within 1.1 km of the well pad than those at which prenatally exposed children in urban studies had lower developmental and IQ scores (Colborn et al., 2012).

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 Related Literature on Health and Shale Gas Development

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. 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.

McKenzie et al. (2012) focuses on the health risk of air emissions from well pads in Colorado. The study collected emissions measurements in Garfield County and then estimated chronic and sub-chronic non-cancer indices and cancer risks from exposure to the measured emissions for residences less than 1/2 mile and more than 1/2 mile from wells. The study 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. These results indicate that health effects from air emissions from shale gas development warrant further study and prospective studies should focus on the health effects associated with air pollution. The authors replicated the findings from Garfield County in Battlement Mesa, CO and determined that there are 8 major areas of public health concern: water contamination, truck traffic, health effects from air emissions, noise and light pollution, strain on health care systems, accidents and malfunctions, psychosocial stress from community changes and housing value depression (Witter et al., 2013).

Bamberger & Oswald (2012) are the first peer-reviewed study to link human and animal health with natural gas development. Their study is supporting evidence of the need for further scientific studies addressing the potential health impacts caused by shale gas extraction practices. The authors interviewed 24 case study participants who are animal owners and live near gas drilling development around the country. Although their study is not an epidemiological analysis, nor is it a study that identifies specific chemical exposures related to shale gas development, it provides evidence that there are health risks present in natural gas development. Their study illustrates the potential impacts on animals by reporting on numerous cases of sudden death of cows, dogs, poultry, birds, goats, amphibians and fish. Their study also indicates that there are many common health problems reported in humans, such as upper respiratory, dermatological, neurological, and gastrointestinal health impacts.

The few studies focused on the air quality and health of people in Dish, Texas have yielded mixed results.[17] For example, the Texas Department of State Health Services (DSHS) conducted biological testing for 28 residents to determine levels of VOCs in their blood and found that the

[17]These studies are not peer-reviewed, but are indicative of the current controversy regarding health and environmental effects of shale gas development.

levels in the blood were similar to the US population (DSHS, 2010). VOCs have a half-life of about 4 hours in some cases and so determining exposures and prolonged exposures is difficult to determine with a single test. While another study, surveying 31 residents, found that 61 percent of the health impacts self-reported by the residents are known health effects of the VOCs detected in the air in 2009 (Subra, 2009; WEE, 2009).

2.4 Selected Environmental Health Literature

The exact biological mechanisms through which air or water pollution impacts infant health are not yet well understood. However, in the last decade, the environmental health literature has grown with many studies linking air pollution and infant health outcomes. Table 1 lists selected recent works that study the infant health impacts of exposures to pollutants that have been linked to drilling activities. For example, a recent multi-country evaluation explored the heterogeneous impacts of maternal exposure to particulate matter (PM) and term birth weight and found in meta-analysis that increased exposure to PM10 reduced term birth weight by 8.9 grams on average (Dadvand et al., 2013). A few recent studies have linked exposure to polycyclic aromatic hydrocarbons (PAHs) during pregnancy with increased risk of intrauterine growth retardation (one cause of low birth weight), as well as both term and pre-term low birth weight (Dejmek et al., 2000; Vassilev et al., 2001; Perera et al., 2005). Benzene is one of the most commonly measured air pollutants associated with shale gas development and has been linked to a reduced birth weight of 58 grams, 66 grams and 77 grams in recent studies, respectively (Chen et al., 2000; Aguilera et al., 2009; Slama et al., 2009).

Stillerman et al. (2008) review the epidemiological literature and find associations between low birth weight and maternal exposures to PM, SO_2, CO, NO_x, VOCs and ozone. Most of the studies cited looked at these pollutants in isolation, but with shale gas development mothers are likely exposed to many at the same time and there is little research that examines any compounding effects.[18] Unfortunately, many of the epidemiological studies do not take into account socio-economic status and so the observed relationships could reflect unobserved factors that may be correlated with pollution and infant health outcomes (i.e. urban areas).

There is a growing literature in environmental 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.[19] 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 for residences within 8 km of the air pollution monitor. However, they also detect longer gestational periods and calculate that almost all of the improvements in birth weight can be linked to increased gestational periods, rather than intrauterine growth restriction (IUGR).

Currie & Schmieder (2009) explore the Environmental Protection Agency's (EPA) Toxic Release Inventory (TRI) to look at some of the pollutants that are not commonly measured, such as toluene and fugitive volatile organic compounds (VOCs). These are mentioned with gravest concern in the public health literature addressing public health concerns associated with shale gas

[18]See Currie et al. (2009); Shah & Balkhair (2011); Stieb et al. (2012); Glinianaia et al. (2004); Sram et al. (2005) for other reviews of past literature related to air pollution and birth outcomes.

[19]See Currie, Zivin, Mullins, & Neidell (2013) for a review of the economics literature on short and long term impacts of early life exposure to pollution.

development (Witter et al., 2008; Korfmacher et al., 2013; Schmidt, 2011; Shonkoff, 2012). Currie & Schmieder (2009) find that a 2 standard deviation increase in toluene increased low birth weight by 1.9 percent and find that exposure to VOCs reduced birth weight on average and increased low birth weight by 0.87 percent.[20]

Relying on this extensive literature exploring the relationship between infant health and air pollution to provide biological plausibility to the results that follow, I build on the previous literature by using the natural experiment of the introduction of shale gas wells, rich controls for confounding maternal characteristics, and homogenous groups of mothers to investigate the effects of shale gas development on infant health.

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

[20]Agarwal et al. (2010) use the TRI to investigate the effects of TRI on infant mortality and find that carcinogenic air pollutants (i.e. BTEX) have the most adverse effects on infant mortality. They also find that non-carcinogenic/non-developmental/non-reproductive toxins have statistically significant effects on infant mortality. And when the authors control for air pollution, they find that toxics in the water have adverse effects on infant 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 analyses that follow, I control explicitly for these, as well as month of birth, year of birth, the interaction, and gender of the child.[21] 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.[22] Low birth weight is a latent variable as defined and so I also present the 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), congen-

[21]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.

[22]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 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.

ital anomalies, and infant mortality (death in the first year).[23] Another potential measure of health at birth is the 5 minute American Pediatric Gross Assessment Record (APGAR) score.[24] 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).[25]

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, 2013b). 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) 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 2 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

[23] 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).

[24] 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).

[25] 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.

be drilled. The localized data I use in this analysis is actually quite similar to the characteristics of the rest of the state.[26] 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 3 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 3. 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, when controlling for county time trends, Table 4 suggests no changes in these economic variables after shale gas development.

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

[26]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.

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. This is a constant concern in the literature that attempts to exploit variation in health at birth (see Currie & Walker (2011)). 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.[27] 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 significant independent interest to the policy debate around shale gas development.

One important caveat is that, like all such studies, I can observe health at birth for only those babies that are born alive. Also, I can only observe births for those mothers who "choose" to get pregnant. If the composition of mothers "choosing" to get pregnant changes with the introduction of shale gas development, then the health that I observe may not be indicative of the average health

[27] There are some other clues in the current literature regarding shale gas development: 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.

of those living near wells in these neighborhoods.[28]

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 5 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 3 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 7 shows the trend in premature birth. Again, as was suggested by Figure 3, there does not appear to be a clear relationship between drilling and premature birth.

[28] 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.

4.2 Statistical Estimation Framework

I proceed by estimating models informed by the graphical evidence to investigate the effects of proximity to gas wells on infant health. First, I use the cross-sectional difference estimator to check for pre-existing differences in the characteristics of mothers whose residences are located within 2.5 km of a shale gas well. Given the similarity, I then use a difference-in-differences model –in which mothers exposed 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.

The cross-sectional difference specification takes the following form:

$$Outcome_i = \beta_0 + \beta_1 D_i^{2.5km} + \alpha_i + \varepsilon_i \tag{1}$$

$Outcome_i$ is a function of a measure of distance from the resource well, a random error term (allowing for specific correlation in health by county), α_i, a county, month and year specific effect. $D_i^{2.5km}$ is an indicator variable set to one if the mother's residence is within 2.5 km of a well. I present these results within 5 and 15 km of any well, with and without maternal characteristics. To examine variation in other mother characteristics, I substitute those characteristics for $Outcome_i$ as the dependent variable.

The difference-in-difference specification adds an indicator variable for if the birth occurs after the closest well was spudded ($Post_i$) and the interaction of this indicator with the distance indicator ($D_i^{2.5km}$). 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:

$$\begin{aligned} Outcome_i = \delta_0 + \delta_1 X_i + \delta_0 D_i^{2.5km} + \delta_1 Post_i \\ + \delta_2 D_i^{2.5km} * Post_i + \alpha_i + \chi_i + \varepsilon_i \end{aligned} \tag{2}$$

α_i are birth month and year fixed effects, and χ_i are county fixed effects. X_i are mother and birth characteristics.

The estimated impact of shale gas drilling on infant health is given by the term δ_2 and is the difference-in-differences estimator. χ_i is designed to capture any unobserved time-invariant characteristics of each county in the sample. α_i are included to address seasonal and secular time trends. The standard errors in these models are clustered at the mother's residence county. The vector X_i 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.

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. For example, the 2.5 km comparison group is composed of infants whose mother's residence is within 2.5 km of a permit or future drilled well. The 2.5 km affected group is thus defined as those infants that are born after a shale gas well is completed within 2.5 km of their mother's residence. 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 and that the birth outcomes are similar on average. 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. This concern is discussed in detail in Section 2.2.1. 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:

$$\begin{aligned} Outcome_i = \delta_0 + \delta_1 X_i + \delta_0 D_i^{2.5km} + \delta_1 Post_i + \delta_3 PWSA_i \\ + \delta_2 D_i^{2.5km} * Post_i + \delta_4 D_i^{2.5km} * PWSA_i + \delta_5 PWSA_i * Post_i \\ + \delta_6 D_i^{2.5km} * Post_i * PWSA_i + \alpha_i + \chi_i + \varepsilon_i \end{aligned} \tag{3}$$

where the other controls are the same as the main equation (2). δ_6 is the triple-difference estimator of the impact of proximity to a well after drilling for homes on 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. First, I limit the sample to births that took place before any drilling began and estimate equation (1) using residences within 5 km from future gas wells. In Table 4: 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 also estimate equation (2) and use the difference-in-difference estimator to see if there are any changes in mother characteristics after drilling began. In Table 4: 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.[29]

5.2 The Impact of Shale Gas Development on Low and Term Birth Weight

To more fully examine pre-drilling trends in birth outcomes, I first present estimates of equation (1) in columns (1) and (3) of Table 5, including birth month, year and county fixed effects, but no other control variables. In columns (2) and (4), I present estimates that include maternal characteristics. A reliable indication that the estimation strategy is sound occurs when these two estimates do not differ in magnitude or significance from each other. The estimates β_1 from this specification are simply a measure of the average difference in low (term) birth weight for residences within 2.5 km of a future gas well compared to residences within 5 km of a future well. Including maternal controls has little impact on the estimates. Living closer to a future drilling site is associated with a 0.2 percentage point reduction in low birth weight and a 15 gram increase in term birth weight, on average. These differences in low birth weight and term birth weight are suggestive of heavier infants and shows that birth outcomes may have been better off prior to drilling in the closest proximity to future drilling sites.[30]

Table 5 shows the main results from estimating equation (2). Distance to a (future) well is held fixed at 2.5 km for these models. Each coefficient represents an estimate of δ_2 –my difference-in-difference estimator– from a separate regression. Columns (5) and (7) show a model that controls only for month and year of birth and county fixed effects. Adding controls for observable char-

[29]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).

[30]To make sure that this is not driven by the comparison group, I also estimate equation (1) with residences within 15 km of a future well. These differences are similarly suggestive of better birth outcomes closest to future drilling sites prior to drilling (Appendix Table A1).

acteristics of the mother should only reduce the sampling variance while leaving the coefficient estimates qualitatively unchanged. Columns (6) and (8) 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.[31] 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).

5.3 The Impact of Shale Gas Development on Alternative Measures of Health

Table 6 presents similar estimates to Table 5 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, comparing outcomes before and after drilling at 2.5 km from a well head. The first column of each measure is estimated without maternal characteristics and the second column of each measure includes maternal characteristics. Again, controlling for maternal characteristics does not have an appreciable effect on the estimates. 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

[31]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.

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.[32]

Following Currie, Davis, et al. (2013), I address the issue of precision using a summary index measure of infant health. 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).

5.4 The Impact of Shale Gas on Infant Health 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.[33] Table 7 presents the results for equation (3).[34] This formally tests whether there are differences between water source in the infant health outcomes detected in the main results (δ_6 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.

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

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

[34]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.

increased noise, stress from community change).[35]

5.5 Robustness Checks

Table 8 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 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.[36]

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.[37] 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

[35] 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 5. Results available upon request.

[36] A more detailed discussion of mobility is presented in Appendix Section A.1.

[37] (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.

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.[38]

Table 9 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_2 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 5 and 6. Table 9: 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 5 and 6.

An important issue to explore is whether the effects of exposure to shale gas drilling are the

[38]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 activity. 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.

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 9 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 smoking. 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.3.

5.6 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 10, column (5)).[39]

6 Discussion and Interpretation

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 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

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

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.[40]

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 premature 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). Despite emissions from shale gas development making up a small percentage of the total emissions measured in the entire state of Pennsylvania, shale gas development can be a source of substantial aggregate local

[40]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.

pollution in rural areas that do not have established air pollution sources. These results suggest that requiring air pollution monitoring of drillings 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.

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.[41] 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.[42]

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

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

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

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, 2010a). 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.[43]

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).

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.

[43] 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).

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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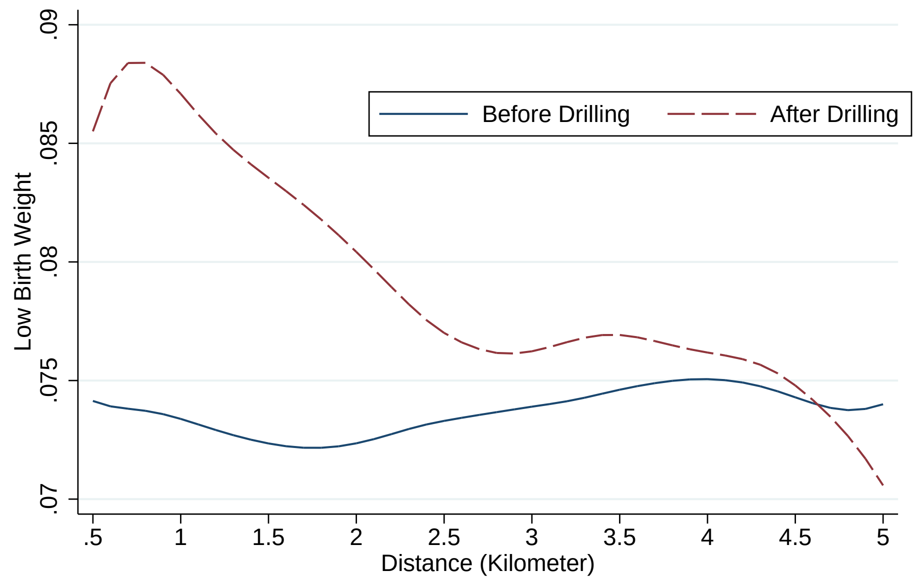
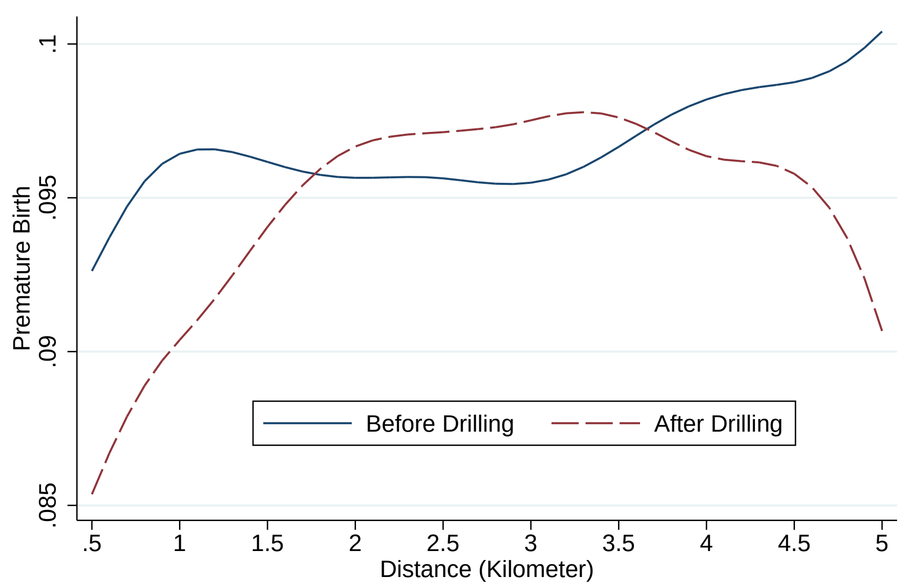


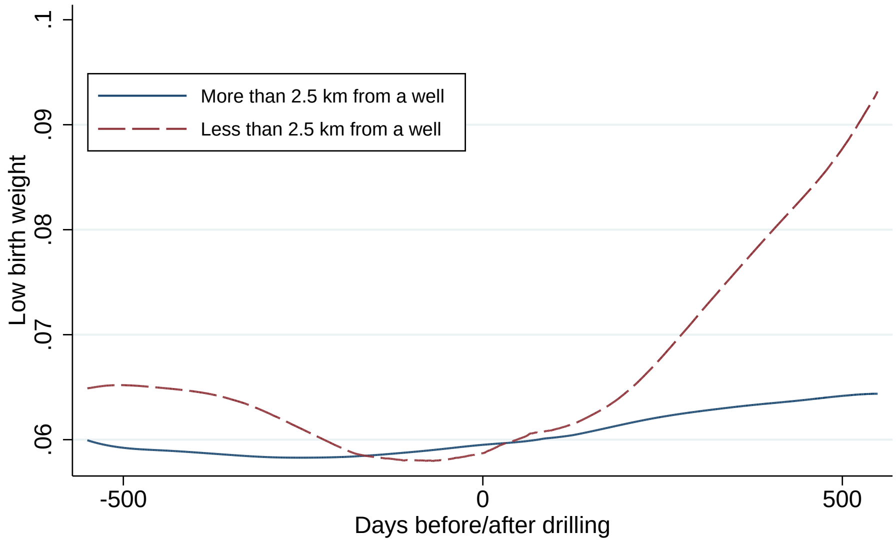
Results from a local polynomial regressions (bandwidth=0.1 km) of low birth weight on distance from closest well's future/current location. Source: Author calculations from Pennsylvania Department of Health Vital Statistics.

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



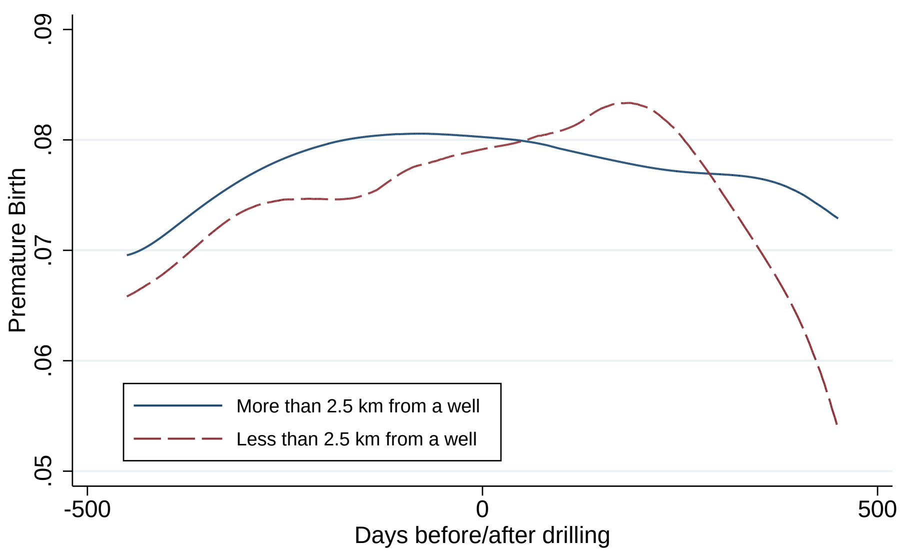
Results from a local polynomial regressions (bandwidth=0.1 km) of premature birth on distance from closest well's future/current location. Source: Author calculations from Pennsylvania Department of Health Vital Statistics.

Figure 3: 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 5: 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 7: Prematurity Trends Before and After Drilling

Table 1: Selected Studies Showing Effects of Environmental Air Pollution on Infant health

Pollutant	Study	Location	Sample	Outcomes	Effects
CO	Currie et al. (2009)	NJ	305,530	LBW	1 unit change in CO increases LBW by 8%
				BW	1 unit change in CO reduces BW by 16.65g
NO2	Currie & Walker (2011)	PA & NJ	409,673	LBW, premature	E-ZPass reduced LBW and prematurity by 10.8 and 11.8
CO	Coneus & Spiess (2011)	Germany	1,154	BW	High exposure to CO leads to 289 g lower average BW
Particulates	Dadvand et al. (2013)	Multi-Country		TBW	Increased exposure to PM reduced TBW (-8.9g)
PAHs	Dejmek et al. (2000)	Czech Republic	4,883	IUGR	Associated with IUGR
	Vassilev et al. (2001)	NJ	199,474	TBW, LBW	Associated with LBW and TBW
	Perera et al. (2005)	NYC	373	BW, gestation	Associated with BW and gestation
Benzene	Chen et al. (2000)	Beijing, China	792	BW	Benzene exposure reduced BW by 58g
	Aguilera et al. (2009)	Barcelona, Spain	570	BW	BTEX exposure reduced BW by 77g
	Slama et al. (2009)	France	271	BW	Benzene exposure reduced BW by 68g
	Zahran et al. (2012)	US	3.1m	BW	Exposure to benzene reduced BW by 16.5g
				LBW	Increased odds of a very LBW infant
Toulene	Currie & Schmieder (2009)	US	5279	LBW	2 sd increase in toulene increases LBW by 1.9%
VOCs				LBW, BW	Fugitive VOCs reduced birth weight and increased LBW
SO2	Lavaine & Neidell (2013)	France	5652	BW, gestation	Reduced SO2 increased BW and gestation by 3% and 1.5

Notes: BW= birth weight; LBW=low birth weight; TBW=term birth weight; PAHs=Polycyclic aromatic hydrocarbons.

Table 2: 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 3: 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 4: Pre- and Post- Drilling Differences in Average Characteristics of Births Close to Well Locations

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
			Characteristic of Mother					
	LBW	Term Birth Weight	Education (years)	Teen Mom	Dropout	Black	Smoked	Born in PA
			Panel A: Pre-drilling differences in characteristiscs					
Within 2.5 km of well	-0.00196	9.520*	-0.290***	0.00261	0.0067	-0.00735	0.00959	0.0301***
	(0.0019)	(4.794)	(0.0903)	(0.00337)	(0.00998)	(0.00607)	(0.0104)	(0.00862)
Sample Size	43522	40175	43426	43582	43582	43582	43582	43582
R^2	0.004	0.01	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, their interactions 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 5: Impact of Well Location on Low and Term Birth Weight

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Pre-drilling (5 km)				*Pre- and post- drilling (2.5 km)*			
	Low Birth Weight		Term Birth Weight		Low Birth Weight		Term Birth Weight	
Within 2.5 km of well	-0.00196	-0.00240	9.52*	15.16***	-0.000790	-0.00178	18.2	24.01
	(0.0019)	(0.00198)	(4.794)	(4.784)	(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	43522	43522	40175	40175	21610	21610	19978	19978
R^2	0.004	0.018	0.0099	0.074	0.008	0.021	0.013	0.075
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. Standard errors are clustered at the mother's residence county. The sample is limited to singleton births. All regressions include indicators for month and year of birth, their interactions, 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. For pre-drilling, columns (1)-(4) contain all observations within 5 km of a well or permit prior to drilling. For pre- and post-drilling, columns (5)-(8) contain the primary research sample: those residences within 2.5 km of a well or permit, before and after drilling. Signifance: * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

Table 6: 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 (weeks)		Premature	
Within 2.5 km * post-drilling	-46.16***	-46.62***	0.0254**	0.0251**	-0.0811	-0.0771	0.000517	-0.000343
	(13.84)	(12.52)	(0.0099)	(0.0101)	(0.0559)	(0.0513)	(0.00616)	(0.00681)
Sample Size	21610	21610	21646	21646	21204	21204	21204	21204
R^2	0.013	0.061	0.026	0.029	0.014	0.021	0.008	0.012
	SGA		Congenital Anomaly		Infant Death		Summary Index	
Within 2.5 km * post-drilling	0.0180**	0.0181**	-0.00210	-0.00193	-0.00079	-0.00075	0.0255**	0.0264**
	(0.00720)	(0.00764)	(0.00194)	(0.00189)	(0.00149)	(0.00143)	(0.0105)	(0.0101)
Sample Size	21524	21524	21646	21646	21646	21646	21646	21646
R^2	0.008	0.040	0.006	0.008	0.007	0.042	0.014	0.045
Maternal Characteristics	no	yes	no	yes	no	yes	no	yes

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. Standard errors are clustered at the mother's residence county. The sample is limited to singleton births. All regressions include indicators for month and year of birth, their interactions, 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 7: 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: See Table 5. Each column is a different regression. The full model is a triple difference, with important coefficients reported above. Source: Author calculations from Pennsylvania Department of Health Vital Statistics. Note: LBW= low birth weight; TWB= term birth weight; SGA= small for gestational age. Significance: * p<0.10, ** p<0.05, *** p<0.01.

Table 8: 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 5. Each column is a different regression. 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 9: Robustness Checks, Shale Gas Development on Birth Measures

	(1)	(2)	(3)	(4)
	Low Birth Weight	Term Birth Weight	Birth Weight	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 5. Each panel is a separate regression. All regressions include controls for maternal characteristics and county-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 10: Falsification Tests on Impact of Well Location

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Baseline Estimates			Permit Date			Random date		
	LBW	TBW	Premature	LBW	TBW	Premature	LBW	TBW	Premature
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(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 5. Each panel is a separate regression. All regressions include controls for maternal characteristics and county-time trends. Columns (1), (2) and (3) are the baseline estimates from Tables 5 and 6. 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.

A Appendix

A.1 Changes in Community Composition

Changes in community composition associated with shale gas development is one of the primary threats to using a difference-in-difference approach in a repeated cross-sectional framework used in this paper. Changes in community characteristics are primarily caused by migration in and out of communities with development activities. There are multiple reasons why families might move in response to drilling. For example, due to increased local economic activity in these communities, it is possible that families move into these communities to benefit from the improved economic conditions. If those who move towards improved economic activity have better (worse) health, then this would improve (reduce) the average health in the community. Alternatively, mothers who value their children's health may be more likely to move away from communities where drilling is taking place. This migratory effect would lower the average health of the observed births. However, it is also possible that those who are more likely to move away are families who are experiencing the worse health effects of drilling. This migratory effect would increase the average health of the observed births. Another form of migration may stem from the influx of workers entering these communities, but existing evidence suggests that greater shale gas production does not result in a less educated population (Weber, 2013; Muehlenbachs et al., 2014). Thus, it is not clear whether selection or composition of the mother characteristics would lead me to overestimate or underestimate the health impacts of close proximity to drilling activity.This issue is present in all empirical work using vital statistics, where each birth occurs only once.

I do not find any evidence of changes in the average demographics of mothers living near wells after drilling or in the probability that they move during the observed period. This, however, could mask heterogeneity in the responses across mothers. Following Currie, Zivin, Meckel, et al. (2013), I use the sample of mothers who had multiple births during 2003-2010 to define whether the mother moved at any point during the time frame. I do not find a systematic relationship between low SES factors and the likelihood of moving. For example, I find that the least educated (high school or less) and smokers are more likely to move in response to drilling and that college educated mothers, African American mothers and teen mothers are less likely to move.[44] I do not find a statistically significant difference in the incidence of movers amongst Medicaid recipients, WIC recipients or those who have private insurance. Moms who were born in Pennsylvania are more likely to move after drilling.[45]

Muehlenbachs et al. (2014) use Census tract level data to investigate changes in neighborhood composition associated with shale gas development. Using 33 tract level attributes, they estimate the effect of the number of wellbores within 20 km of the centroid of the census tract on changes in neighborhood compositional changes from 2000 to 2012. The find very few economically significant effects, with no one attribute changing more than 1% over the 12 year period. They find a slightly smaller population and a slightly smaller per capita income, but no changes in education or other factors that are correlated with infant health. The authors conclude that any changes in neighborhood composition induced by shale gas development are quite small. These findings support my claims that changes in community composition is not likely to explain the results in this paper.

A.2 Discussion of Mechanisms

The research design used in this paper does not depend on a clear mechanism of exposure for the findings to provide defensible estimates of the effects of drilling on infant health. This is advantageous given the controversy regarding potential mechanisms and levels of exposure. However, some consensus is forming in the literature about the potential risks, their probabilities and which mechanisms of pollution exposure most fully explain my results.

To assist in facilitating the conversation regarding risk mitigation priorities, Krupnick et al. (2013) surveyed 215 experts in government, industry, universities and nongovernmental organizations to identify priority environmental risks related to shale gas development. The experts had a

[44] Muehlenbachs et al. (2014) find increases in housing prices, on average. This may force lower socio-economic groups to move out of these communities.

[45] Results available upon request.

high degree of consensus about the specific risks to mitigate. Sources of surface water contamination were linked to site preparation, storage of fracturing fluids, on-site pits for storing flow back and produced water and treatment of flow back water. Ground water contamination was linked to flow back water storage, but was considered unlikely and required a long time horizon. Air quality concerns were linked to venting of methane during both the drilling and hydraulic fracturing phases. Experts identified surface water impacts to lakes, rivers and streams as the most dominant concern for ecological health. Other risks identified were related to road and well pad construction, pipelines and leaky casing/cementing.

Even if ground water contamination is more widespread than has been currently estimated, a growing area of the economics literature suggests that avoidance behavior may affect the measurement of the impacts of pollution.[46] People move away from polluted areas, stay indoors when there are ozone warnings and drink bottled water to avoid chemical contamination in public water drinking sources (Currie, 2011; Gamper-Rabindran & Timmins, 2011; Neidell, 2004; Graff Zivin & Neidell, 2009; Graff Zivin et al., 2011). The environmental health literature has very few studies that measure drinking water contamination effects on fetal health. A recent study found little effects, on average, of water contamination in NJ on low birth weight or premature birth (Currie, Zivin, Meckel, et al., 2013). The study did find statistically significant impacts on the least educated mothers and may be suggestive of avoidance behavior or other unobserved factors driving these differences. Given that most attention has been paid to ground water contamination in the media, individuals close to drilling sites are more likely to be aware and mitigate risks associated with water rather than air exposures. Muehlenbachs et al. (2014) find that housing prices are responsive to perceptions of groundwater contamination risk in Pennsylvania and lead to large and significant reductions in property values for properties on ground water suggesting that individuals closest to drilling activity are well aware of the water contamination concerns. Therefore, pregnant women close to drilling operations are likely to be aware of the water pollution risks and are not as

[46]Well casing failure is estimated to be 6% of new wells drilled in 2010 in Pennsylvania Ingraffea (2012) or 90 well failures in 2010.

likely to be exposed through drinking water sources.[47] As reported in the main text, I do not find differences in birth outcomes between residences on public water versus those on ground water. This does not rule out systemic ground or surface water contamination, but is suggestive that the mechanism behind the results is air pollution or maternal stress. Although maternal stress and birth outcomes is an under-developed area of research, there are some recent studies that suggest a relationship between maternal stress and low birth weight and gestational age (Rondo et al., 2003; Dole et al., 2003; Camacho, 2008; Eskenazi et al., 2007; Lindo, 2011). Mothers living closest to drilling activity are most likely to be affected by noise, light and visible aspects of the drilling process, so I cannot rule out maternal stress as an additional factor.

There are many potential mechanisms that are impacting public health and explain the results in this paper.[48] Even with better data, there is unlikely to be just one mechanism or one pollutant that explains the results.

A.3 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

[47] As with Currie, Zivin, Meckel, et al. (2013), I do find larger effects for mothers who are high school dropouts. This may indicate that less educated mothers are not mitigating the risks as effectively as mothers who are better educated. Results are available upon request.

[48] See public health discussion papers for more: Finkel et al. (2013); Shonkoff (2012); Mitka (2012); Finkel & Law (2011); Colborn et al. (2011); Schmidt (2011); Shelley (2011).

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 5 and 6 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. Standard errors are clustered at the mother's residence county. 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, their interactions, 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 5. Each panel is a separate regression. All regressions include controls for maternal characteristics and county-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 5. Each panel is a separate regression. All regressions include controls for maternal characteristics and county-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. * $p<0.10$, ** $p<0.05$, *** $p<0.01$