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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 de- tailed location data on maternal addresses and GIS coordinates of gas wells, this study examines singleton births to mothers residing close to a shale gas well from 2003–2010 in Pennsylvania. The introduction of drilling increased low birth weight and decreased term birth weight on average among mothers living within 2.5 km of a well compared to mothers living within 2.5 km of a future well. Adverse effects were also detected using measures such as small for gestational age and APGAR scores, while no effects on gestation periods were found. These results are robust to other measures of infant health, many changes in specification and falsification tests. In the intensive margin, an additional well is associated with a 7 percent increase in low birth weight, a 5 gram reduction in term birth weight and a 3 percent increase in premature birth. These findings suggest that shale gas development poses significant risks to human health and have policy implications for regulation of shale gas development.

Keywords

infant health; shale gas development; air pollution; water pollution; low birth weight

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[6] 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.

[16] 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.

[17] Johnson and 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. (2014) use linked birth and schooling records in Florida and find that birth weight has a significant impact on schooling outcomes for twin births.

[24] Only one maternal characteristic shows a significant change with drilling: mothers observed after drilling are more educated than those observed prior to drilling (results not shown). Increased college completions among mothers would potentially improve observed infant health in these communities. However, this does suggest some selection and so I include these and other controls in all the subsequent results.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 and Greenstone, 2003b; Dehejia and Lleras-Muney, 2004).

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] 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 and McGinty, 2013). With this expansion, it is becoming increasingly common for shale gas development to take place in close proximity to where people live, work and play.

The expansion of shale gas development (SGD) in the US has brought with it a national debate that seemingly lacks a consensus over its economic, environmental, health and social implications. There is growing evidence that shale gas development creates jobs and generates income for local residents in the short run (Allcott and Keniston, 2014; Bartik et al., 2016; Feyrer et al., 2017; Hausman and Kellogg, 2015; Mason et al., 2015). In addition to its economic benefits, many claim that a move to natural gas (and away from petroleum- or coal-based energy) will support U.S. energy independence and national security. Shale 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 coal and other fossil-fuel energy sources per unit of heat produced (Chen et al., 2017). Globally, the shale boom has improved ambient air quality and displaced coal-based electricity, especially for areas with coal-fired power plants (Johnsen et al., 2016). However, these benefits may come with local costs associated with drilling activity in communities where it takes place. These costs may include reduced environmental quality through local air pollution (Colborn et al., 2012; Litovitz et al., 2013; Witter et al., 2013), water contamination (Warner et al., 2012; Olmstead et al., 2013; Hill and Ma, 2017), increased truck traffic (Graham et al., 2015) and health. Concerns over perceived ground water contamination have caused a discount of housing prices to compensate for the risk and an approximately $19 million increase in bottled water purchases in 2010 in response to SGD in Pennsylvania (Muehlenbachs et al., 2015; Wrenn et al., 2016). This is further supported by a recent cost-benefit analysis that found substantial environmental costs associated with health damages from air pollution emitted by SGD totaling $27.2 billion (Loomis and Haefele, 2017).

In utero exposure to air pollution has been linked to adverse birth outcomes, lower educational attainment, labor market outcomes and future health problems (See Currie and

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[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).

Schmieder (2009); Currie (2009); Currie et al. (2014b) for summaries of this research). In particular, a large literature has linked air pollution (e.g. particulate matter (PM), carbon monoxide (CO), sulfur dioxide ($S0_2$), nitrogen oxide (NO_x)) from coal-fired power plants with low birth weight, premature birth and infant mortality both within the US and in the developing world.[4] With natural gas touted as a transition fuel between coal-based electricity and renewable options, infant health is one way to compare costs across alternative options. While coal is undeniably worse than natural gas with respect to resource extraction and energy generation, concerns regarding emissions associated with shale gas should be studied (Chen et al., 2017).

The impact of shale gas development on health has become the focus of a growing body of literature. To my knowledge, Hill (2012) is the first study to assess the impact of shale gas development on infant health. Concurrent health studies include case studies (Bamberger and Oswald, 2012), health impact assessments (McKenzie et al., 2012), toxicological assessments of specific chemicals (Colborn et al., 2011), self-reported health symptoms (Ferrar et al., 2013) and studies exploiting administrative records such as birth certificates, hospital records or electronic medical records (EMR) to study asthma, pneumonia, fatigue, migraine, sinus effects, and birth outcomes (Hill, 2013; McKenzie et al., 2014; Stacy et al., 2015a; Rasmussen et al., 2016; Casey et al., 2016; Tustin et al., 2017; Currie et al., 2017; Whitworth et al., 2017; Peng et al., 2018).[5] All but one of the infant health studies find a positive association between drilling and poor birth outcomes measured by premature/ preterm birth (PTB) or low birth weight (LBW). Due to a lack of consistency in outcomes, proximity, and exposure metrics used, it is challenging to compare findings across these studies.

To assess the impact of shale gas development on infant health, I build a unique database 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 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 shale gas drilling within small, relatively homogeneous 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 robust estimates of the impact of maternal exposure to shale gas development during pregnancy on birth outcomes.

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

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[4] See Chay and Greenstone (2003a); Currie and Neidell (2005); Jayachandran (2009); Tanaka (2015); Knittel et al. (2015); Sanders and Stoecker (2015); Clay et al. (2016); Arceo Eva et al. (2016); Yang et al. (2017); Yang and Chou (2017); Severnini (2017); Jha and Muller (2017). For example, Yang et al. (2017) found that after a power plant in PA closed down, low birth weight declined by 15 percent and premature birth by 28 percent due to reductions in PM2.5 and S02.

[5] 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; see Vengosh et al. (2014) for a review of the likely effects of water contamination from SGD; see Werner et al. (2015), Stacy (2017), and Balise et al. (2016) for recent reviews of SGD and health related studies.

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. Results for premature birth were mixed and sensitive to specification. The difference-indifferences 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, testing for pretrends in the outcome variables using the sample before drilling, permit dates only, and future wells only, and using a random date to define treatment. The research design is robust to these tests as well as a range of specifications. I examine mobility using the group of mothers with more than one birth and find that there is little evidence of moms moving in response to drilling. I perform a back of the envelope calculation on the costs of these activities using my estimates and the estimated population within 1 mile of drilling from the Wall Street Journal (e.g. 15 million Americans) and estimate that drilling costs more than $230 million per year in the 11 out of 33 gas producing states. This estimate is likely to be a lower bound given that this assessment doesn't include all states with development and that I use a lower bound estimate of the costs associated with low birth weight.

This paper contributes to the literature using a quasi-experimental design and is a combination of the strengths of both the epidemiologic and economic literature described above. First, I improve upon the epidemiologic literature by employing a difference-in-differences design. In particular, I exploit the exogeneity of drilling conditional on leasing and permitting, which results in statistically homogenous treated and comparison groups. This provides a more stable comparison group than in Currie et al. (2017) that compares to those living within 3–15km. Second, I improve upon the economics literature by using the strengths of the epidemiologic literature by looking at multiple measures of adverse infant health outcomes which may be indicative of different aspects of drilling exposure. Preterm birth is indicative of preterm premature rupture of membranes, which can result from genetics, stress or low socio-economic status (SES) (Goldenberg et al., 2008). Low birth weight and small for gestational age (SGA) are more related to intrauterine growth restriction (IUGR), which is more consistently related to air pollution (Stieb et al., 2012b; Sun et al., 2015; WHO, 2005). Congenital abnormalities indicate exposure to a teratogen during pregnancy. Given the inconsistency in measured outcomes in existing studies, I simultaneously estimate impacts for all outcomes within the same sample and identification strategy. This is particularly useful for policy given the mixed findings in the existing studies and that none of these studies directly test exposure mechanisms. Third, I improve upon the economics literature by thoroughly controlling for predictors of infant health and estimating the extensive and intensive margins of drilling. I include controls for insurance status, WIC, previous risky pregnancy, parity, and smoking status. I also measure heterogeneity across SES subgroups and test whether moms are moving in response to drilling. Importantly, I contribute to the literature by measuring the effect of an additional well on birth outcomes, which is perhaps more relevant to policy-making than simple binary measurements of exposure.

The rest of the paper proceeds as follows: section I presents background and context and section II describes the data. Section III presents graphical evidence and section IV describes the estimation strategy. Sections V and VI presents results and robustness checks. Section VII provides interpretation and discussion of the results. Section VIII concludes.

I Background

I.I A Brief Shale Gas Overview for Pennsylvania

In Pennsylvania, shale gas development involves primarily high-volume hydraulically fractured horizontal wells drilled into the Marcellus Shale and more recently, the Utica Shale. Hydraulic fracturing is a process to stimulate a well that uses water to fracture the rock or shale beneath the ground. On average, in Pennsylvania, it involves injecting approximately 4–8 million gallons of water mixed with sand and fracturing chemicals into the well and using pressure to fracture the shale about 6,500–7,500 ft below the surface (Chen and Carter, 2016). Shale plays are heterogeneous and so the distance drilled and quantity of water required differ across varied geological formations. The entire process of completing a natural gas well takes, on average, 3–9 months to finish: access road and well pad construction occurs for a month (0–4 weeks) prior to the spud date, drilling the well takes about 30 days (vertical drilling for 0–2 weeks and horizontal drilling for 4–8 weeks), preparation for hydraulic fracturing takes 1–2 months, hydraulic fracturing takes about 7 days, flowback occurs for 2–8 weeks and clean up and testing takes about a month before the well goes into production (Casey et al., 2015; Graham et al., 2015). During the first few months, diesel trucks bring in materials required for the drilling process, averaging 1500–2000 truck trips per well completion in Pennsylvania. During the first 30 days after well stimulation, 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 (Kondash et al., 2017).

Most wells are drilled on private property that has been leased to oil and gas companies.[1]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.

The identification strategy used in this paper depends on the assumption that drilling is exogenous relative to locations that are permitted but not yet drilled. However, areas that are permitted but not drilled may be different from areas that experience active drilling. For example, areas without active drilling may not have as many property owners willing to lease mineral rights or the industry may prioritize leasing in areas with the most productive shale. Appendix Figure A1 overlays the parcels with leases from Drillinginfo with the strata of shale depth from EIA. For counties where we have lease data, the extent of leasing is densest along the deepest contours and more sparse along the shallower contours, except in the northeastern part of the state such as Bradford County. To examine this further, I linked the lease and depth data to the wells and permits used in these analyses to test whether there are substantial differences.[7] There are no differences in leasing defined by the proportion of acres leased within Census block groups between permitted and drilled wells. The average

Census block group in the data is 40 percent leased for both permitted and drilled locations. In the top 10 drilled counties, this jumps to 60 percent, but is again the same across permitted and drilled locations. Permits that are drilled seem to be explained by shale depth as opposed to some difference in community preference as proxied for by leasing activity.

I.II 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. Below I review the current state of the scientific evidence.

I.II.1 Water Pollution—There are a number of mechanisms by which shale gas development might contaminate ground and surface water sources and thereby impact either public or private drinking water. According to a recent assessment by EPA, these mechanisms include: spills of hydraulic fracturing (HF) fluids prior to mixing with large quantities of water or produced water after hydraulic fracturing has taken place, injection of hydraulic fracturing fluids into wells with inadequate mechanical integrity (e.g. faulty well casings), injection of HF fluids directly into groundwater sources, discharge of inadequately treated hydraulic fracturing wastewater to surface water, and disposal or storage of hydraulic fracturing wastewater in unlined pits (EPA, 2016; Osborn et al., 2011; Jackson et al., 2013; Olmstead et al., 2013; Warner et al., 2013).[8] The EPA report identified 1,084 chemicals reported to be used in hydraulic fracturing fluids and 599 chemicals detected in produced water(EPA, 2016). Of the 599 chemicals detected in produced water, only 77 were also reported to be used in hydraulic fracturing fluid– which is not a great match. The report found that chemicals used in HF fluid varied greatly across regions, which limits external validity(EPA, 2016).[9] Elliott et al. (2017) provides a review of these chemicals for reproductive and developmental toxicity.[10]

The lack of reliable information about what chemicals are used leaves the scientific community testing many different chemicals across regions, with little overlap among detected chemicals. Studies of groundwater contamination have primarily used private drinking water wells and assessed proximity to shale gas wells to assess contamination (e.g. within 5 km of gas wells versus larger distances) (Hildenbrand et al., 2016; Osborn et al., 2011; Jackson et al., 2013). Studies have found increases in organics (many naturally occurring such as chlorides, bromides and iodides, arsenic, selenium, manganese, strontium, barium, heavy metals, beryllium), volatile and semivolitile organic compounds (e.g. BTEX, 2-Butanone), diesel range organic compounds, solvents (e.g. methanol, dichloromethane), and methane (Drollette et al., 2015; Hildenbrand et al., 2015, 2016; Yan et al., 2016;

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[7] Available upon request.

[8] Scientists face challenges in assessing the potential for contamination due to limited baseline data on water quality, lack of publicly available data regarding the chemicals used in fracturing uid, the sheer number of chemicals use and naturally occurring contaminants returning to the surface in the process of drilling and hydraulic fracturing.

[9] See Chen et al. (2017) for more information about specific chemicals of concern. The EPA Report has a large appendix characterizing each chemical with citations.

[10] Toxicity information was lacking for 781 (76%) chemicals. Of the remaining 240 substances, toxicological studies suggested reproductive toxicity for 103 (43%), developmental toxicity for 95 (40%), and both for 41 (17%). Of these 157 chemicals, 67 had or were proposed for a federal water quality standard or guideline.

Alawattegama et al., 2015; Burton et al., 2016). Some studies have not found any evidence of contamination, leaving whether SGD impacts water quality a hotly debated question (Li et al., 2016). One study assessing groundwater-sourced public water systems' water quality found that SGD wells were associated with an increase in SGD-related chemicals for wells drilled within 1 km of the groundwater source (Hill and Ma, 2017).

Surface water impacts are more likely to be associated with the handling of shale gas waste. Waste water treatment and discharge is associated with elevated levels of barium, strontium, bromides, chlorides, benzene, and total dissolved solids exceeding the maximum contaminant level for drinking water (Olmstead et al., 2013; Vengosh et al., 2014; Hladik et al., 2014; Lester et al., 2015; Ferrar et al., 2013). Treated produced water (containing naturally occurring bromide and iodide) are potential sources of toxic disinfection byproducts (DBPs): iodinated trihalomethanes (THMs) and brominated haloacetonitriles (HANs) in surface water (Parker et al., 2014).[11] Endocrine disrupting chemicals measured in surface water near waste effluent in Colorado and West Virginia are of concern for reproductive health (Kassotis et al., 2015).

I.II.2 Air Pollution—Despite less attention in the media, air pollution is gaining more recent attention by researchers. All stages of shale gas development have the potential to produce hazardous air pollution emissions (Kargbo et al., 2010; Schmidt, 2011). Air pollution has become a more immediate concern following studies in Colorado that discovered higher levels of volatile organic compounds (VOCs), methane and other hydrocarbons near drilling sites (Colborn et al., 2012; Pétron et al., 2012). Other emissions associated with combustion include particulate matter, poly-cyclic aromatic hydrocarbons, sulfur oxides and nitrogen oxides (Colborn et al., 2012). More recent studies have also assessed the air pollution contribution of the many truck trips necessary to build and fracture a well (McCawley, 2017; Goodman et al., 2016).

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, starting in 2011, indicates modest emissions of CO, NO_x, PM_{10}, SO_x and VOCs (PADEP, 2013a).[12] 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

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[11] This is also true for groundwater public drinking water systems that treat their water prior to distribution.

[12] According to this emissions inventory, shale gas wells emit carbon monoxide, NOx, PM10, PM2.5, SOx, volatile organic compounds (VOCs), Benzene, ethylbenzene, formaldehyde, hexane, toulene, xylene, trimethylbenzene, CO2, and Methane (Author's calculations of wells drilled 2011–2016).

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, 2013b). These levels surpass the singlelargest industrial source of NO_x pollution in the 11-county northeast region, a coal-fired power plant in Northampton County that emitted 2,000 tons in 2011 (Legere, 2013).

As mentioned above, Pennsylvania DEP began requiring companies drilling Marcellus shale gas wells to report annual estimates of air emission to an inventory starting in 2011. In Table 1, I estimate the intensive margin of the number of wells in a zip code on the annual tons of each pollutant aggregated to that zip code from 2011 to 2015. I also estimate tertiles of wells to capture intensity. Each additional well contributes an average of 0.5 tons of CO, 2 tons of NO_x, 0.07 tons of $PM_{2.5}$, 0.03 tons of SO_x, and 0.17 tons of VOCs per year. The average zip code in 2011 experienced 14 tons of CO, 41 tons of NO_x, 1.4 tons of $PM_{2.5}$, 0.5 tons of SO_x, and 8 tons of VOCs. In the subset of wells that were spudded prior to 2011, the average well produced 2 tons of CO, 4.7 tons of NO_x, 0.14 tons of $PM_{2.5}$, 0.04 tons of SO_x, and 0.63 tons of VOCs in 2011. The top tertile (14–213 wells) of zip codes experience an average of 28 tons of carbon monoxide (CO), 90 tons of NO_x, 2.6 tons of $PM_{2.5}$, 1.8 tons of SO_x, and 9 tons of volatile organic compounds (VOC) per year. Babies exposed to shale gas development within 10 km face an average of 24 wells (max of 240) in 2010 and is fairly similar to the tertiles used in Table 1 Although there isn't a direct way to measure the contribution of these emissions to ambient air quality, they do represent a modest and potentially significant amount of emissions for these rural areas.

Of interest is whether wells continue to produce emissions after drilling and entering into production. To test this, I estimate the amount of reported emissions per year per pollutant using years since spud date as the regressors for all wells reported in the emissions inventory from 2011–2015 (Appendix Table A1). For the most part, emissions are largest for the year of the spud date and the first year after drilling occurred, but emissions continue for most pollutants out to years 4 or 5. Due to this evidence, I estimate models using wells drilled from 2006–2010 and determine exposure by wells drilled prior to birth as opposed to restricting just to drilling activity during gestation.

I.III Pollution and Health Literature

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.[13] All of the air pollutants emitted by shale gas

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

development described above have been associated with adverse birth outcomes (see Online Appendix for more detail). 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). The epidemiological literature relating water pollution to reproductive health is more limited (see Quansah et al. (2015) and Nieuwenhuijsen et al. (2013) for recent reviews).

There is a growing literature within health economics that addresses the most common air pollutants associated with SGD described above utilizing quasi-experimental designs and rich controls for potential confounders to identify the infant health effects of ambient air pollution. See Currie et al. (2014b) for a review of the economics literature on short and long term impacts of early life exposure to pollution. For example, Currie and Walker (2011) estimate that reductions in air pollution from E-Z Pass result in reductions of low birth weight (LBW) between 8.5–11.3 percent and 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 and Neidell (2013) use the natural experiment of a strike that affected 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.

With natural gas touted as a transition fuel between coal-based electricity and renewable options, infant health is one way to compare costs across alternative options. To date, even within the epidemiological literature, studies of the effects of living near coal mining (underground or mountain top) on birth outcomes are extremely limited. All three studies focus on WV: one found an increased risk of low birth weight (16 percent increase in most intensive areas) and one study found an increased risk of congenital anomalies with mountain top removal mining associated with worse outcomes, but was later refuted by the third study when the authors controlled for hospital of birth (Ahern et al., 2011b, a; Lamm et al., 2015). See Hendryx (2015) and Boyles et al. (2017) for systematic reviews of the public health literature. However, recent papers in the economics literature have exploited plant openings and closings or being downwind from a plant to identify the causal impact of coal-fired power plants on infant health and have found adverse birth outcomes: a 5 percent reduction in continuous birth weight as the grid transitioned from nuclear to coal in Tennessee (Severnini, 2017), a 6 percent increase in low birth weight for infants 20 miles downwind of a power plant (Yang et al., 2017), 15 percent decreased risk for low birth weight once the plant closed (Yang and Chou, 2017), and 3,500 infant deaths per year as of 1962 associated with the expansion of the power grid between 1938 and 1962 (Clay et al., 2016). A recent paper focused on storage of coal at power plant locations found that a 10 percent increase in PM2.5 from coal storage increased infant mortality rates by 6.6 percent (Jha and Muller, 2017).

I.III.1 SGD and Health Literature—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 (e.g. toxicological assessment). For example, Colborn et al. (2011) find that more than 75% of the chemicals could affect the skin, eyes, and other sensory organs, and the respiratory and gastrointestinal systems. Chronic exposure is particularly concerning because approximately 40–50% could affect the brain/nervous system, immune and cardiovascular systems, and the kidneys; 37% could affect the endocrine system; and 25% could cause cancer and mutations. These may have long-term health effects that are not immediately expressed after a well is completed. Recent studies have found increased hospitalizations for cardiac conditions (Jemielita et al., 2015), increased risk of three types of asthma measures (Rasmussen et al., 2016), increased risk of hospitalization for pneumonia (Peng et al., 2018), and increased prevalence of fatigue, migraine and sinus effects for residents living near development (Tustin et al., 2017).

A growing body of literature has attempted to address the potential reproductive health effects of shale gas development. All of these studies are retrospective analyses of birth certificate records or electronic medical record data and focus on proximity to maternal residences as the definition of “exposure.” In Colorado, McKenzie et al. (2014) find an increased risk of congenital heart defects with the highest quartile of exposure compared with the absence of any gas wells within a 10-mile radius of the maternal residence. They also found a reduction in premature birth and low birth weight for the highest quartile of exposure. Hill (2013) finds an increase in the latter two measures of around 30 percent for oil, natural gas and coalbed methane wells. Using a similar research design in Texas, Whitworth et al. (2017) finds an increase in premature birth of 14 percent and an increase in fetal death upwards of 50 percent. Using a case-control analysis, Whitworth et al. (2199) find a 20 percent increase and 15 percent increase in preterm birth for any wells and producing wells within 0.5 miles of the maternal residence, respectively.

Focusing on the three studies in Pennsylvania, Stacy et al. (2015a) study three counties in Southwestern Pennsylvania from 2007–2010 and Casey et al. (2016) study two hospitals in the Geisinger Health System from 2009–2013.[14] Currie et al. (2017) study birth records from Pennsylvania from 2004–2013. Stacy et al. (2015a) use inverse distance weighted number of wells within 10 miles of the maternal residence and create quartiles to define exposure (compare 4th to 1st quartiles; omitting mothers with no wells within 10 miles). Casey et al. (2016) create an“activity index” and use quartiles of the index (compare 4th (average 124 wells, median 8) to 1st quartile (average 6 wells, median 0), but include those with no wells within 20 km). [15]Currie et al. (2017) utilize a difference-in-difference study design comparing close (e.g. 0–1, 1–2, 2–3km) versus further away (e.g. all PA or 3–15km) in Pennsylvania using county fixed effects. Stacy et al. (2015a) find a reduction in birth weight and an increase in small for gestational age (SGA) of 34 percent. Casey et al. (2016) find an increase in premature birth that ranges from 40 to 90 percent and an increase in the prevalence of risky pregnancies. Currie et al. (2017) find a 25 percent increase in low birth weight for the 0–1km group. The 2–3km buffer suggests a 16 percent increase in low birth

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[14] Both of these study populations are contained within the population studied in this paper.

[15] According to the authors, the index does not distinguish between pregnant women living near several producing wells versus well pads under development.

weight. The 1–2km buffer is not as consistent or statistically precise as the 0–1 or 2–3km buffers. Other measures studied include continuous birth weight and a health index. Currie et al. (2017) further estimate their models using maternal fixed effects but these models are not statistically significant, nor are they consistent with all of their primary findings.

In the discussion section (Section VII), I compare and contrast my results with those cited above and also provide discussion of interpretation.

II 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. 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 total, the analysis uses 2,459 natural gas wells spudded between 2006 and 2010. 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; approximately 40 percent of permits do not become a well (author calculation from PA DEP data). This information is used to define a potential control group for those infants born to residences close to existing gas wells. The assumption is 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. Figure 1 shows drilled and permitted wells through 2010 along the strata of shale depth. For the most part, wells that are drilled are clustered along the deepest shale strata and permitting is more random.

My second source of data comes from restricted-access vital statistics natality and mortality data from Pennsylvania for the years 2003 to 2010. The restricted-access version of these birth certificate records contain residential addresses geocoded to latitude and longitude and unique identifiers for the mother, father and infant. This precision is essential to my identification strategy because the consequences of drilling are highly localized. To construct the analysis data set, I combine the spatially identified wells and maternal residences and calculate proximity to the nearest wells.

The vital statistics contain important maternal characteristics such as race, education, age, marital status, WIC status, insurance type, previous risky pregnancy 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.[1] I exclude multiple births in all analyses because plural births are more likely to have poor reproductive health independent of exposures to environmental pollution.

I focus on low birth weight (LBW), premature birth and term birth weight (TBW) as the primary outcomes of interest. Low birth weight, defined as birth weight less than 2500 grams, and premature birth, defined as gestation length less than 37 weeks, are commonly used as key indicators of infant health and have been shown to predict adult health and well-being.[1] I also present the continuous measure of term birth weight, defined as birth weight for infants who reach full term at 37 weeks gestation, to study whether there is an average effect on the birth weight distribution as opposed to these more extreme health outcomes. Other birth outcomes that I examine include the continuous measure of birth weight, gestation (measured in weeks), small for gestational age (SGA; defined as 10th percentile of weight distribution for the gestational week of birth), an indicator for whether the APGAR score is less than 8 to predict an increased need for respiratory support, congenital anomalies, an infant health index and infant mortality (death in the first year).[18]

Table 2 provides summary statistics for the universe of births in Pennsylvania from 20032010. The first column reports characteristics of all births and the second column reports average characteristics of births for mothers' residences within 2.5 km of where a shale gas well has been drilled or will be drilled. The localized data I use in this analysis is actually quite similar to the characteristics of the rest of the state. Mothers who live close to shale gas development are less likely to be 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. Columns (3) and (4) provide summary statistics for the primary difference-in-difference (DD) analysis sample; the sample is restricted to those mothers' residences within 2.5 km of a gas well or permit and I compare residences before and after drilling. 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, likely to do with the shale gas boom coinciding with the Great Recession. However, Table 3 suggests no changes in these economic variables after shale gas development.[19]

III Graphical Evidence

If living close to a drilled well has a negative impact on infant health, 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 (e.g. dose response). Figure 2 shows the low birth weight (LBW) and premature birth gradients 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. The primary effect appears to be within 2.5 km but

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[18] 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 and Dietz, 2010). This paper uses the World Health Organization weight percentiles calculator (WHO, 2011). Another potential measure of reproductive health is the 5 minute American Pediatric Gross Assessment Record (APGAR) score. The physician rates the infant a 0, 1, or 2 on each of 5 dimensions (heart rate, breathing effort, muscle tone, reex 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). Most of these outcomes has been previously examined in both the epidemiological and economics literature (e.g., Currie and Walker (2011)). Following Currie et al. (2014a), I also construct a single standardized measure to address examining multiple outcomes and multiple hypothesis tests. 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.

[19] An examination of fertility over time suggests a consistent number of births within 2.5 km of the well head. Muehlenbachs et al. (2015) do not end any changes in neighborhood composition using Census data at the tract level from 2000–2012 in Pennsylvania.

persists out to almost 5 km (consistent with regression results). In contrast, we do not see a clear trend in premature birth over distance (regresion results are mixed depending on extensive or intensive measures).

In Figure 3, I explore pre-trends in these two outcomes across treatment (e.g. drilled wells) and control (e.g. permitted wells) groups, which addresses the validity of my difference-in-difference design. Prior to drilling in 2008, trends appear parallel and indicate a diverging trend once drilling begins.

A primary threat to my identification strategy is that the population of mothers may change in response to drilling. One way to test this is to graph the gradient in observable maternal characteristics. In Figure 4, I graph this gradient out to 20 km.[20] The gradient is very similar within 5 km of the nearest gas well before and after drilling. If anything, moms after drilling may be more college educated, which is consistent with my regression results. However, the characteristics change meaningfully beyond 5 km, and moms who live more than 5 km from a gas well before or after drilling are more likely to be college educated, less likely to have their birth paid for by Medicaid, less likely to participate in WIC and less likely to smoke. This suggests selection into living very close to drilling/future drilling and that those who live closer may have lower SES than those who live 15–20 km away. This could drive adverse outcomes related to living very close to drilling, which is why I use permitted locations that are similarly close to mothers’ residences since these groups are more homogeneous and statistically similar.

IV Empirical Strategy

I exploit the variation over time and across space in the introduction of shale gas wells in Pennsylvania during 2003–2010. Combining gas well data and vital statistics allows the comparison of infant health outcomes of those living near a gas well and those living there before drilling began. Rather than compare aggregated areas, I know specific locations where shale gas drilling has taken place and the dates of when drilling began. The specific location data allow me to compare reproductive health within very small areas in which mothers are likely to be more homogeneous in observable and unobservable characteristics than in aggregate comparisons.

Relying on cross-sectional variation alone, however, would be problematic if mother characteristics vary within the small radius of interest that are unobservable to the researcher. If, for example, the location of gas drilling occurs where the neighborhoods are already economically distressed, then the variation in health outcomes may reflect socio-economic status, as opposed to living in close proximity to shale gas development. I therefore examine localized reproductive health outcomes before and after shale gas development exploiting permitted but not-yet-drilled wells as a comparison. I use 2.5 km (approximately 1.5 miles) as the primary distance of interest for the main specifications that

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[20] This is the largest distance used as a treated group in related studies. McKenzie et al. (2014) use 10 miles, Stacy et al. (2015b) use 10 miles, Casey et al. (2016) uses 20km, Whitworth et al. (2017) use 10 miles and Currie et al. (2017) use 15 km.

follow due to my graphical analyses as well as due to the precision of the effect at this distance for robustness checks.[21]

My primary model is a difference-in-difference model – in which mothers living within 2.5 km from a shale gas well or permit before drilling are used as a control for those exposed after drilling began – to estimate the impact of exposure to shale gas development on birth outcomes. Thus, the counterfactual change in infant health for mother's residences close to a shale gas well is estimated using births prior to drilling at the same distance from the well bore location or permitted location (e.g. those permits that become a well by 2011 are treated differently than those permits that are not drilled by 2011). These models take the following form:

$$Outcome_{it} = \beta_1[Well \leq X]_{it} + \beta_2[Post]_{it} + \beta_3[Well \leq X]_{it} * [Post]_{it} + \beta_4 X_{it} + \gamma_t + \chi_c + \epsilon_{it} \quad (1)$$

where $Outcome_{it}$ is either low birth weight, prematurity and other measures of reproductive health for each infant i born in month-year t. $[Well \leq X]_{it}$ is either an indicator for any gas well or the number of gas wells within Xkm of the mother's residence. $[Post]_{it}$ is an indicator for whether the birth occurs after the spud date of the nearest well of the maternal residence. The estimated impact of shale gas development on infant health is given by the coefficient β_3 and is the difference-indifferences estimator comparing before and after drilling holding the distance Xkm fixed for wells, future wells and permits.[22] The vector X_{ict} contains mother and child characteristics including indicators for whether the mother is African American, Hispanic, four mother education categories (less than high school (left out category), high school, some college, and college or more), mother age categories (teen mom (left out category), 19–24, 25–34 and 35+), indicators for smoking during pregnancy, an indicator for receipt of Women, Infants, and Children (WIC), three health care payment method categories (Medicaid, private insurance, and self-pay), mother's marital status, parity, previous risky pregnancy and an indicator for sex of the child. Indicators for missing data for each of these variables were also included. γ_t are indicators for the year, month and year*month to allow for systematic trends. χ_c are indicators for each mother's county of residence. Standard errors are clustered at the county.[23]

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[21] In Appendix Tables A3 and A4, I report different proximities to gas wells for the definition of treatment and show that for distances up to 5 km, the results are fairly robust.

[22] By including permitted wells not drilled, this estimation strategy becomes more than just a pre-post analysis. This identification strategy assumes that infants born within a similar distance to a permit that is a potential future

[23] Due to the localized nature of this estimation strategy, there is little variation within zip codes to allow for zip code fixed effects. Models with zip code fixed effects are qualitatively similar but less precisely estimated. Results available upon request.

V Results

V.I Differences in Characteristics of Mothers Close to a Well

To test the validity of my research design, I estimate equation (1) and use the difference-indifference estimator to see if there are any changes in mother characteristics after drilling began well would face similar ex ante conditions as those born close to a permit that did become a well during the period I have gas well data for (2003–2011). 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. I test these assumptions and do not find any observable differences in the characteristics of mothers who live close to a future well versus a permitted and not yet drilled well.

(e.g. replace birth outcomes with indicators for maternal characteristics). In Table 3: Panel B, I do not find any indication that maternal characteristics are changing in response to shale gas development. In Appendix Table A2, I show that there are no statistically significant differences in maternal characteristics for any potential proximities (e.g. 2km-3.5km).

V.II The Impact of Shale Gas Development on Birth Outcomes

Table 4 shows the results from estimating (equation 1) on low birth weight, term birth weight and premature birth. Distance to a well, including future and permitted, is held fixed at 2.5 km for these models. Each coefficient represents an estimate of β_3 – the difference-in-difference estimator – from a separate regression. Columns (1), (3) and (5) show a model that controls only for month and year of birth, month*year and county fixed effects. Adding controls for observable characteristics of the mother should only reduce the sampling variance while leaving the coefficient estimates qualitatively unchanged. Columns (2), (4) and (6) add maternal characteristics and show that controlling for maternal characteristics has controlling for maternal characteristics has little effecton the estimated coefficients for low birth weight and term birth weight. 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. I do not find any statistically significant effect for premature birth. Thus, mothers who give birth after drilling are more likely to have reduced weight babies, but they come to term. This difference indicates an overall increase in low birth weight of 24 percent (base of 5.7 percent) and a decrease in term birth weight of 1.5 percent (base of 3416 grams), on average.[25]

The results are qualitatively similar when I estimate equation (1) for other distances up to 5 km from a gas well or permit (See Appendix Table A3). As the buffer of exposure expands, the point estimates become smaller, indicating a dose response relationship, with effects dissipating beyond 3.5 km. The advantage of using permits as the counterfactual is that I can

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[25] Overall prevalence is calculated as follows: 0.0136/0.057=23.9 percent low birth weight and 49.6/3416 = 1.5 percent reduction in term birth weight.

look at only residences that are going to be very close to gas wells at some point in the observable future, which should account for the economic benefits for households receiving lease royalties from the industry.[26]

Table 5 presents estimates of (equation 1) for changes in birth weight, 5 minute APGAR scores less than 8, gestation (weeks), small for gestational age (SGA), congenital anomaly, and an index for infant health due to having multiple outcomes of interest.[27] As before, each column presents estimates from a separate regression, comparing outcomes before and after drilling at 2.5 km from a well head or permit. I present results with maternal controls due to there being little appreciable difference for the models without these controls (results available upon request). Looking across all reproductive health 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 shows no difference with the introduction of SGD (similar to the findings for premature birth). I do not find any impact on congenital anomaly, despite McKenzie et al. (2014) finding an increase in Colorado. A drilled shale gas well has a small and statistically significant effect on the summary index, increasing the probability of an adverse reproductive health 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 et al., 2014a).

V.III Well Density

Given the finding that the introduction of shale gas development adversely affects birth outcomes in a binary or extensive margin framework, it follows to consider how the density of well development might impact the main outcomes of interest. For the primary sample used in Table 4, the average number of wells drilled at 2.5 km prior to birth is 0.6 wells (s.d. 2.12) with a range of 0 to 35. When limited to those who have at least one well drilled within 2.5 km prior to birth (the “treatment group”) the average increases to 2.98 wells (s.d. 2.62). In Table 6, I present findings that regress infant health on well density. I find that for each additional shale gas well drilled prior to birth within 2.5 km, low birth weight increases by 0.3 percentage points and term birth weight is reduced by 5 grams. Unlike the previous

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[26] Permitted wells must have already gone through the leasing process and households that lease their mineral rights will have received signing bonuses previously. These benefits can only reach an approximate 3km buffer where horizontal drilling can reach minerals and would result in royalties. At very close proximities (e.g. < 1km), I see some indication that birth outcomes are improved by drilling. There is a large and growing literature that suggests positive income shocks can have a positive effect on birth outcomes (Almond et al., 2011; Hoynes et al., 2015) and so this ending would be consistent with that hypothesis. Royalties may mitigate the risks of close exposure.

[27] Following Currie et al. (2014a), I address the issue of precision using a summary index measure of infant health. 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.

specification, I also find that each additional well increases premature birth by a similar 0.3 percentage points.[28]

As before, these findings are consistent across proximity buffers from 2 to 5 km, as shown in Appendix Table A4, and also show some degree of dose response for low birth weight and premature birth. At 2 km, estimates for LBW and preterm birth are about 0.4 percentage points and drop to about 0.02 percentage points at 5 km. The relationship for term birth weight shows less of a dose response, but peaks at 2.5 km with 5 grams and drops to < 1 gram at 5 km.

VI Robustness Checks and Heterogeneity of Impacts

VI.I Heterogeneity by Maternal Characteristics

The economics literature measuring health effects of pollution considers avoidance behavior to be an important factor to explore (Currie (2009); Neidell (2004); Currie et al. (2014b)). If families engage in avoidance behavior (e.g. move, use water purification or purchase bottled water (Wrenn et al., 2016), avoid going outside during drilling), then the health effects measured could be a lower bound. To assess this, the literature tests heterogeneity across characteristics to determine whether there are differential impacts by SES (Currie et al., 2013b; Sanders and Stoecker, 2015). This would not reflect a biological difference, but would provide evidence for or against maternal behavioral responses to shale gas. Table 7 contains estimates of heterogeneity for three primary measures of infant health: low birth weight, term birth weight, and premature birth (each reported as a separate panel). Each column and coefficient represents an estimate of β_3 in equation (1) from a separate regression to explore whether the effects of exposure to shale gas drilling are the same for different subgroups of the population. For the most part, the results for low birth weight and term birth weight indicate that there is not much heterogeneity of impacts across demographic groups–shale gas development has detrimental impacts on all subgroups. However, high school dropouts and moms on Medicaid do experience larger impacts with increases in low birth weight of about 4 percentage points and college educated mothers have slightly smaller impacts of about 1 percentage point.[29] No subgroups have statistically significant impacts for prematurity and similar to before, the signs of the coefficients are not consistently positive or negative.

In Hill (2012), I also report 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. I found that moms may be moving in response to shale gas development (an increase of 2.2. percentage points), but it was not statistically significant. Despite some potential increased mobility of these mothers, I found that the results are

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[28] I also estimate models using tertiles of wells and find that the top tertile (> 3 wells) has a similar sized effect as the extensive margin results for low birth weight and term birth weight, however, the top tertile increases premature birth by 2 percentage points, in contrast to the null finding in the extensive margin results.

[29] The pre-drilling mean for these three groups are substantially different from the overall average. The percentchanges relative to the mean for both HS dropouts and Medicaid reect a 50 percent increase, while the effect for college educated moms reects a 25 percent increase, which is the same as the main effect. I tested the differences between these and the main results and only the results for Medicaid are statistically different [pvalue=0.01]

qualitatively similar for those who stay as those who move and indicate that the main results are not driven by maternal mobility.

VI.II Sensitivity Analyses

Additional robustness checks were performed to make sure the main specifications are robust to different counterfactual groups, additional controls and subsets of counties associated with production and drilling. These results are reported in Appendix Table A6. First, I limit the sample to mothers who were born in Pennsylvania to test whether migration from out of state is driving the main findings. The results are very similar for the 83 percent of moms who were born in PA.[30]

Next, I report the estimates using the 10 most drilled counties and the 10 most producing counties (these are not the same) and find similar results indicating that it is not just drilling or production driving these findings.[31]

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. For example, (Currie and Walker, 2011) 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. In Hill (2012), I compared residences close to a well (a range of proximities as before of 2–3.5km) and residences a little further away (5, 10 and 15km), before and after drilling.[32] The results are consistent with the main findings for low birth weight and term birth weight, but as described in the graphical evidence section, there may be selection into proximity and so this in not a preferred specification.

VI.III 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 among mothers who do not have multiple births during the sample. I investigate this possibility by estimating equation (1) 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

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[30] This does not perfectly address this question since migration can also occur within PA.

[31] Other robustness checks were reported in Hill (2012). First, I showed the results for restricting the sample to infants born within 2 years (before and after) of the spud date for the closest well. This specifcation is designed to address any possible concerns about unequal prior and post observation periods for each location or concerns about unobserved and differential sorting in the mothers living close to drilled versus permitted wells. The point estimates are somewhat smaller, but qualitatively similar to the estimates in Tables 4 and 5. Next I showed 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) indicating a 1.89 percentage point increase. Finally, I reported the results from adding the continuous distance to the closest well, as well as the number of wells drilled within 5 km of the maternal residence. Again, the point estimates are very similar to those reported in Tables 4 and 5 and suggest most of the effect is driven by proximity to the closest well.

[32] In Hill (2012), I used up to 15 km as the comparison group and reported it as 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. 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 trafic, 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.

spurious effect (Table 8). I also run models on future wells and repeat the well density models using number of future wells. These models are also consistent with no impact and are consistent with the conclusion that shale gas development has an adverse impact on birth outcomes.

VII Discussion

My results suggest that shale gas development can have adverse effects on the health of people living nearby, namely that of prenatal infants. For the extensive margin, babies born of mothers who lived within 2.5 km of at least one gas well during pregnancy experienced adverse birth outcomes. I find supportive evidence that these effects persist out to 3.5 km of a mother's address and are consistent across multiple specifications. For the intensive margin, or estimating the impact of well density, I find that each additional well drilled within 2.5 km of the mother's residence increases low birth weight and premature birth by 0.4 percentage points and reduces term birth weight by 5 grams.

These results are reasonable for three reasons. First, most areas with shale gas development in Pennsylvania are rural areas with relatively low prevalence of low birth weight (5.7 percent) compared to the state average of 7 percent (for singleton births only).[33] The studies cited in this paper that assess low birth weight impacts of air emissions from other sources (e.g. EZ-Pass, mountain-top coal mining) report baseline average prevalence of low birth weight of 9 or more percent (Currie and Walker, 2011; Ahern et al., 2011b) and therefore mechanically lower relative effect sizes. However, the average birth weight in this population is almost identical to the state average and is 1.5 percent relative to the mean, which is not large, and is very similar or smaller than the average impact on birth weight of exposure to air emissions in other studies (Severnini, 2017; Lavaine and Neidell, 2013; Yang and Chou, 2017). Second, most of the existing literature has studied the effects of air pollution on infant health on a pollutant-by-pollutant basis. In this case, I am identifying the health effects of exposure to the disamenity itself, which according to the air emissions inventory emits a wide variety of pollutants. Some, such as NO_x, are much higher than the largest pre-drilling emitter in the region.[34] Each of these contaminants have been separately associated with the birth outcomes measured in this paper, while SGD increases exposure to all of these during active drilling and production. Thus, it is not surprising that my estimates are larger than some of those found in the literature, especially those that are studying one pollutant. Finally, these results are smaller than or similar in magnitude to the existing literature studying the infant health impacts of shale gas development (Stacy et al., 2015b; Casey et al., 2016; Currie et al., 2017; Whitworth et al., 2017, 2199).

My study builds upon the existing literature measuring the infant health impacts of shale gas development. Due to inconsistency in measures used across existing studies, it is challenging to compare and interpret measured impacts. My results are consistent with Currie et al. (2017) for low birth weight and Stacy et al. (2015a) for small for gestational age. While I do

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[33] Using the pre-drilling mean of low birth weight for the analysis sample, the effect size is 24 percent relative to the mean, whereas the effect size is 19 percent relative to the state average.

[34] As mentioned in the background section of the paper, the largest industrial source of NOx in the 11-county region is a power plant that produces 2,000 tons per year. Shale wells in 2011 produced 16,000 tons of NOx in aggregate.

not find an impact on premature birth in the extensive margin, my intensive margin results indicate that premature birth may be impacted, especially at the highest tertile of exposure. This most closely relates to the inverse distance weighted quartile measures used in the epidemiologic literature and is consistent with Casey et al. (2016) and Whitworth et al. (2017). Although exact mechanisms are difficult to ascertain with the data currently available, the increase in small for gestational age and low birth weight in the extensive margin without a symmetric increase in premature birth indicates that infants born to mothers exposed to any drilling are coming to full term, but are small, as would be the case where drilling persistently increases local air or water pollution. Whereas, preterm labor may be induced by air pollution or stress at higher intensities of drilling and therefore explain the symmetric intensive margin impacts on preterm birth and low birth weight (Dole et al., 2003; Stieb et al., 2012b; Sun et al., 2015).

These results suggest that requiring air and water pollution monitoring of drilling sites could assist researchers and public health officials in efforts to ascertain exposure pathways for residents living nearby and inform policies to mitigate any risks that are likely to be very localized. In 2011, PA DEP began requiring the shale gas industry to report emissions of these pollutants into an emissions inventory so that policy makers can better address these exposures in the future.

The 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 mothers 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 is likely to suffer, which is reflected in literature that finds pollution to be one potential mechanism by which SES affects health (Neidell, 2004). 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.

VII.I Cost Estimates

While the economic benefits and costs of shale gas development are quantifiable, the public health benefits and costs might be more difficult to assess. This paper provides evidence that maternal exposure within at least 1.5 miles of SGD is detrimental to fetal development. Due to shale gas development occurring only recently in Pennsylvania, the number of infants observed close to existing wells is quite small relative to other more populated areas with SGD. This translates to a cost of $4.1 million.[35] As a back-of-the envelope estimate, there are more than 2.8 million American women of reproductive age with a well within a mile of their homes (Gold and McGinty, 2013; Howden and Meyer, 2010).[36] Using the current fertility rate of 64 per 1,000 women in this age group nationally (Martin et al., 2012), there

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[35] Combining hospital costs attributable to low birth weight ($15,100 in additional hospital costs)(Russell et al., 2007), estimates for special education services ($5,200)(Chaikind and Corman, 1991; Augenblick et al., 2007) and decreased earnings ($76,800)(Currie et al., 2013a), an arguably conservative estimate is $96,500 in added cost for each low birth weight child. This figure excludes medical bills after the first year, parental lost earnings and other costs and is, hence, a lower bound estimate of costs.

[36] Using The Wall Street Journal estimate that over 15 million Americans live within 1 mile of an oil or gas welldrilled since 2000, and using a rough estimate that half of those people are women and forty percent of them are ages 18–44.

are over 170,000 pregnant women living 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 which amounts to a cost of more than $230 million per year in these 11 states.

VIII Conclusions

My study seeks to understand and quantify the impacts of shale gas development on infant health. 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.

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. 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.

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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Appendices

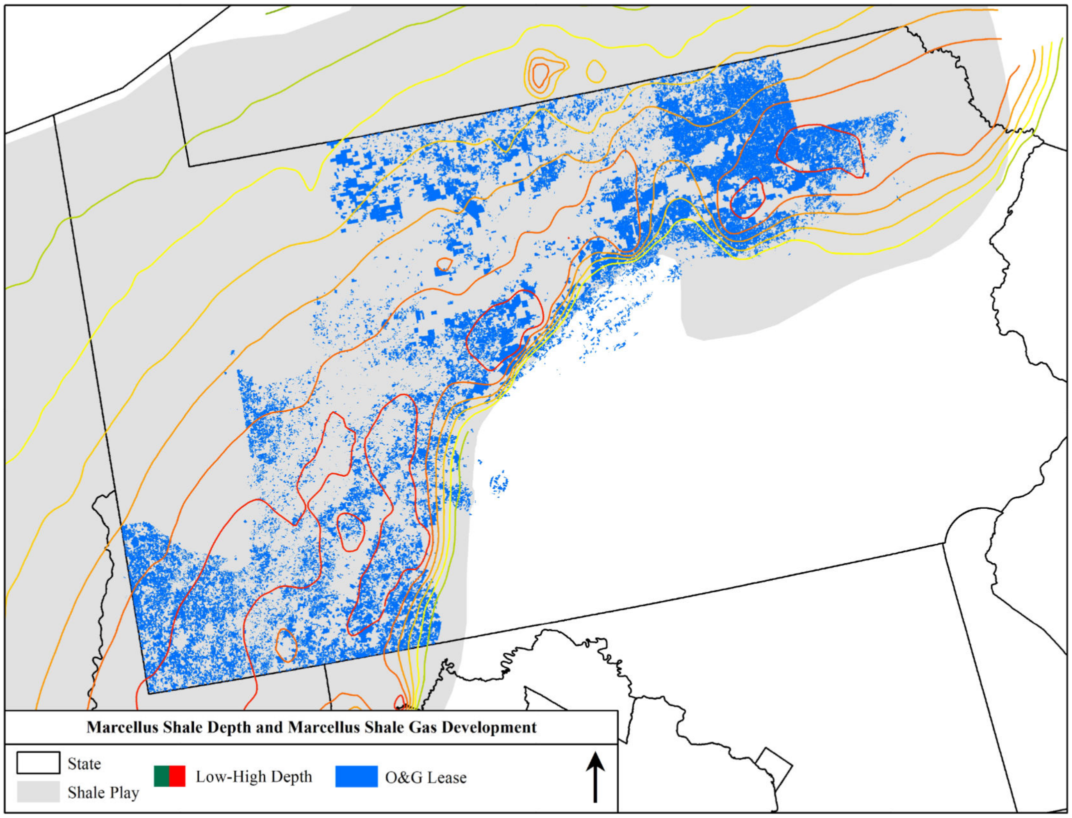

Figure A1:
Map of Leasing through 2010

Table A1:

Emissions from Shale Gas Wells First 5 Years after Spud Date

	(1) co	(2) nox	(3) pm10	(4) pm25	(5) sox	(6) voc
Year of Spud	2.188***	7.938***	0.282***	0.259***	0.107***	0.585***
	(0.0517)	(0.136)	(0.00614)	(0.00537)	(0.00538)	(0.0463)
One Year Since Spud	2.241***	6.709***	0.225***	0.202***	0.0656***	1.008***
	(0.0532)	(0.140)	(0.00632)	(0.00552)	(0.00558)	(0.0473)
Two Years Since Spud	0.595***	1.351***	0.0612***	0.0550***	0.00860	0.719***
	(0.0577)	(0.152)	(0.00685)	(0.00596)	(0.00607)	(0.0501)
Three Years Since Spud	0.378***	0.661***	0.0289***	0.0256***	0.00985	0.427***
	(0.0603)	(0.158)	(0.00715)	(0.00622)	(0.00628)	(0.0523)
Four Years Since Spud	0.321***	0.438**	0.0213**	0.0172**	0.00334	0.502***
	(0.0737)	(0.193)	(0.00874)	(0.00760)	(0.00765)	(0.0648)
Five Years Since Spud	0.178*	0.250	0.0107	0.00882	0.00101	0.731***
	(0.100)	(0.264)	(0.0119)	(0.0104)	(0.0104)	(0.0892)
Observations	13,650	13,650	13,610	13,555	13,472	14,073

	(1) co	(2) nox	(3) pm10	(4) pm25	(5) sox	(6) voc
R-squared	0.215	0.299	0.204	0.218	0.038	0.067
Dep. Var Mean	1.242	3.805	0.136	0.123	0.0436	0.675

Table A2:

Differences in characteristics for analysis sample using DD estimator by Distance

	(1) Teen Mom	(2) Dropout	(3) Black	(4) Smoked	(5) WIC	(6) Medicaid	(7) Born PA	(8) Moved
Within 2km * post-drilling	0.00464	−0.00150	0.00181	−0.00366	−0.0195	−0.0288	−0.0198	−0.00125
	(0.00704)	(0.00927)	(0.00457)	(0.0254)	(0.0276)	(0.0273)	(0.0133)	(0.0124)
Observations	14,131	14,131	14,131	14,131	14,026	14,131	14,131	14,060
R-squared	0.015	0.046	0.022	0.031	0.072	0.098	0.025	0.043
Within 2.5 km * post-drilling	0.000550	−0.0132	0.00343	0.00277	−0.00501	−0.0204	−0.0222	0.0191
	(0.00666)	(0.0118)	(0.00308)	(0.0196)	(0.0246)	(0.0282)	(0.0163)	(0.0131)
Observations	21646	21646	21646	21646	21469	21646	21646	21511
R-squared	0.012	0.039	0.016	0.026	0.061	0.078	0.020	0.042
Within 3km * post-drilling	−0.00351	−0.0206	0.00443	−0.0210	−0.0221	−0.0426	−0.0209	0.0159
	(0.0108)	(0.0193)	(0.00550)	(0.0234)	(0.0304)	(0.0371)	(0.0139)	(0.0123)
Observations	28,910	28,910	28,910	28,910	28,655	28,910	28,910	28,741
R-squared	0.010	0.032	0.016	0.025	0.061	0.073	0.017	0.041
Within 3.5km * post-drilling	−0.0140	−0.0258	−0.000432	−0.0234	−0.0451	−0.0451	−0.0160	0.0120
	(0.0108)	(0.0217)	(0.00694)	(0.0266)	(0.0349)	(0.0419)	(0.0173)	(0.0112)
Observations	36,447	36,447	36,447	36,447	36,100	36,447	36,447	36,228
R-squared	0.009	0.029	0.015	0.024	0.057	0.069	0.015	0.040

Notes: See Table 3 for specification details.

Significance:

* $p<0.10$,

** $p<0.05$,

*** $p<0.01$.

Table A3:

The Effect of Shale Gas Development on Infant Health by Distance

	(1) d < 2 km	(2) d < 2:5 km	(3) d < 3 km	(4) d < 3:5 km	(5) d < 4 km	(6) d < 4:5 km	(7) d < 5 km
Panel A: Low Birth Weight							
Well in ‘d’ km * post-drilling	0.0127**	0.0136**	0.0115**	0.00912**	0.00533	0.00288	0.00194
	(0.00512)	(0.00511)	(0.00510)	(0.00391)	(0.00406)	(0.00415)	(0.00428)
Observations	14,113	21,610	28,865	36,393	44,690	52,325	59,369
R-squared	0.023	0.021	0.019	0.019	0.018	0.018	0.017
Pre-drilling Mean	0.0584	0.0571	0.0579	0.0579	0.0576	0.0574	0.0575
Panel B: Term Birth Weight							
Well in ‘d’ km * post-drilling	−38.05*	−49.58***	−30.84**	−29.69**	−15.34	−10.25	−7.311
	(21.49)	(14.04)	(14.20)	(12.59)	(9.781)	(11.56)	(9.457)
Observations	13028	19978	26637	33572	40,277	47,105	53,391
R-squared	0.077	0.075	0.078	0.077	0.078	0.076	0.075
Pre-drilling Mean	3415	3416	3415	3412	3412	3415	3415
Panel C: Premature							
Well in ‘d’ km * post-drilling	−0.00962**	0.000354	0.00460	−0.00184	−0.000704	0.000242	0.00273
	(0.00403)	(0.00664)	(0.00455)	(0.00483)	(0.00564)	(0.00503)	(0.00446)
Observations	13,843	21,189	28,309	35,661	43,741	51,139	57,981
R-squared	0.017	0.012	0.010	0.010	0.009	0.009	0.008
Pre-drilling Mean	0.0802	0.0785	0.0791	0.0791	0.0782	0.0783	0.0786

Notes: See Table 4 for specification details.

Significance:

* p<0.10,

** p<0.05,

*** p<0.01.

Table A4:

Impact of Number of Wells by Proximity

	(1) d < 2 km	(2) d < 2:5 km	(3) d < 3 km	(4) d < 3:5 km	(5) d < 4 km	(6) d < 4:5 km	(7) d < 5 km
Panel A: Low Birth Weight							
Wells in ‘d‘ km * post-drilling	0.00410*	0.00306***	0.00232***	0.00122**	0.000266	0.000194	0.000209
	(0.00231)	(0.000931)	(0.000758)	(0.000509)	(0.000433)	(0.000302)	(0.000260)

	(1) ***d*** **< 2 km**	(2) ***d*** **< 2:5 km**	(3) ***d*** **< 3 km**	(4) ***d*** **< 3:5 km**	(5) ***d*** **< 4 km**	(6) ***d*** **< 4:5 km**	(7) ***d*** **< 5 km**
Observations	14,049	21,524	28,756	36,241	44,442	51,994	58,976
R-squared	0.023	0.021	0.020	0.019	0.018	0.018	0.017
Pre-drilling Mean	0.0583	0.0570	0.0578	0.0578	0.0575	0.0573	0.0575
Panel B: Term Birth Weight							
Wells in 'd' km * post-drilling	−3.857	−5.386***	−4.716***	−3.152***	−2.429***	−1.438**	−0.930**
	(2.609)	(1.632)	(1.331)	(0.818)	(0.644)	(0.570)	(0.415)
Observations	12,694	19,463	25,969	32,692	40,067	46,822	53,049
R-squared	0.080	0.076	0.078	0.077	0.079	0.076	0.075
Pre-drilling Mean	3415	3416	3415	3412	3412	3415	3415
Panel C: Premature							
Wells in 'd' km * post-drilling	0.00366*	0.00257**	0.00212**	0.000889	0.000281	0.000235	0.000406
	(0.00210)	(0.00123)	(0.000889)	(0.000718)	(0.000602)	(0.000398)	(0.000331)
Observations	13,784	21,109	28,206	35,519	43,506	50,825	57,606
R-squared	0.017	0.011	0.010	0.010	0.009	0.008	0.008
Pre-drilling Mean	0.0803	0.0785	0.0790	0.0789	0.0781	0.0781	0.0786

Notes: See Table 6 for specification details.

Significance:

* p<0.10,

** p<0.05,

*** p<0.01.

Table A5:

Robustness Check: Future Number of Wells by Proximity

	(1) ***d*** **< 2 km**	(2) ***d*** **< 2.5 km**	(3) ***d*** **< 3 km**	(4) ***d*** **< 3.5 km**
Panel A: Low Birth Weight				
Wells in 'd' km * future	−0.000223	−0.000133	8.19e-05	6.12e-06
	(0.000449)	(0.000341)	(0.000172)	(0.000139)
Observations	14,049	21,524	28,756	36,241
R-squared	0.023	0.021	0.020	0.019
Panel B: Term Birth Weight				
Wells in 'd' km * future	0.977	0.318	0.410	0.730**
	(1.342)	(0.588)	(0.359)	(0.272)
Observations	12,694	19,463	25,969	32,692

	(1) ***d* < 2 km**	**(2)** ***d* < 2.5 km**	**(3)** ***d* < 3 km**	**(4)** ***d* < 3.5 km**
R-squared	0.080	0.076	0.078	0.077
	Panel C: Premature			
Wells in ‘d’ km * future	0.000394	0.000172	0.000352	0.000290
	(0.000412)	(0.000476)	(0.000273)	(0.000227)
Observations	13,784	21,109	28,206	35,519
R-squared	0.017	0.011	0.010	0.010

Notes: See Table 6 for specification details. Instead of existing wells, this table looks at future wells.

Significance:

*p<0.10,

**p<0.05,

*** p<0.01.

Table A6:

Robustness Checks

	(1) **Low Birth Weight**	**(2)** **Term Birth Weight**	**(3)** **Premature Birth**
	Panel A: Mom Born in Pennsylvania		
Within 2.5 km * post	0.0128***	−50.87***	−0.00523
	(0.00466)	(15.99)	(0.00645)
Observations	17,491	15,814	17,155
R-squared	0.022	0.081	0.012
Pre-drilling Mean	0.0576	3415	0.0791
	Panel B: Top 10 Major Production Counties		
Within 2.5 km * post	0.0160*	−44.52***	−0.00303
	(0.00726)	(12.03)	(0.0104)
Observations	15,052	13,627	14,789
R-squared	0.025	0.081	0.017
Pre-drilling Mean	0.0573	3415	0.0790
	Panel C: Top 10 Major Drilling Counties		
Within 2.5 km * post	0.0175**	−46.66***	0.000296
	(0.00576)	(12.36)	(0.00978)
Observations	13,208	11,951	12,957
R-squared	0.024	0.076	0.016
Pre-drilling Mean	0.0559	3423	0.0783

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

Significance:

[*] $p<0.10$,

[**] $p<0.05$,

[***] $p<0.01$.

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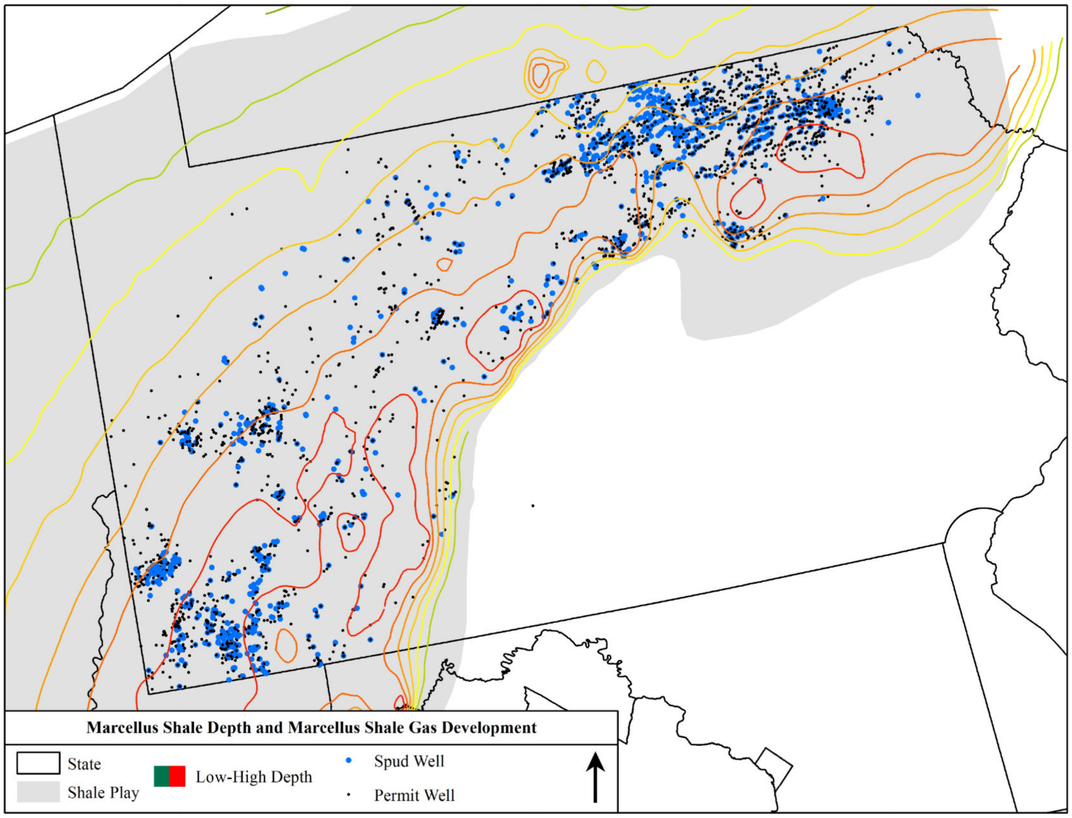
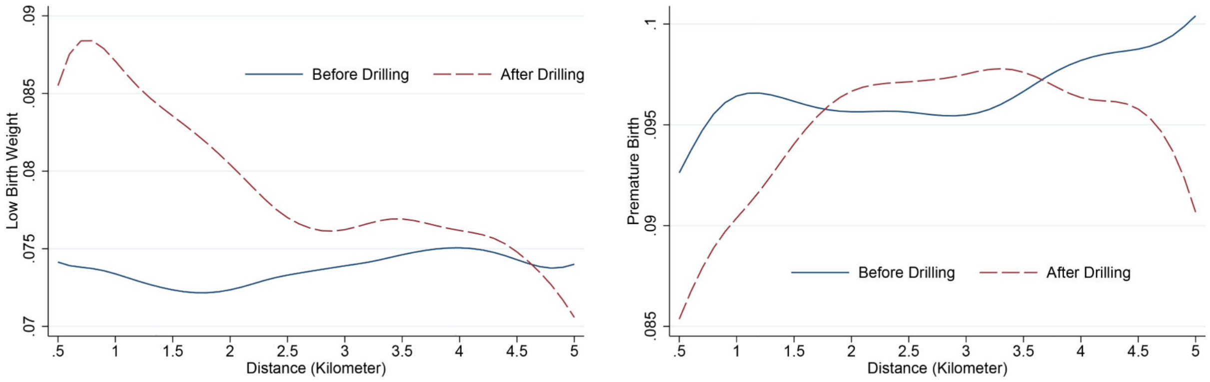


Figure 1:
Map of Shale Gas Development and Permitting through 2010

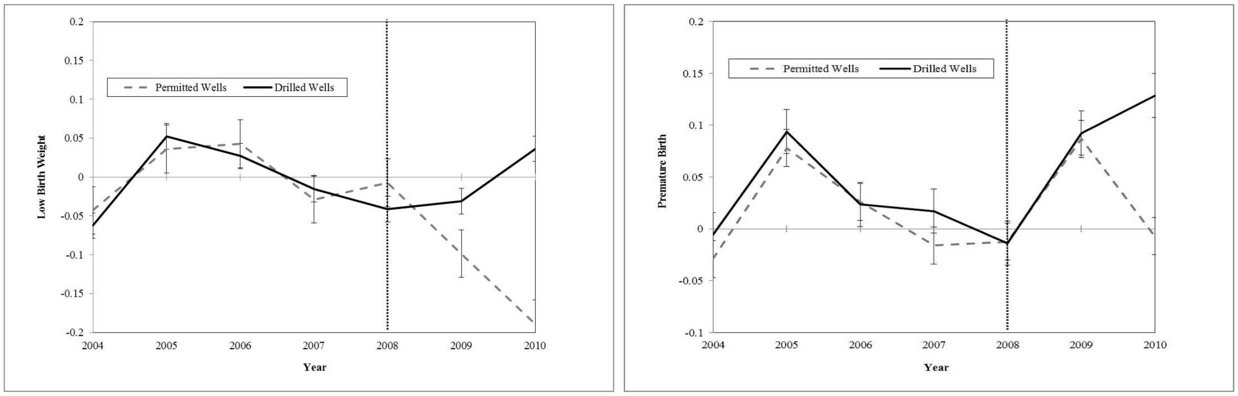


Low Birth Weight

Premature Birth

Figure 2:

Distance Gradients of Infant Health by Nearest Well Results from a local polynomial regressions of low birth weight on distance from closest well's future/current location or on days before/after spud date. Observations within 5 km of a well.



Low Birth Weight Premature Birth

Figure 3:

Time Trends of Infant Health Within 2.5 km of Drilled and Permitted Wells Results are from a regression with an interaction term for drilled well * year including county, birth month and year fixed effects. Observations are the main difference-in-differences sample or those mothers within 2.5 km of a drilled well or permitted well.

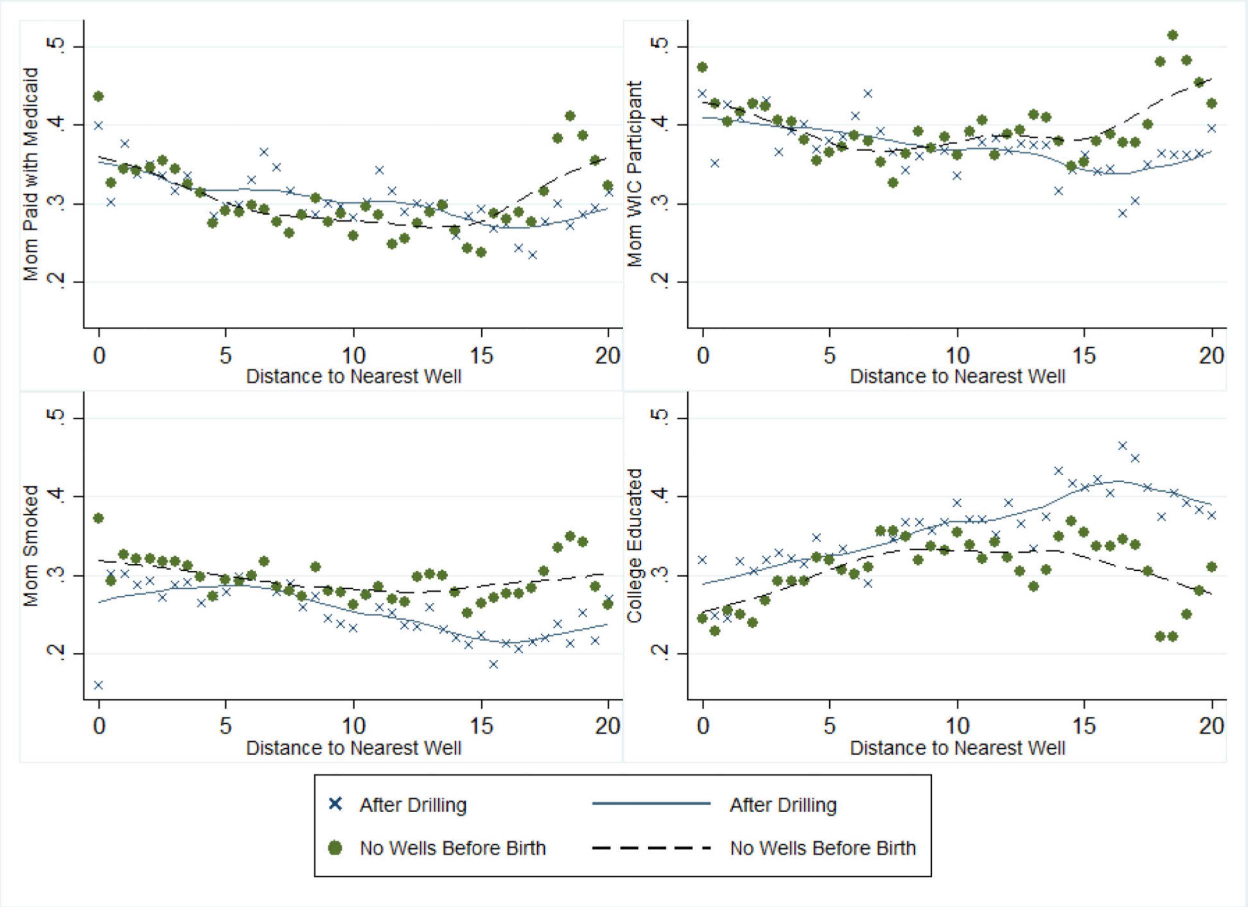


Figure 4:

Distance Gradients of Maternal Characteristics by Nearest Well Distance bins are 0.5 km, smoothed using “lpoly” (degree 0, bandwidth 15).

Table 1:

Pollution Per Well and Tertiles Aggregated to Zip Code 2011–2015

	(1) **CO**	**(2)** **CO**	**(3)** NO_x	**(4)** NO_x	**(5)** $PM_2.5$	**(6)** $PM_2.5$	**(7)** SO_x	**(8)** SO_x	**(9)** **VOC**	**(10)** **VOC**
# wells	0.526***		2.048***		0.0639***		0.0325***		0.172***	
	(0.0567)		(0.171)		(0.00543)		(0.00500)		(0.0597)	
3–5 wells		3.271		13.28		0.395		0.514**		1.074
		(2.928)		(9.060)		(0.289)		(0.256)		(3.042)
6–13 wells		13.30***		45.02***		1.472***		1.271***		3.835
		(3.305)		(10.23)		(0.326)		(0.289)		(3.434)
14–213 wells		27.47***		89.83***		2.630***		1.777***		9.023**
		(3.934)		(12.17)		(0.388)		(0.344)		(4.087)
log prod	0.552***	0.443**	1.806***	1.627***	0.0633***	0.0598***	0.0336**	0.0241	0.281	0.247
	(0.193)	(0.202)	(0.580)	(0.626)	(0.0185)	(0.0200)	(0.0170)	(0.0177)	(0.203)	(0.210)
Observations	1,172	1,172	1,172	1,172	1,172	1,172	1,172	1,172	1,172	1,172
R-squared	0.697	0.688	0.730	0.707	0.724	0.699	0.500	0.494	0.651	0.650
Dep. Var Mean	15.35	15.35	45.85	45.85	1.482	1.482	0.507	0.507	8.742	8.742

Notes: Data are from the PA DEP Air Emissions Inventory for Unconventional Natural Gas Operations 2011–2015. Units are tons/year. Emissions are aggregated to zip code-year. Regressions include year and zip code fixed effects. First column for each pollutant is number of reported wells in that zip code-year. Second column provides tertile estimates.

Significance:

*p<0.10,

**p<0.05,

***p<0.01.

Table 2:

Summary Statistics by Sample

	All Births	Residences within 2.5 km of well			T-Stat
		Total	Before	After	for difference
Characteristics of birth					
Birth weight (grams)	3321	3340	3343.23	3310.30	2.70**
Term birth weight (grams)	3407	3415	3418.39	3383.15	3.30***
Gestation in weeks	38.77	38.76	38.76	38.71	1.33
Premature	0.08	0.08	0.076	0.077	−0.09
Low birth weight (LBW)	0.07	0.06	0.055	0.063	−1.52
Small for gestational age (SGA)	0.11	0.10	0.098	0.106	−1.25
APGAR 5 minute	8.81	8.89	8.886	8.885	0.07
Female	0.49	0.49	0.485	0.495	−0.95
Mother’s Characteristics					
Drop Out	0.164	0.113	0.112	0.118	−0.88
High School	0.270	0.296	0.297	0.288	0.93
Some college	0.260	0.299	0.299	0.293	0.64
College plus	0.298	0.290	0.289	0.299	−1.07
Teen Mom	0.057	0.048	0.047	0.049	−0.34
Mom Aged 19–24	0.265	0.268	0.267	0.274	−0.65
Mom Aged 25–34	0.527	0.547	0.545	0.559	−1.31
Mom Aged 35 and older	0.150	0.137	0.140	0.117	3.03**
Mom Black	0.156	0.025	0.025	0.024	0.15
Mom Hispanic	0.092	0.011	0.011	0.010	0.57
Married at time of birth	0.575	0.632	0.633	0.626	0.71
Mom Smoked While Pregnant	0.227	0.299	0.299	0.300	−0.13
Received WIC	0.385	0.398	0.395	0.427	−2.94**
Medicaid	0.272	0.326	0.320	0.376	−5.45***
Private Insurance	0.576	0.567	0.569	0.549	1.84
Wells within 2.5 km					
# of wells before birth	0.000	0.333	0.000	2.89	−19.30***
# of wells during gestation	0.000	0.188	0.000	1.714	−93.13***
Observations	1098884	21610	19246	2364	

Notes: The samples described here include only singleton births.

Significance:

*p<0.10,

**p<0.05,

***p<0.01.

Table 3:

Post- Drilling Differences in Average Characteristics of Mothers Close to Wells

	(1) Teen Mom	(2) Dropout	(3) Black	(4) Smoked	(5) WIC	(6) Medicaid	(7) Born PA	(8) Moved
	Differences in characteristics for analysis sample using DD estimator							
Within 2.5 km * post-drilling	0.000550	−0.0132	0.00343	0.00277	−0.00501	−0.0204	−0.0222	0.0191
	(0.00666)	(0.0118)	(0.00308)	(0.0196)	(0.0246)	(0.0282)	(0.0163)	(0.0131)
Observations	21646	21646	21646	21646	21469	21646	21646	21511
R^2	0.012	0.039	0.016	0.026	0.061	0.078	0.020	0.042
Pre-drilling Mean	0.0496	0.117	0.0243	0.307	0.404	0.323	0.815	0.0756

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. Robust standard errors are clustered at the mother's residence county. All regressions include indicators for month and year of birth, birth*year and residence county fixed effects.

Significance:

[*] $p<0.10$,

** $p<0.05$,

*** $p<0.01$.

Table 4:

Impact of Well Location on Birth Outcomes

	(1) Low Birth	(2) Weight	(3) Term Birth	(4) Weight	(5) Premature	(6)
Within 2.5 km *post-drilling	0.0144**	0.0136**	™47.82***	™49.58***	0.00118	0.000354
	(0.00537)	(0.00511)	(15.12)	(14.04)	(0.00597)	(0.00664)
Observations	21610	21610	19978	19978	21,189	21,189
R-squared	0.008	0.021	0.013	0.075	0.008	0.012
Pre-drilling Mean	0.057	0.057	3416	3416	0.079	0.079
Maternal Characteristics	No	Yes	No	Yes	No	Yes

Notes: Each coefficient is from a different regression. The sample is limited to singleton births and to the sample with a well/permit within 2.5 km. All regressions include indicators for month and year of birth, month*year, residence county indicators, an indicator for drilling before birth (defined by closest well), an indicator for residence within 2.5 km of a well or future well and the interaction of interest of Within 2.5km*post-drilling. 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, selfpay, other). Indicators for missing data

Significance:

*p < 0.10,

**p < 0.05,

***p < 0.01.

Table 5:

Difference-in-Difference Estimates of the Effect of Drilling on Alternative Health Measures

	(1) Birth Weight	(2) APGAR < 8	(3) Gestation	(4) SGA	(5) Congenital Anomaly	(6) Summary Index	(7)
Within 2.5 km * post-drilling	−47.02 ***	0.0251 **	−0.0143	0.0181 **	−0.00193	0.0264 **	
	(12.16)	(0.0101)	(0.0664)	(0.00764)	(0.00189)	(0.0101)	
Observations	21,583	21646	21,631	21524	21,646	21646	
R-squared	0.061	0.029	0.020	0.040	0.008	0.045	
Pre-drilling Mean	3340	0.104	38.74	0.0993	0.00562	−0.0372	

Notes: Each coefficient is from a different regression. See Table 4 for details about included covariates.

Significance:

*p<0.10,

**p<0.05,

***p<0.01.

Table 6:

Impact of Well Density on Birth Outcomes

	(1)	(2)	(3)	(4)	(5)	(6)
	Low Birth Weight		**Term Birth Weight**		**Premature**	
Wells within 2.5 km *post	0.00308***	0.00306***	™4.864***	™5.386***	0.00266**	0.00257**
	(0.000868)	(0.000931)	(1.783)	(1.632)	(0.00121)	(0.00123)
Observations	21610	21610	19978	19978	21,189	21,189
R^2	0.009	0.021	0.013	0.076	0.008	0.011
Pre-drilling Mean	0.057	0.057	3416	3416	0.079	0.079
Maternal Characteristics	No	Yes	No	Yes	No	Yes

Notes: Each coefficient is from a different regression. The sample is limited to singleton births and to having a well or permit within 2.5 km. All regressions include an indicator for drilling before birth (defined by closest well), number of wells within 2.5km (including future wells) and the interaction of interest: number of wells within 2.5km *post-drilling. See Table 4 for details about other included covariates.

Significance:

*p<0.10,

**p<0.05,

***p<0.01.

Table 7:

Shale Gas Development on Maternal Subgroups

	(1) High School dropout	(2) Smoker	(3) Nonsmoker	(4) Medicaid	(5) WIC	(6) College
Panel A: Low Birth Weight						
Within 2.5 km *post	0.0432	0.0186	0.0122 **	0.0413 ***	0.0138 **	0.0105
	(0.0268)	(0.0132)	(0.00470)	(0.0120)	(0.00645)	(0.00995)
Observations	2,434	6,465	15,145	7,047	8,541	6,260
R-squared	0.072	0.034	0.018	0.029	0.024	0.029
Pre-drilling Mean	0.0847	0.0830	0.0456	0.0747	0.064	0.0414
Panel B: Term Birth Weight						
Within 2.5 km *post	−42.09	−56.15	−51.36 **	−62.97 *	−38.30	−49.61 *
	(41.26)	(37.10)	(19.04)	(36.70)	(29.02)	(28.45)
Observations	2,191	5,773	13,763	6,375	7,748	5,699
R-squared	0.131	0.064	0.042	0.077	0.076	0.055
Pre-drilling Mean	3305	3272	3479	3325	3349	3494
Panel C: Premature						
Within 2.5 km *post	0.0181	−0.00393	−0.000441	−0.00579	−0.00160	0.000744
	(0.0233)	(0.00950)	(0.00753)	(0.0136)	(0.0142)	(0.0134)
Observations	2,409	6,338	14,851	6,973	8,418	6,122
R-squared	0.070	0.026	0.015	0.027	0.021	0.030
Pre-drilling Mean	0.0896	0.0867	0.0749	0.0859	0.0782	0.0713

Notes: Each coefficient is from a different regression. See Table 4 for details about included covariates.

Significance:

*p<0.10,

**p<0.05,

***p<0.01.

Table 8:

Falsification Tests on Impact of Well Location

	(1)	(2)	(3)	(4)	(5)	(6)
	Permit Date			**Random date**		
	Low Birth Weight	**Term Birth Weight**	**Premature**	**Low Birth Weight**	**Term Birth Weight**	**Premature**
Within 2.5 km *post	−0.000106	−5.03	−0.00149	0.00103	−1.152	−0.00654
	(0.00682)	(12.382)	(0.00897)	(0.00303)	(11.5)	(.00789)
Sample Size	19246	17795	18854	21610	19978	21204
R^2	0.009	0.013	0.009	0.021	0.075	0.012

Notes: See Table 4 for included covariates. Each panel is a separate regression. All regressions include controls for maternal characteristics and time trends and county fixed effects. Columns (1)- (3) 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 occurred after (post) the permit date. Columns (4)-(6) use a random date to define post birth.

Significance:

*p<0.10,

**p<0.05,

***p<0.01.