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THE IMPACT OF OIL AND GAS EXTRACTION ON INFANT HEALTH

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ABSTRACT

The benefits and costs of resource extraction are currently being hotly debated in the case of shale gas development (commonly known as "fracking"). Colorado provides a unique research environment given its long history of conventional oil and gas extraction and, most recently, shale gas development. To define exposure, I utilize detailed vital statistics and mother's residential address to define close proximity to drilling activity. Using a difference-in-differences model that compares mothers residing within 1 km of a wellhead versus 1-5 km, I find that proximity to wells reduces birth weight and gestation length on average and increases the prevalence of low birth weight and premature birth. I also find an increase in gestational diabetes and hypertension for mothers living near wells. These results are robust to multiple specifications and suggest that policies to mitigate against the risks of living near oil and gas development may be warranted.

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A data appendix is available at http://www.nber.org/data-appendix/w30684

1 Introduction

US energy and environmental health policy lacks critically needed information regarding the economic, environmental, health and social implications of rapidly expanding oil and natural gas drilling (OGD) operations. One of the central innovations of the oil and gas industry in the U.S. is the use of high-volume horizontal hydraulic fracturing (HVHF) to gain access to formerly inaccessible formations, such as unconventional sources like shale. The "Shale Revolution", as it has been coined, has increased domestic production by 88% for natural gas and 137% for crude oil from 2005 to 2019 (DOE, 2021). With the recent increase in oil prices in 2022 due to geopolitical conflicts and inflationary pressures from the COVID-19 Pandemic, there is a new interest in expanding domestic onshore and offshore drilling in the U.S. Due to public attention and policy interest in assessing the health impacts of SGD there is a growing literature in economics that have found adverse birth outcomes for communities living near drilling (Currie et al., 2017; Hill, 2018; Hill and Ma, 2022; Willis et al., 2022). Much of the public fear, and recent academic research, centers around the recent growth in unconventional sources, such as shale gas, but mostly ignores more conventional forms of oil and gas development.[1] This paper fills this gap in the literature by studying the infant health effects in a state with multiple types of resources and development activities.

In this paper, I exploit the expansion of oil, gas and coalbed methane development, including vertical and horizontal wells in Colorado, to provide new quasi-experimental evidence of the infant health impacts of resource extraction. In addition to the growing economic literature, there is also a large epidemiological literature assessing associations between communities with drilling and birth outcomes (see Deziel et al. (2020) for a recent review). One of these studies found protective effects for preterm birth and low birth weight in Colorado and increased risk of birth defects (McKenzie et al., 2014). I find that there is positive selection into exposure to drilling in Colorado that may explain these counter-intuitive findings. Mothers living within 1 km of drilling are higher educated, more likely to be married, less likely to smoke, higher income, less likely to be teenaged and less likely to be on Medicaid. This selection may be explained by siting of drilling in particular counties in Colorado that

[1] There is an economic literature studying the 1970s oil boom, but this literature has focused on labor market outcomes and not infant health (Jacobsen and Parker, 2016; Jacobsen et al., 2021).

are also population centers or where industry can lease large amounts of property. Given these level differences (and no evidence of pretrends), I use a difference-in-differences research design to compare birth outcomes for maternal residences close (e.g. 0-1 km from a nearest well) to slightly further away (1-5 km from a nearest well), before and during/after drilling to estimate the average effect of living in close proximity to any well during pregnancy. The parallel trends assumption is tested by examining the observable characteristics of the mothers and pre-trends in the outcomes of interest across time and distance. A range of specifications are estimated in an effort to provide evidence that the research design is robust. I also estimate models of well density, mother fixed effects, extreme health outcomes, maternal health outcomes, and show robustness to the inclusion of controls for maternal income and insurance status.

I find both statistically and economically significant effects on infant and maternal health. I find that for the extensive margin, birth weight decreased and low birth weight (LBW) prevalence increased, on average. I also find impacts on gestational age and the prevalence of preterm birth (PTB). For LBW and PTB the magnitude of the impacts is about 25% relative to the pre-drilling mean. This effect size is similar in magnitude to other studies on SGD (Currie et al., 2017; Hill, 2018). I find consistent evidence as well for intensive margin models. For example, an additional well drilled within 1 km reduces birth weight by 2.5 grams, on average. I test sensitivity to spatial fixed effects (zip code, county), maternal fixed effects, and well fixed effects and the results are qualitatively robust. I also find an increase in gestational diabetes and hypertension for moms, which is consistent with one other study in Texas (Willis et al., 2022). The results are also robust to multiple specification checks, changes in temporal and spatial sample restrictions (e.g., no spatial restriction, within 15 km) and placebo regressions.

One major threat to my identification is that OGD leads to community and local economic changes that could in turn impact birth outcomes either through compositional changes or through economic shocks. A large and growing literature in economics has shown that OGD has impacts on housing values (Muehlenbachs et al., 2014; Gopalakrishnan and Klaiber, 2014; Bennett and Loomis, 2015), employment effects(Weber, 2011; Marchand, 2012; DeLeire et al., 2014; Wrenn et al., 2015; Feyrer et al., 2020), royalty payments and wage income (Hardy and Kelsey, 2015; Brown et al., 2016; Feyrer et al., 2020), educational response (Cascio and Narayan, 2015) and local governmental finance (Newell and Raimi, 2015). Other studies have shown impacts on migration (Wilson, 2022), fertility (Kearney and Wilson, 2018), and teen pregnancy (Owen, 2022).[2] Consistent with this literature, I find a 50% increase in the likelihood of teen motherhood in these communities. When I remove these mothers, my results hold, indicating that my main results are not driven by this increase. I also find some suggestive evidence that moms are more likely to move after drilling for lower order births (between 1st to 2nd and between 2nd to 3rd births) and less likely to move for higher order births (3rd to 4th births). Overall, I find modest impacts on mobility around a 1-4% increased likelihood of moms ever moving in response to drilling. When I limit to moms who never move, my main results are robust. Finally, I investigate fertility impacts and do not find consistent evidence of a large fertility impact, which is inconsistent with the prior literature (Kearney and Wilson, 2018).[3]

Finally, given that my main findings pool all wells drilled prior to birth, I use interaction models to understand whether certain types of drilling may be driving the overall effects. First, I interact with wells that are producing prior to pregnancy to understand if results are driven by newly drilled wells or older producing wells. I find most of the effect is driven by new wells, but producing wells have a small additional impact that is not statistically significant. Second, I estimate the effect of horizontal wells versus vertical wells and find that there is no statistical difference between these well types in Colorado. One other study has found slightly larger impacts for horizontal drilling in Texas (Willis et al., 2022), so this may show that vertical drilling in Colorado is not the same as what occurs in other states. Finally, I compare coalbed methane, oil and natural gas wells and find the largest impacts for coalbed methane, but adverse impacts for all three well types. These heterogeneity analyses indicate that all types of extraction activities are associated with adverse birth outcomes and that perhaps the policy debate should also include conventional natural gas, oil and other resource types.

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[2]See (Black et al., 2021) for a recent review of the economics literature studying the economic, environmental and health impacts of fracking.

[3]I aggregate to county and Kearney and Wilson (2018) aggregate to the commuting zone which may explain the inconsistency. My study is at an even finer spatial scale of within 5 km. I rule out fertility explaining the main results.

The economic benefit of drilling for natural gas is potentially huge for landowners, states, and industry. Many have written about the promise of this energy boom to improve the U.S. economy (Aguilera and Radetzki, 2013; Ames et al., 2012; Linn et al., 2014; Mason et al., 2015; Hausman and Kellogg, 2015; Bartik et al., 2019; Feyrer et al., 2020) and potentially public health from the reduction in the use of coal for electricity production (Johnsen et al., 2019). Any benefit-cost analysis requires taking into account the local external costs of drilling activities, and this paper provides robust estimates related to the health costs for birth outcomes in affected communities.

2 Oil and Gas Development in Colorado

2.1 Drilling and Production Overview

Colorado has had a long history of resource extraction, with the first wells drilled in the 19th Century and more recent development being regulated and managed by the Colorado Oil and Gas Conservation Commission (COGCC) starting in the 1950s. As of 2012, Colorado was the 6th largest producer of natural gas and 9th largest producer of oil. From 2007 to 2011 (last year of this study), oil and natural gas production increased 64% and 27%, respectively. Figure A1 shows trends over this period by resource type (e.g. wet gas, dry gas, coalbed methane or coal gas, oil) and shows trends in the utilization of horizontal drilling. Much of the increase in horizontal drilling began after 2005 across all resource extraction activities. There is a large amount of conventional, or vertical, drilling that occurs during this period, motivating the inclusion of these types of wells in this study.

2.2 Oil and Gas Development As A Potential Pollution Source

Pathways for human exposure (e.g. air, water) from oil and gas development (OGD) and high-volume hydraulic fracturing (HVHF) have become more well-defined in the peer-reviewed literature as of late. HVHF operations have been linked to surface and groundwater contamination, (Hill and Ma, 2017, 2022; Bonetti et al., 2021) and emissions of harmful air pollutants occur throughout the life cycle of HVHF development (Zhang et al., 2199). For both water and air pollution, the economic literature has found most of the impacts to occur during the drilling and hydraulic fracturing phases, with smaller amounts of pollution occurring during the production phase. Other studies have found increased light pollution following development that could also have adverse effects on pregnancy outcomes (**?**Smith and Wills, 2018). See these papers and a recent review by Black et al. (2021) that describe in detail the environmental mechanisms of exposure.

2.3 Reproductive Health Outcomes and Unconventional Drilling

Using the above literature review of potential contaminants, I searched the economic and epidemiological literature to better understand whether these contaminants are likely to impact reproductive health (as measured by low birth weight and premature birth). In the Appendix Table A1, I provide a tabular literature review of pertinent studies associated with each air pollutant. Most, if not all, contaminants are likely to contribute to the risk of adverse birth outcomes. The magnitude of the findings in this paper are well within the range of findings in these other studies.

Concurrently to the research reported here, there have been multiple studies in the epidemiology literature addressing birth outcomes to mothers who live in proximity to natural gas development (see Deziel et al. (2020) for scoping review) and three other studies in the economic literature based on unconventional (shale) gas development in Pennsylvania (Currie et al., 2017; Hill, 2018; Hill and Ma, 2022). Most of these studies consistently find adverse birth outcomes for mothers living in communities with drilling.

3 Data Sources

My analysis is based upon a data set acquired from the Colorado Oil and Gas Conservation Commission (COGCC) that contains information on each well drilled in Colorado since 1985.[4] The data set contains information on location of well (latitude and longitude), spud date (timing that drilling began), first production date, test dates, total depth date (when

[4]These data are self-reported by industry, however, they are required to submit this data to the state. The data quality improves over time.

vertical drilling completed), directional drilling (also called horizontal), resource type (i.e. oil, gas or coal bed methane), geological formation, company, and other details.

My second source of data comes from birth certificate records from the Colorado Department of Public Health and the Environment (CDPHE) from 2000 to 2011. The natality records contain detailed information on every birth in the state including health at birth and background information on the mother and father which includes race, education, marital status, as well as, prenatal care and whether the mother smoked or drank alcohol during her pregnancy. My study makes use of the mother's exact address (geocoded to latitude and longitude), which is merged to the oil and gas locations to define proximity to drilling.[5]

I make use of four primary reproductive health outcomes.[6] Birth weight is defined as the weight of the infant measured at birth in grams. Gestation length is defined as the number of weeks of gestation. Low birth weight (LBW), defined as birth weight less than 2500 grams, is commonly used as a key indicator of infant health, and hence is one of the outcomes examined. Premature birth, defined as gestation length less than 37 weeks, is associated with a greater risk for short and long term complications, including disabilities and impediments to growth and mental development. I also explore different levels of low birth weight and premature birth, as well as large for gestational age.

3.1 Descriptive Statistics

Table 1 provides summary statistics for the primary difference-in-difference (DD) analysis sample. In the DD model, I compare residences within 1 km of a gas well to those $1-5$ km from a gas well.[7] Most of the statistically significant differences between these two samples are actually not very economically important (e.g. are small in magnitude). However, mother characteristics closest to wells (1 km) are indicative of better socio-economic status versus those further away ($1-5$ km). Those mothers who reside within 1 km are more educated,

[5]CDPHE performed this merge and released the data stripped of geographical indicators, except those I requested specifying distance to nearest wells within 30 km of each mother's residence.

[6]Other outcomes that may be of interest, such as fetal/infant mortality and congenital anomalies are very rare events. When restricting the data set to those very close to gas wells or permits, there are insufficient cases in Colorado for there to be a measurable effect for these outcomes.

[7]In the analysis that follows, the sample is restricted to those mothers' residences within 5 km of an oil or gas well that was drilled within 2 years (before and after) of the timing of birth to limit other confounding and unobserved changes in these communities.

Table 1: Summary Statistics For Difference-in-Difference Sample

	Sample Means		T-Stat
	Within 1km	1-5 km	of Difference
Characteristics of Birth			
Birth weight	3299.98	3267.58	-4.09***
Gestation Length	38.86	38.80	-2.13*
Premature	0.065	0.074	2.43*
Low birth weight (LBW)	0.055	0.060	1.3
Very low birth weight (vLBW)	0.007	0.009	1.73
Female Child	0.48	0.49	2.37*
Mother's Demographic Characteristics			
Age	27.50	27.01	-5.38***
Education	13.59	13.26	-5.90***
White	0.955	0.924	-8.53***
Black	0.004	0.022	9.66***
Asian	0.016	0.021	2.24*
Other race	0.025	0.034	3.46***
Hispanic	0.306	0.347	5.77***
Smoked during pregnancy	0.067	0.089	5.45***
Married	0.770	0.736	-5.14***
Previous Risky Pregnancy	0.204	0.207	0.48
Parity	2.082	2.049	-1.91
Characteristics of Oil and Gas Wells near residence			
Average distance to closest well	0.61	2.55	137.90***
Number of wells drilled in year of birth	5.21	6.52	11.00***
Number of wells drilled within 5 km of residence	126.48	44.74	-74.70***
Sample Size	6448	14241	

* p<0.10, ** p<0.05, *** p<0.01

more white, less likely to smoke while pregnant, and more likely to be married. To look at these differences for births that occur before or after the nearest well is drilled, I also show distance gradients of maternal characteristics in Appendix Figure A2. These show a consistent relationship for both births before and after drilling near wells that suggest higher SES mothers are more likely to be exposed to drilling at close proximity. The difference in levels for maternal characteristics observed beyond 5 km are one reason I limit to within 5 km for my main results (and show robustness to this decision in the robustness checks in Section 6.4). I control for the observable characteristics of the mother in the empirical specifications that follow.

Table 1 also contains some information about the levels of exposure of oil and gas development in these communities. As you can see, the intensity of drilling for those very close to development is much greater than those a little further away: those living 1 km from a well are near 126 wells within $1-5$ km on average compared to 45 wells for those further away. The average number of wells drilled within 5 km in the year of birth is fairly similar, however, indicating that I am comparing similar communities with respect to drilling intensity, just exploiting proximity (close versus further away) to identify the causal impact of interest.

Appendix Table A2 provides summary statistics for the universe of births in Colorado from 2000-2011. The first column provides information on all births, and the second column provides information on births to mothers' residences within 5 km of where an oil or gas well has been drilled or will eventually be drilled. The localized data I use in this analysis is actually quite similar to the characteristics of the rest of the state. Column 3 provides a decomposition of birth weight of residences within 2 km of a well to gauge the importance of the various observable mother characteristics. These control variables are included in all my subsequent regression analysis, but, for simplicity, I do not report these coefficients in the main tables of the paper.

4 Graphical Evidence

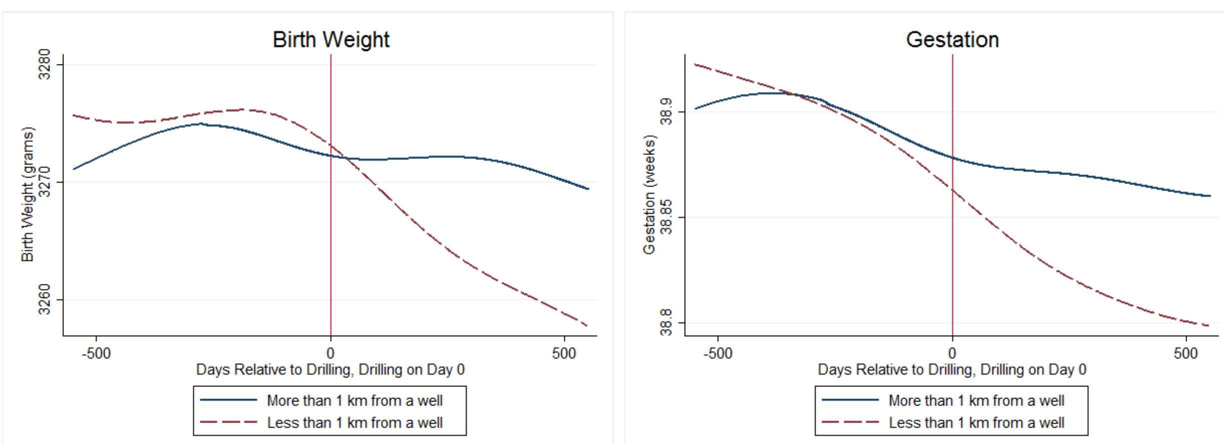


Figure 1: Birth Weight and Gestation Trends Before and After Drilling within 5 km.

If living close to a drilled well has a negative impact on infant health at birth, we should see average birth weight for mother's residences in close proximity to wells fall after when drilling begins. Moreover, we should observe larger impacts for homes closest to drilling activity. The notion that the reduction in birth weight (gestation) close to a well reflects the causal impact of living near drilling activity would be supported if the decline coincides with when drilling begins and does not reflect a preexisting downward trend in health for these mother's residences. Figure 1 shows the birth weight and gestation gradient of time with respect to when drilling begins within 1 km and between 1 and 5 km of the well locations. This gradient is measured for births 500 days before and during/after drilling. If the birth weight decline reflected a preexisting trend, we would see a consistent downward trend over this time period. Instead, I find a fairly sharp decrease in birth weights (gestation) coincident with the spud dates (defined as time=0).[8] Figure 1 also provides supportive evidence that there are parallel trends in the outcomes prior to drilling.

5 Empirical Strategy

In order to estimate a causal estimate of the effect of oil and gas development on reproductive health outcomes in affected communities, I employ a difference-in-differences research design. In this paper, my affected or "treated" group are those babies who are born to mothers who live within 1 km of a nearest well and that nearest well had a spud date (the date the drilling began) prior to the birthdate on the birth certificate. My comparison groups are those mothers who live 1 km from their nearest well that has not yet been drilled or those mothers who live 1-5 km from their nearest well, before or during/after drilling. This allows me to exploit the expected dose-response relationship: the closer a mother lives to a well, the more likely she is exposed, and the stronger the potential detected effect. But it also has the advantage of comparing mothers who all live relatively close (all within 5 km or less than 3 miles) to development and therefore are likely to be more homogeneous in both observable and unobservable factors.

An important caveat for my empirical strategy is that, I can observe health at birth for only those babies that are born alive. Also, I can only observe births for those mothers who

[8]The spud date is the date that the drill bit hit the ground, but building the well pad happens about $1-3$ months prior to that date on average. These graphs also use birthdate as the relevant date, when it is unlikely that drilling happening on the child's birthdate (e.g. time=0 in the graph) would influence birth outcomes. Due to the somewhat fuzzy nature of this timing, there does appear to be a slight trend prior to time=0, but for the most part, these graphs suggest that the differences coincide with the timing of drilling.

choose to get pregnant. If the composition of mothers choosing to get pregnant changes with the introduction of resource extraction, then the health that I observe may not be indicative of the average health of those living near wells in these neighborhoods. Furthermore, oil and gas development has been shown to increase migration and this also could change the composition of mothers living near drilling (Wilson, 2022).[9] There are a few ways that I address this issue. First, I show that most observable characteristics are not changing in response to development activities.[10] While this does not mean that unobservables are unchanged, it provides some reassurance that this identification strategy is sound. Second, for mothers who have more than one baby during my window of interest, I study whether they move after drilling began and do not find any statistically significant changes in mobility in response to development activities.[11] Third, although I cannot measure unobserved miscarriages, I test whether there is a change in sex ratio in these communities in response to development activities and find that there are no changes in sex ratio. This indicates that my findings are not likely to be driven by selection into a live birth. Finally, due to concerns about historical drilling contaminating the results and migration driving the results, I limit to births that occur within 2 years of the nearest well's spud date (i.e., birthdate $+/-2$ years of spud date) for the main results.[12]

My main equation takes the following form:

$$Outcome_{ijt} = \beta_0 + \beta_1 D_{ijt}^{1km} + \beta_2 Post_{ijt} + \beta_3 D_{ijt}^{1km} * Post_{ijt} + \beta_4 X_{ijt} + \gamma_t + \omega_j + \epsilon_{ijt} \quad (1)$$

[9]It is possible that mothers who value their children's health are more likely to move away from communities where drilling is taking place. This migratory effect would lower the average health of the observed births. However, it is also possible that those who are more likely to move are families who are experiencing the worse health effects of drilling. This migratory effect would increase the average health of the observed births. Thus, it is not clear whether selection or composition of the mother characteristics would lead me to overestimate or underestimate the health impacts of close proximity to drilling activity.

[10]There is an increase in teenage mothers after drilling, which reflects that areas with drilling had less teen moms prior to drilling than areas further from drilling. See Table 1 and Figure A2 for distance gradient of maternal characteristics. I control for maternal age in my main results and also run regressions excluding teen moms and show my main results are not driven by this change.

[11]There is no statistically significant relationship between the DiD estimator and the probability of moving, however, some magnitudes could be interpreted as economically meaningful (Table A16). To address this, I also estimate regressions on mothers that do not move, and the results are qualitatively similar to my main results (Table A17).

[12]I show robustness to this decision in Tables A12 and A13 and show no restriction, within 4 years (i.e., $+/-4$ years) and within 2 years. This is discussed in Section 6.4 Robustness Checks.

where $Outcome_{ijt}$ is birth weight, gestation, premature birth or low birth weight for each infant i born in location j in quarter-year t. $Post_{ijt}$ is an indicator for the birth occurring after the spud date, and D_{ijt}^{1km} is an indicator of whether the residence was 1 km from a current or future wellhead. β_3 is the coefficient of interest on $D_{ijt}^{1km} * Post_{ijt}$ and is the difference-in-difference estimator. ω_j is a zip code fixed effect and is designed to capture any unobserved time-invariant characteristics of each zip code in the sample.[13] γ_t are year, quarter and quarter-by-year fixed effects included to control for systematic trends over time. The standard errors in these models are clustered at the mother's residence zip code. The vector X_{ijt} contains mother and child characteristics including indicators for whether the mother is White, Black, Asian, other race (left out category) and/or Hispanic, four mother education categories (less than high school (left out category), high school, some college, and college or more), mother age categories (teen (left out category), 19-24, 25-34 and 35+), indicators for smoking or drinking during pregnancy, mother's marital status, previous risky pregnancy, current risky pregnancy, parity and an indicator for sex of the child. Starting in 2007, the birth certificate record contained information on insurance payment type (e.g. Medicaid, private insurance, self-pay, other), receipt of Women Infants and Children (WIC) supplemental nutritional support, and income categories.[14]

I augment the main model in multiple ways: (1) mother fixed effects, (2) nearest well fixed effects, and (3) interact the post dummy with # of wells for the intensive margin (i.e., density of drilling models). I also change the comparison group to be within 2 km in Appendix Table A11, and within 15 km and no distance restriction in Appendix Tables A12 and A13.

[13] I also report models where j is 1) county in Appendix Table A10, 2) well id for nearest well in Appendix Table A5, and 3) mother id in Appendix Table A4. Zip code is the smallest geographical unit that allows for studying the same communities over time, given the nearest well can change with more drilling and mothers who have more than one birth may be different from those that have one child. This is why the zip code FE models are my preferred specification.

[14] See Appendix Table A14.

6 Results

6.1 Differences in Characteristics of Mother's Close to a Well

My estimation strategy hinges on the relative similarity between mothers residing within 1 km of a well to mothers residing $1-5$ km of a well at the time of the observed birth. While this is somewhat supported by the graphical evidence, I formally estimate these differences. I proceed by estimating the pre-drilling differences for those within 1 km using the full sample of residences within 5 km.

Table 2: Differences in Average Characteristics Close to Well Locations

	(1) Teen Mom	(2) High School Drop Out	(3) Hispanic	(4) Smoked	(5) Married	(6) Risky Pregnancy
	Panel 1: Pre-drilling differences in characteristiscs					
Within 1 km of well	-0.0260***	-0.0513**	-0.0446	-0.0106	0.0369	-0.00755
	(0.00549)	(0.0253)	(0.0341)	(0.00797)	(0.0247)	(0.0116)
Sample Size	15,705	15,705	15,705	15,705	15,705	15,705
R^2	0.028	0.133	0.190	0.044	0.046	0.200
	Panel 2: Pre- and post-drilling differences in characteristics					
Post-drilling	0.0231**	-0.00861	-0.00881	-0.0321	-0.00629	-0.0525***
	(0.00955)	(0.0213)	(0.0241)	(0.0210)	(0.0297)	(0.0191)
Within 1 km	-0.0319***	-0.0475*	-0.0461	-0.00832	0.0390	-0.00314
	(0.00577)	(0.0257)	(0.0355)	(0.00872)	(0.0265)	(0.0102)
Within 1 km * post-drilling	0.0262***	0.0227	0.00449	0.00170	-0.0140	-0.0116
	(0.00464)	(0.0182)	(0.0243)	(0.00715)	(0.0176)	(0.00846)
Sample Size	20,689	20,689	20,689	20,689	20,689	20,689
R^2	0.029	0.124	0.176	0.041	0.044	0.208

Note: Each coefficient is from a different regression. Pre-drilling (post-drilling) refers to births that occur before (after) the spud date of the closest well. Standard errors are clustered at the mother's residence zip code. The sample is limited to residences within 5 km of a well, within 2 years of the spud date, and singleton births. All regressions include quarter and year of birth, residence zip code, and quarter*year fixed effects. * p<0.10, ** p<0.05, *** p<0.01

In Table 2, Panel A, I limit the sample to births that took place before the drilling began. I find little evidence of any pre-existing differences in either health at birth or mother characteristics that would be indicative of worse health trends in these communities prior to drilling. Although some differences are statistically significant, these communities boast heavier babies, more education, and less teen moms prior to drilling within 1 km of a future well. All of these characteristics indicate potentially better health outcomes, not worse. This does suggest selection into the locations where drilling takes place, but it goes in a direction that we may not have anticipated. Often, new industrial activity is correlated with poor, less educated communities. Fortunately, any bias would push my main estimates towards a null effect, and any adverse effects detected are certainly not reflective of a pre-existing adverse health trend.

To further test the validity of my research design, I also estimate equation 1 and use the difference-in-differences estimator to determine if there are any changes in mother characteristics after drilling began. Results are reported in Table 2, Panel B. Mothers who gave birth after drilling occurred within 1 km of their residence have an increased likelihood to be teen moms, consistent with at least one other study that found an increase of 7.2 births per 1000 among teenage white mothers (Owen, 2022). Although this shows a change in the composition of mothers, teen moms still make up a very small proportion of the population (6 percent, see Appendix Table A2). I also estimate models removing teen mothers and show that the results are consistent and that this change in the composition of mothers is not driving the primary effect (see Table A8 Panel E). In my main models discussed in the next section, I include controls for these and more characteristics in all specifications to help account for any changes in composition of who selects into a live birth after drilling begins.

6.2 The Impact of Oil and Gas Extraction on Infant Health

I present my main findings in Table 3 with and without maternal characteristics. Estimates with and without characteristics do not change much in magnitude or significance, providing confidence in the estimation strategy. Estimating equation (1) in Table 3– my difference-in-difference specification– I find that birth outcomes are adversely affected by drilling activity within 1 km of the maternal residence. The estimate for birth weight is 35.79 grams, with mother characteristics included, and is statistically significant at the 1 percent level. In addition to reduced average birth weight, residences within 1 km of a well have births with reduced gestational periods, increased prevalence of LBW of 1.70 percentage

Table 3: Impact of Well Location on Birth Outcomes

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Birth Weight		Gestation		Low Birth Weight		Premature	
	Panel A: Pre-drilling differences in birth outcomes							
Within 1 km of well	67.04***	52.29***	0.125***	0.127***	-0.0147*	-0.0114	-0.0264***	-0.0252***
	(10.91)	(11.24)	(0.0401)	(0.0354)	(0.00761)	(0.00744)	(0.00498)	(0.00488)
Sample Size	15,703	15,703	15,704	15,704	15,703	15,703	15,704	15,704
R^2	0.017	0.055	0.016	0.029	0.013	0.028	0.012	0.022
Maternal Characteristics	no	yes	no	yes	no	yes	no	yes
	Panel B: Pre- and post-drilling in birth outcomes							
Post-drilling	-0.115	-7.909	-0.0431	-0.0695	0.00566	0.00964	-0.00631	-0.00230
	(30.13)	(28.77)	(0.0607)	(0.0647)	(0.0118)	(0.0121)	(0.00818)	(0.00798)
Within 1 km	61.79***	48.47***	0.128***	0.129***	-0.0159**	-0.0130*	-0.0250***	-0.0236***
	(11.14)	(10.87)	(0.0441)	(0.0401)	(0.00676)	(0.00662)	(0.00455)	(0.00454)
Within 1 km * post-drilling	-38.89***	-35.79***	-0.108**	-0.114***	0.0180***	0.0170***	0.0216***	0.0215***
	(11.40)	(11.13)	(0.0421)	(0.0408)	(0.00564)	(0.00543)	(0.00443)	(0.00457)
Sample Size	20,687	20,687	20,687	20,687	20,687	20,687	20,687	20,687
R^2	0.014	0.055	0.014	0.025	0.011	0.025	0.011	0.021
Maternal Characteristics	no	yes	no	yes	no	yes	no	yes

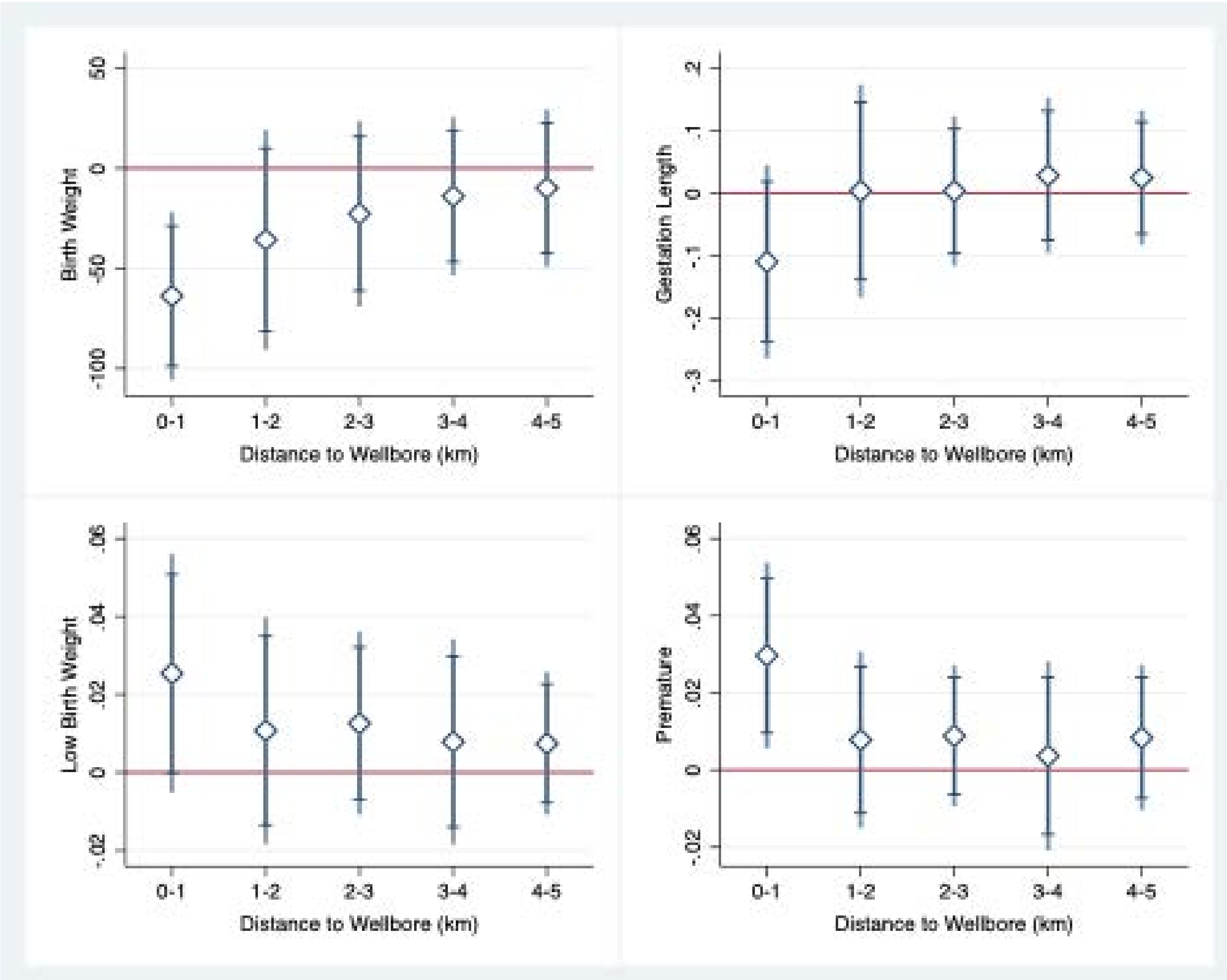
Note: Each coefficient is from a different regression. Post-drilling refers to births that occur after the spud date of the closest well. Standard errors are clustered at the mother's residence zip code. The sample is limited to residences within 5 km of a well, within 2 years of nearest spud date, and singleton births. All regressions include quarter and year of birth, residence zip code, and quarter*year fixed effects. Maternal characteristics include mother black, mother Hispanic, mother Asian, mother education (hs, some college, college), mother age (19-24,25-34, 35+), female child, smoking during pregnancy, drinking during pregnancy, indicators for parity, indicator for previous/current risky birth and marital status. * p<0.10, ** p<0.05, *** p<0.01

points and increased prevalence of premature birth of 2.15 percentage points.[15] To explore if this effect is persistent, I present the estimates for distance bins out to 5 km in Figure 2 and present in Appendix Table A3 estimates from equation (1) using 1.5 km and find a persistent, but less precise, reduction of birth weight of 25.55 grams, on average. This effect does not persist past 2 km and suggests that there may be a threshold of exposure between $1.5 - 2$ km from an oil or natural gas well (approximately 1 mile).

To assess robustness of these results, I also estimate equation (1) with mother fixed effects and well id fixed effects (Tables A4 and A5). Comparing siblings, except for gestation, however, the qualitative magnitudes are similar to my main results and are statistically significant (Table A4). Comparing births around the same nearest well is another possible way to identify the effects of drilling on birth outcomes. Unfortunately, the nearest well over

[15] Due to the imprecise nature of the oil and gas well dates, I also estimate the main results using conception date as the date of interest to define exposure. These results are qualitatively similar to the main findings and are available upon request.

Figure 2: Birth Outcome Impacts of Drilling within 5 km



Note. Figure plots coefficients from a model with binary distance bins (0-1, 1-2, ... 4-5) indicating any drilling before birth within that bin. Also included are binaries for wells within these distance bins ever and a binary for post-drilling. The model limits to the main sample described in Table 3 and includes the same controls and fixed effects.

time is not a constant spatial location, with new wells becoming drilled across the landscape. Furthermore, the average residence that has a well at any time within 1 km of the maternal residence is exposed to an average of 7 wells within 1 km prior to birth.[16] Despite these limitations, I show in Table A5 that my main results are robust to including the nearest well as a fixed effect.

[16]If I drew concentric circles around wells to identify births within some proximity of a central well, many times these births would be assigned to multiple wells and I would need to weight my regression appropriately. This led me to compare within zip codes, which are the smallest unit to capture communities over time. It is also why I report models using density of wells, which does not easily translate to a well FE model.

Intensive Margin: Well Density In Table 4, I present results analogous to Table 3 in Panel A except with a continuous measure of treatment defined by number of wells drilled prior to birth. In Table 4 Panel B, I show the impact of well density by when wells were drilled, either prior to conception or during gestation (i.e., *inutero*). Here, I present the intensive margin results with zip code fixed effects (as in Table 3) and mother fixed effects (as in Appendix Table A4). The intensive margin results consistently suggest an adverse health impact associated with each additional well drilled before birth for birth weight, gestation and low birth weight (LBW), although these results are only statistically significant for LBW. The results for premature birth are opposite signed and not precisely estimated. Unlike the extensive margin in a mother fixed effects model (Appendix Table A4), I only find a statistically significant effect for low birth weight. It is very possible that I do not have enough sample to estimate the impact off of the intensive margin (i.e., each additional well drilled) across siblings. This is consistent with findings from Pennsylvania: Hill and Ma (2022) found strong impacts of the intensive margin for exposure to gas wells near public drinking water sources in a mother fixed effects model with a larger sample exposed, but Currie et al. (2017) did not find statistically precise effects of the extensive margin when assessing proximity to maternal residence due to small sample. In Panel B, I find suggestive evidence that wells drilled before conception as well as wells drilled during pregnancy have impacts on adverse birth outcomes. In Figure A3, I show coefficients for number of wells in different distance bins and find the majority of the impact on birth weight is within 1 km, consistent with my extensive margin results (See Appendix Table A6 for full specification coefficients).[17]

Levels of Low Birth Weight and Premature Birth Low birth weight and premature birth are arguably arbitrary cut-offs and are an attempt to get at a latent variable - the threshold at which children require additional medical support in their first few weeks of life. Appendix Table A7 reports three categories of severity for each of these measures. For levels of low birth weight, oil and gas extraction primarily increased the probability of being

[17]The coefficients change slightly when the number of wells in other distance bins are included in the model. Table 4 only includes # of wells within 1 km, whereas Table A6 controls for # of wells within each distance, as shown in the table. The specification where multiple distance bins are included results in the effect on birth weight becoming slightly larger and statistically significant.

Table 4: Impact of Well Density on Birth Outcomes

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Birth Weight		Gestation		Low Birth Weight		Preterm Birth	
	Panel A: # of wells before birth							
# of wells within 1km	1.425**	-0.713	0.00470**	-0.0221***	-0.000705**	0.000963*	-0.000403	0.000429
	(0.648)	(1.159)	(0.00214)	(0.00361)	(0.000309)	(0.000519)	(0.000273)	(0.00109)
post-drilling	-7.962	-0.0392	-0.0787	0.00496	0.00872	-0.0300	-0.00239	-0.0186
	(29.64)	(53.64)	(0.0661)	(0.121)	(0.0126)	(0.0235)	(0.00834)	(0.0170)
# of wells within 1km * post drilling	-1.170	-1.821	-0.00343	-0.000930	0.000809**	0.00279*	-0.000350	-1.78e-05
	(0.982)	(2.065)	(0.00324)	(0.00456)	(0.000360)	(0.00147)	(0.000277)	(0.000684)
	Panel B: # of wells before conception & inutero							
# of wells within 1km	1.401**	-0.682	0.00450**	-0.0222***	-0.000714**	0.000970*	-0.000400	0.000436
	(0.654)	(1.098)	(0.00212)	(0.00361)	(0.000313)	(0.000513)	(0.000271)	(0.00107)
post-drilling	-8.616	1.979	-0.0856	0.0118	0.00888	-0.0306	-0.00224	-0.0191
	(29.91)	(54.01)	(0.0661)	(0.125)	(0.0126)	(0.0245)	(0.00830)	(0.0166)
# of wells within 1km * before conception	-1.425	-2.017	-0.00527	-0.00464	0.000600*	0.00316**	-0.000333	0.000313
	(0.876)	(1.763)	(0.00460)	(0.00438)	(0.000342)	(0.00146)	(0.000384)	(0.000947)
# of wells within 1km * inutero	0.0156	-2.129	0.00611	0.00604	0.00147**	0.00210*	-0.000477	-0.000667
	(2.123)	(1.865)	(0.00451)	(0.0148)	(0.000650)	(0.00120)	(0.000438)	(0.000556)
Sample Size	20,653	4,062	20,653	4,060	20,653	4,062	20,653	4,060
R^2	0.053	0.706	0.025	0.634	0.024	0.559	0.020	0.564
Dep Var Mean	3278	3298	38.82	38.80	0.0582	0.0544	0.0714	0.0663
Zip code FE	YES		YES		YES		YES	
Mom FE		YES		YES		YES		YES

Note: Each column and panel represents a separate regression. Standard errors are clustered at the mother's residence zip code. The sample is limited to residences within 5 km of a well and singleton births. All regressions include quarter and year of birth, residence zip code, and quarter*year fixed effects. Maternal characteristics include mother black, mother Hispanic, mother Asian, mother education (hs, some college, college), mother age (19-24,25-34, 35+), female child, smoking during pregnancy, drinking during pregnancy, indicators for parity, indicator for previous/current risky birth and marital status. * $p<0.10$, ** $p<0.05$, *** $p<0.01$

slightly low birth weight by 1.1 percentage points and increase the probability of being very low birth weight by 0.3 percentage points. In contrast, exposure increased the rate of all levels of premature birth: the probability of being slightly premature ($34-37$ weeks) increased by 1.4 percentage points, the probability of being moderately premature ($32-34$ weeks) increased by 0.3 percentage points and the probability of being very premature increased by 0.5 percentage points.

Heterogeneity by Maternal Characteristics Birth outcomes are associated with different subgroups, as shown in the marginal effects reported in Table A2. Prior work has shown that families of lower SES are more likely to be impacted by environmental exposures (Almond et al., 2018). In Appendix Table A8, I present results for various potentially important subgroups. Most notably, the results for white non-Hispanic mothers are quite a bit more pronounced than the main results in the paper. And the results for smokers are very large, suggesting that maternal smoking may have a compounding effect.[18] Some may be concerned that migration is driving these results. Although it is an imperfect measure of mobility, I find very similar results for mothers who were born in Colorado. Lastly, as previously discussed, there are more teen mothers after drilling began that could be driving my results. In Table A8 Panel E, I present the results limiting to mothers aged 19-35 years old, and the main results are robust to this restriction. Therefore, I conclude that migration or changes in composition may influence my main results but are not driving them entirely.

Heterogeneity by Well Type & Production This paper is motivated by a dearth of research using quasi-experimental approaches to assess the health impacts of all drilling types including oil, natural gas, coalbed methane and vertical/horizontal drilling. Thus far I have been pooling all well types and also not accounting for the production status of wells nearby at the time of pregnancy and birth. In Table 5, I present heterogeneity of impacts by producing wells (Panel A), horizontal wells (Panel B), and resource type (Panel C). I find that most of the impacts in my main results are from newly spudded wells, but that producing wells may also add some adverse effect that is not statistically significant (Table 5 Panel A). For horizontal wells, I find that they are not very different from vertical wells in terms of impacts (Table 5 Panel B). This is consistent with other research, however, most other research find a slightly larger impact for horizontal wells (Willis et al., 2021). Lastly, it appears that coalbed methane wells are contributing the most to adverse birth outcomes, but that oil and natural gas wells (if you add the post-drilling and oil or gas interaction terms) are still contributing to the impacts I estimate in the main models. In particular, coalbed methane wells seem to have a very large impact on preterm birth (Table 5 Panel C Column 4).

6.3 Impact of Drilling on Maternal Health and Health Care

I find some indication in this paper of positive selection into living near drilling in Colorado: families who live very close (within 1 km) to drilling have higher income and are more educated (See Section 6.1). In Table 6, I find some indication of pre-drilling differences that

[18] This has been found in other papers as well (Currie et al., 2009).

Table 5: Heterogeneity of Impacts by Well Type

	(1)	(2)	(3)	(4)
	Birth Weight	Gestation	Low Birth Weight	Premature
	Panel A Producing Wells			
Within 1 km	36.74***	0.0742**	-0.0180***	-0.00631
	(11.24)	(0.0371)	(0.00539)	(0.00699)
Post-drilling	-8.021	-0.0701	-0.00230	0.00951
	(28.73)	(0.0645)	(0.00799)	(0.0123)
Within 1 km * post-drilling	-19.57*	-0.0315	0.0151**	0.0109
	(10.36)	(0.0341)	(0.00619)	(0.00666)
Within 1 km * post-drilling * producing	-7.724	-0.0736	-0.00555	-0.0174**
	(22.29)	(0.0613)	(0.0116)	(0.00720)
	Panel B Horizontal Wells			
Within 1 km	36.20***	0.0708*	-0.0173***	-0.00570
	(11.31)	(0.0361)	(0.00510)	(0.00655)
Post-drilling	-7.748	-0.0687	-0.00284	0.00891
	(28.74)	(0.0648)	(0.00796)	(0.0124)
Within 1 km * post-drilling	-21.79*	-0.0446	0.0185**	0.0142
	(12.64)	(0.0477)	(0.00741)	(0.00866)
Within 1 km * post-drilling * horizontal	3.182	0.0120	-0.00903	-0.0116
	(15.72)	(0.0566)	(0.00607)	(0.00784)
	Panel C Oil, Gas or Coalbed Methane Wells			
Within 1 km	35.19***	0.0748**	-0.0184***	-0.00593
	(10.91)	(0.0373)	(0.00531)	(0.00690)
Post-drilling	-6.405	-0.0729	-0.00197	0.00859
	(28.36)	(0.0645)	(0.00800)	(0.0120)
Within 1 km * post-drilling	-63.49*	0.0323	0.0124	0.0344***
	(34.01)	(0.0966)	(0.0131)	(0.0111)
Within 1 km * post-drilling * oil	44.63	-0.0713	0.00156	-0.0257**
	(36.94)	(0.0924)	(0.0124)	(0.0107)
Within 1 km * post-drilling * gas	25.37	-0.0841	0.0117	-0.0229**
	(20.06)	(0.0631)	(0.00854)	(0.00921)
Sample Size	20,653	20,653	20,653	20,653
R-squared	0.053	0.024	0.020	0.024
Zip FE	YES	YES	YES	YES
Distance restriction (km)	5	5	5	5
Dep Var Mean	3278	38.82	0.0714	0.0582

Note: Each column represents a separate regression. Standard errors are clustered at zip code. The sample is limited to a four-year window surrounding drilling (i.e. 2 years prior and 2 years after), residences within 5 km of a well and singleton births. All regressions include quarter and year of birth, zip, and quarter*year fixed effects. Maternal characteristics are included (see Table 3 for list). * p<0.10, ** p<0.05, *** p<0.01

could indicate better health and resources with respect to reproductive health for families living within 1 km of future drilling. For example, mothers who gave birth within 1 km from

Table 6: Impact of Well Location on Maternal Health, Prenatal Care, & Fertility

	(1) Complications of pregnancy	(2) Lung Disease	(3) Labor Complications	(4) Fetal Death (male/female	(5) Prenatal	(6) ln(births)
Post-drilling	0.00600	0.0237***	-0.0462**	-0.0281	-0.104***	-0.0259
	(0.00408)	(0.00388)	(0.0188)	(0.0271)	(0.0100)	(0.0343)
Within 1 km	-0.00764	0.000299	-0.000599	-0.00301	0.0404***	0.0401
	(0.00695)	(0.00244)	(0.00886)	(0.00905)	(0.0113)	(0.0420)
Within 1 km * post-drilling	0.0108**	-0.00392	0.00767	-0.0164**	0.00903	0.00964
	(0.00439)	(0.00278)	(0.0162)	(0.00710)	(0.00940)	(0.0417)
Sample Size	20,689	20,689	20,689	20,689	20,576	450
R^2	0.395	0.723	0.128	0.039	0.060	0.995

Note: Each coefficient is from a different regression. Pre-drilling (post-drilling) refers to births that occur before (after) the spud date of the closest well. Standard errors are clustered at the mother's residence zip code. The sample is limited to residences within 5 km of a well and singleton births. All regressions include quarter and year of birth, residence zip code, and quarter*year fixed effects. Pre- and post- drilling regressions also include maternal characteristics. See Table 3 for covariates included. Column 6 is a county-level model. * p<0.10, ** p<0.05, *** p<0.01

future drilling were 2.6 pp less likely to have labor complications and 2.8 pp more likely to have adequate prenatal care compared to those who live $1-5$ km away from future drilling.

A growing literature has looked at maternal health to identify stress during pregnancy (Camacho, 2008; Torche, 2011; Currie and Rossin-Slater, 2013; Currie and Schwandt, 2014). This literature uses hypertension, eclampsia, and diabetes as medical risk factors correlated with maternal stress. Hypertension, eclampsia and gestational diabetes have also been linked to air pollution exposure during pregnancy in the epidemiology literature (Pereira et al., 2012; Hooven et al., 2011; Woodruff et al., 2008). In Table 6, I label these three conditions complications of pregnancy. Additionally, labor complications have been associated with stress during pregnancy as well (Bussières et al., 2015). Table 6 presents results using the difference-in-differences estimator to look at these factors. Interestingly, living within 1 km of an oil or gas well increases the probability of complications of pregnancy (defined as either hypertension, eclampsia or gestational diabetes) by 1.1 percentage points. This is consistent with a study in Texas that found an increase in maternal hypertension (5%) and eclampsia (26%) in communities with OGD (Willis et al., 2022).

Labor complications may also increase, but is not precisely estimated. I do not find increased prevalence of lung disease, but maternal asthma is not well reported in these data. I do not find any changes in prenatal care of the moms associated with oil and gas extraction, which indicates that the adverse birth and maternal outcomes are not caused by changes in access or utilization of prenatal care by mothers exposed to drilling. The male/female sex ratio has been used to measure selection into live birth (Sanders and Stoecker, 2015) and here I find little evidence of oil and gas extraction increasing the prevalence of miscarriage, indicating that the adverse birth outcomes observed are unlikely to be related to selection into live birth. Finally, I do not find strong evidence that fertility increased in counties with residences within 1 km of drilling (less than 1% increase). This is not consistent with other research that has found large increases in birth rates at the commuting zone level associated with the shale boom (Kearney and Wilson, 2018). I include in Appendix Table A9 additional ways to measure changes in fertility.[19] Using the intensive margin, I find that drilling within counties that have wells within 5 km may have less fertility (less than 1% change per additional horizontal or producing well) for contemporaneous drilling. This leads me to conclude that fertility may be changing in response to drilling but is not likely large enough to be driving my results.

6.4 Robustness Checks & Mobility

To provide additional support for the research design, I perform a few robustness checks. I assess robustness to spatial fixed effect, distance restrictions, temporal restrictions, and covariate inclusions. I also estimate placebo regressions. Finally, I assess the main threat to identification: mobility. I measure likelihood a mom moves across pregnancies, and I restrict to the sample that does not move. My main results are qualitatively robust to these checks.

Fixed Effects, Spatial and Temporal Restrictions Most of the results reported in this paper use zip code fixed effects. I have also estimated all of the results using county fixed effects that also include county*year*month-of-birth fixed effects. A comparison with the main results are reported in Appendix Table A10. Choice of location fixed effects does

[19] I aggregate to counties because births in zip codes are sparse for this analysis: the 25%tile was 4 births per year and the median was 24. In Panels A-C, I explore various definitions of exposure defined at the county level. The migration story for jobs may respond both to contemporaneous drilling and cumulative drilling. Panel A explores number of wells by various types (horizontal, vertical, producing) drilled in the year. Panel B looks at binary exposure (any wells drilled in the year). Perhaps we think it is instead cumulative drilling that could impact fertility, and so I include Panel C for cumulative wells by type. Given my study is at a more micro-level than county, I retained in Panel D the exposure to drilling at the maternal residence for births within each county to address issues of drilling occurring within counties but not near maternal residences. Panel D is the result reported in Table A9.

not appreciably change the results. In my main specification, I restrict to within 2 years of a spud date and within 5 km of the nearest well. In Appendix Table A11 I show robustness to comparing within 1 km to 1-2 km. In Appendix Tables A12 and A13 I present regressions relaxing these restrictions for continuous outcomes (birth weight and gestation) and binary outcomes (LBW and PTB), respectively. In columns 1-3, I show no spatial restriction (i.e., all of Colorado), and show no temporal restriction, then 2 years and 4 years restrictions. Analogously, I do the same in columns 4-6 for within 5 km, and in columns 7-9 for within 15 km, varying the temporal restriction in each column. I find that the results are strongly robust for the continuous outcomes (Table A12) both in magnitude and statistical significance, but are less robust for the binary outcomes (Table A13; sign and magnitude but not statistically precise). Across the board, results are stronger with some temporal restriction, but are robust across any spatial restrictions (holding the temporal restriction constant). This further provides suggestive evidence that the main results reflect impacts from newer drilling and not from older producing wells. This is also consistent with Hill and Ma (2022) who found drinking water impacts during gestation but not in models that measured cumulative drilling that occurred prior to pregnancy. Of course, I do find impacts for pre-conception drilling in Table 4, just drilling that occurs within 2 years of pregnancy.

Additional Income and Insurance Covariates In the Appendix, I also present difference-in-difference estimates for the four birth outcomes for the years $2007 - 2011$ in Table A14. The birth certificate records changed in 2007 to include mother's income, insurance status, and whether she received public support from Women Infants and Children (WIC). To make sure that the results are robust to additional controls, especially controls for socio-economic status like income and insurance, I replicate the main table using this sub-sample. For each health measure, I provide 2 columns. The first column includes the same controls as the rest of the paper, and the second column adds these additional income/insurance controls. The results suggest that a drilled well within 1 km of a mother's residence from $2007 - 2011$ results in a decreased birth weight of 30.7 grams and a reduced gestational period of 0.10 weeks, on average. The estimates also suggest a 2.03 percentage point increase in low birth weight and a 1.16 percentage point increase in premature birth. Only the premature estimate becomes less precise with the inclusion of expanded controls for income. These estimates also suggest that the main results in the paper are not driven by earlier time periods, and that the impacts of close proximity to oil and gas wells remain persistent in more recent years.

Placebo Regression Due to my analysis showing evidence of preexisting differences in the communities located closest to drilled wells relative to communities close to future wells or those who live a little further away, I employ a few placebo regressions. Even though the trends are suggestive of better outcomes prior to drilling, it is theoretically possible that the increase in adverse birth outcomes after drilling is driven by differential trends in fertility or migration post-drilling. I investigate this possibility by estimating equation (1) using false spud dates 2 years prior to the actual spud date to define exposure. Table A15 presents baseline estimates and the results of this placebo regression, and I find no evidence of a spurious effect.

Using a date that is a fixed number of years prior may not be a suitable choice if different communities systematically are exposed at different times. To address this, I also perform checks using two random dates, one relative to the spud date and one relative to the birthdate. Using a uniform distribution, I create a random date based upon the number of days in the year of spud or birth and then allow the year to change randomly 5 years before and after. These results in Appendix Table A15 also show no statistically significant effects and provide support for the research design used.

Mobility Prior research has shown large causal impacts of oil and gas development on migration, particularly in North Dakota (Wilson, 2022). To address this threat to my identification, I look at maternal mobility, using the fact that I observe siblings in the birth certificate. I define mobility a few ways: mom ever moved, mom moved between first and second birth, mom moved between second and third birth, and mom moved between third and fourth births. As we get to higher order births, the sample changes because there is selection into who has more than 1 or 2 births. Taking these limitations into account, I present in Appendix Table A16 results for no spatial or temporal limitations and my main sample. I do not find any statistically significant effect of drilling within 1 km prior to birth on the likelihood of moving, however, the magnitudes could be economically meaningful. For example, while overall, I find a 1-4% increase in the likelihood of moving, in my preferred sample, I find a 7% and 10% increase in the likelihood of moving between first and second births and between second and third births, respectively. However, for moms exposed to drilling who have 4 or more children, they are 19% less likely to move compared to moms with 4 or more children further from drilling. Considering birth order changes the picture substantially. Given these qualitative findings of possibly large mobility impacts, I also present results limiting to moms who do not move (Appendix Table A17). My results are qualitatively robust to these restrictions.

7 Discussion

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

My results suggest that babies born of mothers who lived within 1 km of an oil or gas well during pregnancy had lower birth weights on average after drilling. Oil and gas extraction increased the incidence of low birth weight and premature birth in the vicinity of a well by 31 percent and 33 percent, respectively.[20] Furthermore, birth weight and gestation were decreased by 35.8 grams (1.1 percent) and 0.11 weeks (0.3 percent) on average, respectively. While these impacts are remarkably large, they are biologically plausible given the correlations between air pollution (or maternal stress) and birth outcomes found in previous studies.[21] These results are also consistent with those by economists in the context of

[20]Using 2007-2011 data or a mother fixed effect, the results for premature birth are completely attenuated with the inclusion of maternal income, insurance type and WIC indicating that the effect for premature birth is less robust and likely explained by unobserved SES or other factors.

[21]For example, Zahran et al. (2012) found exposure to benzene reduced birth weight by 16.5 grams and increased the odds of a very low birth weight event by a multiplicative factor, and Slama et al. (2009) found that exposure to benzene (one of the likely contaminants associated with oil and gas development) reduced birth weight by 77 grams.

Pennsylvania for low birth weight: Currie et al. (2017) found an increase of 25 % within 1 km compared to $3 - 15$ km, Hill (2018) found an increase of 25% compared to permitted wells within 2.5 km, and Hill and Ma (2022) find an increase of 11% for each additional well drilled near a public drinking water source. 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.

Importantly, the results for maternal risk factors are suggestive of increased stress and exposure to ambient air pollution and are consistent with Willis et al. (2022) in the context of Texas. These results begin to clarify the likely mechanisms that explain the infant health results. The results for different levels of low birth weight and premature birth suggest that oil and gas extraction are not merely increasing those that fall below the threshold, but that there is also an increase in very low birth weight and very premature birth. This suggests that the communities exposed may experience increased infant mortality and certainly higher health care costs associated with these more vulnerable infants.[22]

It is clear from these results that policies intended to mitigate the risks of oil and gas development can have significant health benefits. I find detectable effects of oil and gas development up to 1.5 km from the wellhead. Current required setback distances (distance between wellhead and nearby residences, hospitals and schools) range from 300 ft to 800 ft across the 34 states where oil and gas development is taking place.[23] With detectable infant health effects up to 1 mile away, these set back distances may be deemed insufficient to protect human health (see Ericson et al. (2020) for a discussion of costs associated with increasing setback distances in Colorado). These findings 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.

Context in Existing Literature Concurrently to this study, a few other studies have been published on the reproductive health effects of natural gas development. The results reported in this paper are fairly similar to those found in Pennsylvania (Currie et al., 2017;

[22]Very low birth weight and very premature birth are major risk factors for infant mortality.

[23]COGCC increased the setback from 300 to 500 ft for occupied buildings in 2013. Debate continues in CO about extending setbacks for schools or hospitals to 1000 ft or some have lobbied for 1500-2500ft.

Hill, 2018).[24] Studies in Pennsylvania have focused on shale gas development, whereas my study expands to other types of drilling in Colorado. Given the similarity in results, the findings in this paper suggest that any and all resource extraction is likely to result in adverse birth outcomes, not just shale gas (or what is commonly considered “fracking”).

In contrast to the findings in Pennsylvania, and the findings in this paper, McKenzie et al. (2014) found that maternal residences near the largest number of natural gas wells within 10 miles of the maternal residence in rural Colorado had reduced prevalence of low birth weight and premature birth, but found an increased risk for congenital heart defects using cross-sectional variation from 1996-2009. In this paper, I show proximity to drilling is correlated with higher SES and mothers living within 1 km boast heavier babies and less prematurity prior to drilling. I do not find an increased risk of congenital birth defects, and believe the discrepancy in findings is easily explained by the difference in empirical approaches.

8 Conclusion

Despite substantial policy attention and significant increases in drilling activity across the country, there is little guidance on how environmental and health policy should be designed to protect the health of those citizens who live in close proximity to well development, waste treatment facilities or shale gas supply routes. This paper highlights the importance of protecting reproductive health for women living near oil and gas development activities, and the importance of studying the health effects for individuals living near conventional development activities, not just shale gas.

As a first step, I assembled with the help of CDPHE a unique data set with the latitude and longitude of new mothers and the locations of oil and gas wells in Colorado and calculated spatial-temporal relationships for all births in Colorado. I examine the impacts of living in close proximity to development on low birth weight, birth weight and premature birth using a difference-in-differences estimation strategy. Using very detailed data on the locations of oil and gas wells in Colorado and the dates they are drilled, I estimate that, on average,

[24] The Pennsylvania studies found adverse impacts across the board, but there is some discrepancy regarding whether it increases low birth weight or premature birth or both.

that mothers living within 1 km of a well have reduced birth weight babies and increased prevalence of low birth weight. The result for low birth weight is large indicating an increase relative to the mean of 31 percent. I also find increased prevalence of premature birth and reductions in gestation lengths in these communities. I provide new evidence on mechanisms, showing that newer drilled wells and coalbed methane wells have the largest impacts on infant health. I also address threats to my identification by understanding how oil and gas development in Colorado leads to changes in community composition, migration, and fertility.

While the economic benefits of oil and gas development are easily quantifiable, there may be some hidden external costs. Given that low birth weight and premature birth are strong predictors of education, labor force participation, reduced earnings and future health, the long term costs could be very high for these communities. Further research to inform policymakers about the precise mechanisms of exposure is sorely needed and more research on the health impacts to children and adults, as well as longer term impacts, is certainly warranted.

References

Aguilera, Inmaculada, Mònica Guxens, Raquel Garcia-Esteban, Teresa Corbella, Mark J. Nieuwenhuijsen, Carles M. Foradada, and Jordi Sunyer. 2009. "Association between GIS-based exposure to urban air pollution during pregnancy and birth weight in the INMA Sabadell Cohort." *Environmental health perspectives*, 117(8): .

Aguilera, Roberto F, and Marian Radetzki. 2013. "Shale gas and oil: fundamentally changing global energy markets." *Oil & gas journal*, 111(12): 54–+.

Almond, Douglas, Janet Currie, and Valentina Duque. 2018. "Childhood Circumstances and Adult Outcomes: Act II." *Journal of Economic Literature*, 56(4): 1360–1446.

Ames, Robert M, Anthony Corridore, Joel Nathan Ephross, Edward Hirs, Paul W MacAvoy, and Richard Tavelli. 2012. "The Arithmetic of Shale Gas." *Available at SSRN 2085027*.

Bartik, Alexander W, Janet Currie, Michael Greenstone, and Christopher R Knittel. 2019. "The Local Economic and Welfare Consequences of Hydraulic Fracturing." *American Economic Journal: Applied Economics*, 11(4): 105–55.

Bennett, Ashley, and John Loomis. 2015. "Are Housing Prices Pulled Down or Pushed Up by Fracked Oil and Gas Wells? A Hedonic Price Analysis of Housing Values in Weld County, Colorado." *Society & Natural Resources* 1–19.

Black, Katie Jo, Andrew J Boslett, Elaine L Hill, Lala Ma, and Shawn J McCoy. 2021. "Economic, environmental, and health impacts of the fracking boom." *Annual Review of Resource Economics*, 13 311–334.

Bonetti, Pietro, Christian Leuz, and Giovanna Michelon. 2021. "Large-sample evidence on the impact of unconventional oil and gas development on surface waters." *Science*, 373(6557): 896–902.

Brown, Jason P, Timothy Fitzgerald, and Jeremy G Weber. 2016. "Capturing rents from natural resource abundance: Private royalties from US onshore oil & gas production." *Resource and Energy Economics*, 46 23–38, URL: http://www.sciencedirect.com/science/article/pii/S0928765516300355, DOI: http://dx.doi.org/10.1016/j.reseneeco.2016.07.003.

Bussières, Eve-Line, George M Tarabulsy, Jessica Pearson, Réjean Tessier, Jean-Claude Forest, and Yves Giguère. 2015. "Maternal prenatal stress and infant birth weight and gestational age: A meta-analysis of prospective studies." *Developmental Review*, 36 179–199.

Camacho, Adriana. 2008. "Stress and birth weight: evidence from terrorist attacks." *The American Economic Review*, 98(2): 511–515.

Cascio, Elizabeth U, and Ayushi Narayan. 2015. "Who Needs a Fracking Education? The Educational Response to Low-Skill Biased Technological Change."

Chen, Dafang, Sung-Il Cho, Changzhong Chen, Xiaobin Wang, Andrew I. Damokosh, Louise Ryan, Thomas J. Smith, David C. Christiani, and Xiping Xu. 2000. "Exposure to benzene, occupational stress, and reduced birth weight." *Occupational and environmental medicine*, 57(10): 661–667.

Coneus, Katja, and C. Katharina Spiess. 2011. "Pollution Exposure, Child Health and Latent Factors: Evidence for Germany." *Working Paper*.

Currie, J., M. Neidell, and J.F. Schmieder. 2009. "Air pollution and infant health: Lessons from New Jersey." *Journal of health economics*, 28(3): 688–703.

Currie, J., and R. Walker. 2011. "Traffic Congestion and Infant Health: Evidence from E-ZPass." *American Economic Journal: Applied Economics*, 3(1): 65–90.

Currie, Janet, Michael Greenstone, and Katherine Meckel. 2017. "Hydraulic fracturing and infant health: New evidence from Pennsylvania." *Science Advances*, 3(12): , p. e1603021, URL: http://advances.sciencemag.org/content/3/12/e1603021, DOI: http://dx.doi.org/10.1126/sciadv.1603021.

Currie, Janet, and Maya Rossin-Slater. 2013. "Weathering the storm: Hurricanes and birth outcomes." *Journal of Health Economics*, 32(3): 487–503.

Currie, Janet, and Johannes F. Schmieder. 2009. "Fetal Exposures to Toxic Releases and Infant Health." *The American Economic Review*, 99(2): 177–183.

Currie, Janet, and Hannes Schwandt. 2014. "The 9/11 Dust Cloud and Pregnancy Outcomes: A Reconsideration."Technical report, National Bureau of Economic Research.

Dadvand, Payam, Jennifer Parker, Michelle L. Bell, Matteo Bonzini, Michael Brauer, Lyndsey A. Darrow, and Ulrike Gehring et al. 2013. "Maternal exposure to particulate air pollution and term birth weight: a multi-country evaluation of effect and heterogeneity." *Environmental Health Perspectives*, 121(3): 267–373.

Dejmek, Jan, Ivo Solanský anb Ivan Benes, Jan Lenícek, and Radim J. Srám. 2000. "The impact of polycyclic aromatic hydrocarbons and fine particles on pregnancy outcome." *Environmental Health Perspectives*, 108(12): .

DeLeire, Thomas, Paul Eliason, and Christopher Timmins. 2014. "Measuring the employment impacts of shale gas development."Technical report, Working Paper.

Deziel, Nicole C, Eran Brokovich, Itamar Grotto, Cassandra J Clark, Zohar Barnett-Itzhaki, David Broday, and Keren Agay-Shay. 2020. "Unconventional Oil and Gas Development and Health Outcomes: A Scoping Review of the Epidemiological Research." *Environmental Research*, p. 109124.

DOE, US Department of Energy. 2021. "Economic and National Security Impacts under a Hydraulic Fracturing Ban."

Ericson, Sean J, Daniel T Kaffine, and Peter Maniloff. 2020. "Costs of increasing oil and gas setbacks are initially modest but rise sharply." *Energy Policy*, 146, p. 111749.

Feyrer, James, Erin Mansur, and Bruce Sacerdote. 2020. "Geographic Dispersion of Economic Shocks: Evidence from the Fracking Revolution: Reply." *American Economic Review*, 110(6): 1914–20.

Gopalakrishnan, Sathya, and H Allen Klaiber. 2014. "Is the shale energy boom a bust for nearby residents? Evidence from housing values in Pennsylvania." *American Journal of Agricultural Economics*, 96(1): 43–66.

Hardy, Kirsten, and Timothy W Kelsey. 2015. "Local income related to Marcellus shale activity in Pennsylvania." *Community Development*, 46(4): 329–340.

Hausman, Catherine, and Ryan Kellogg. 2015. "Welfare and Distributional Implications of Shale Gas." *Brookings Papers on Economic Activity.*

Hill, Elaine L. 2018. "Shale Gas Development and Infant Health: Evidence from Pennsylvania." *Journal of Health Economics*, 61(2018): 134–150.

Hill, Elaine L, and Lala Ma. 2022. "Drinking water, fracking, and infant health." *Journal of Health Economics*, 82, p. 102595.

Hill, Elaine, and Lala Ma. 2017. "Shale Gas Development and Drinking Water Quality." *American Economic Review*, 107(5): 522–25.

van den Hooven, Edith H, Yvonne de Kluizenaar, Frank H Pierik, Albert Hofman, Sjoerd W van Ratingen, Peter YJ Zandveld, Johan P Mackenbach, Eric AP Steegers, Henk ME Miedema, and Vincent WV Jaddoe. 2011. "Air pollution, blood pressure, and the risk of hypertensive complications during pregnancy the generation R study." *Hypertension*, 57(3): 406–412.

Jacobsen, Grant D, and Dominic P Parker. 2016. "The economic aftermath of resource booms: evidence from boomtowns in the American West." *The Economic Journal*, 126(593): 1092–1128.

Jacobsen, Grant D, Dominic P Parker, and Justin B Winikoff. 2021. "Are resource booms a blessing or a curse? Evidence from people (not places)." *Journal of Human Resources* 0320–10761R1.

Johnsen, Reid, Jacob LaRiviere, and Hendrik Wolff. 2019. "Fracking, coal, and air quality." *Journal of the Association of Environmental and Resource Economists*, 6(5): 1001–1037.

Kearney, Melissa S, and Riley Wilson. 2018. "Male Earnings, Marriageable Men, and Nonmarital Fertility: Evidence from the Fracking Boom." *Review of Economics and Statistics*, 100(4): 678–690.

Lavaine, Emmanuelle, and Matthew J. Neidell. 2013. "Energy Production and Health Externalities: Evidence from Oil Refinery Strikes in France."

Linn, Joshua, Lucija Muehlenbachs, and Yushuang Wang. 2014. "How Do Natural Gas Prices Affect Electricity Consumers and the Environment?" *Resources for the Future Discussion Paper*(14-19): .

Marchand, Joseph. 2012. "Local labor market impacts of energy boom-bust-boom in western canada." *Journal of Urban Economics*, 71(1): 165–174.

Mason, Charles F, Lucija A Muehlenbachs, and Sheila M Olmstead. 2015. "The Economics of Shale Gas Development." *Annual Review of Resource Economics*, 7(1): .

McKenzie, Lisa M, Ruixin Guo, Roxana Z Witter, David A Savitz, Lee S Newman, and John L Adgate. 2014. "Birth Outcomes and Maternal Residential Proximity to Natural Gas Development in Rural Colorado." *Environmental Health Perspectives*, 122(4): 412–417.

Muehlenbachs, Lucija, Elisheba Spiller, and Christopher Timmins. 2014. "The Housing Market Impacts of Shale Gas Development."Technical report, National Bureau of Economic Research.

Newell, Richard G, and Daniel Raimi. 2015. "Shale public finance: Local government revenues and costs associated with oil and gas development."Technical report, National Bureau of Economic Research.

Owen, Andrew L. 2022. "The Fracking Boom, Labor Structure, and Adolescent Fertility." *Population Research and Policy Review* 1–21.

Pereira, Gavin, Fatima Haggar, Antonia W Shand, Carol Bower, Angus Cook, and Natasha Nassar. 2012. "Association between pre-eclampsia and locally derived traffic-related air pollution: a retrospective cohort study." *Journal of epidemiology and community health* jech–2011.

Perera, Frederica P., Deliang Tang, Virginia Rauh, Kristin Lester, Wei Yann Tsai, Yi Hsuan Tu, and Lisa Weiss et al. 2005. "Relationships among polycyclic aromatic hydrocarbon–DNA adducts, proximity to the World Trade Center, and effects on fetal growth." *Environmental health perspectives*, 113(8): .

Sanders, Nicholas J, and Charles Stoecker. 2015. "Where have all the young men gone? Using sex ratios to measure fetal death rates." *Journal of health economics*, 41 30–45.

Slama, Rémy, Olivier Thiebaugeorges, Valérie Goua, Lucette Aussel, Paolo Sacco, Aline Bohet, and Anne Forhan et al. 2009. "Maternal personal exposure to airborne benzene and intrauterine growth." *Environmental health perspectives*, 117(8): .

Smith, Brock, and Samuel Wills. 2018. "Left in the dark? oil and rural poverty." *Journal of the Association of Environmental and Resource Economists*, 5(4): 865–904.

Torche, Florencia. 2011. "The effect of maternal stress on birth outcomes: exploiting a natural experiment." *Demography*, 48(4): 1473–1491.

Vassilev, Zdravko P., Mark G. Robson, , and Judith B. Klotz. 2001. "Associations of polycyclic organic matter in outdoor air with decreased birth weight: a pilot cross-sectional analysis." *Journal of Toxicology and Environmental Health Part A*, 64(8): 595–605.

Weber, Jeremy G. 2011. "The effects of a natural gas boom on employment and income in Colorado, Texas, and Wyoming." *Energy Economics.*

Willis, Mary D, Elaine L Hill, Andrew Boslett, Molly L Kile, Susan E Carozza, and Perry Hystad. 2021. "Associations between residential proximity to oil and gas drilling and term birth weight and small-for-gestational-age infants in Texas: a difference-in-differences analysis." *Environmental Health Perspectives*, 129(7): , p. 077002.

Willis, Mary D, Elaine L Hill, Molly L Kile, Susan Carozza, and Perry Hystad. 2022. "Associations between residential proximity to oil and gas extraction and hypertensive conditions during pregnancy: a difference-in-differences analysis in Texas, 1996–2009." *International Journal of Epidemiology*, 51(2): 525–536.

Wilson, Riley. 2022. "Moving to Economic Opportunity The Migration Response to the Fracking Boom." *Journal of Human Resources*, 57(3): 918–955.

Woodruff, Tracey J, Rachel Morello-Frosch, and Bill Jesdale. 2008. "Air pollution and preeclampsia among pregnant women in California, 1996–2004." *Epidemiology*, 19(6): , p. S310.

Wrenn, Douglas H, Timothy W Kelsey, Edward C Jaenicke et al. 2015. "Resident vs. Nonresident Employment Associated with Marcellus Shale Development." *Agricultural and Resource Economics Review*, 44(2): 1–19.

Zahran, Sammy, Stephan Weiler, Howard W. Mielke, and Anita Alves Pena. 2012. "Maternal benzene exposure and low birth weight risk in the United States: A natural experiment in gasoline reformulation." *Environmental research*, 112 139–146.

Zhang, Ruohao, Huan Li, Neha Khanna, Alan Krupnick, Elaine Hill, and Daniel M Sullivan., "Air Quality Impacts of Shale Gas Development in Pennsylvania." *Journal of the Association of Environmental and Resource Economists.*