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

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BACKGROUND: Oil and natural gas extraction may produce environmental pollution at levels that affect reproductive health of nearby populations. Available studies have primarily focused on unconventional gas drilling and have not accounted for local population changes that can coincide with drilling activity.

OBJECTIVE: Our study sought to examine associations between residential proximity to oil and gas drilling and adverse term birth outcomes using a difference-in-differences study design.

METHODS: We created a retrospective population-based term birth cohort in Texas between 1996 and 2009 composed of mother–infant dyads (n = 2,598,025) living <10 km from an oil or gas site. We implemented a difference-in-differences approach to estimate associations between drilling activities and infant health: term birth weight and term small for gestational age (SGA). Using linear and logistic regression, we modeled interactions between births before (unexposed) or during (exposed) drilling activity and residential proximity near (0–1, 1–2, or 2–3 km) or far (3–10 km) from an active or future drilling site, adjusting for individual- and neighborhood-level characteristics.

RESULTS: The adjusted mean difference in term birth weight for mothers living 0–1 vs. 3–10 km from a current or future drilling site was −7.3 g (95% confidence interval (CI): −11.6, −3.0) for births during active vs. future drilling. The corresponding adjusted odds ratio for SGA was 1.02 (95% CI: 0.98, 1.06). Negative associations with term birth weight were observed for the 1–2 and 2–3 km near groups, and no consistent differences were identified by type of drilling activity. Larger, though imprecise, adverse associations were found for infants born to Hispanic women, women with the lowest educational attainment, and women living in cities.

CONCLUSIONS: Residing near oil and gas drilling sites during pregnancy was associated with a small reduction in term birth weight but not SGA, with some evidence of environmental injustices. Additional work is needed to investigate specific drilling-related exposures that might explain these associations. https://doi.org/10.1289/EHP7678

Background

Since the early 2000s, shale gas extraction has increased exponentially and now accounts for more than three-quarters of U.S. natural gas production (U.S. Energy Information Administration 2017b). Texas, which lies on multiple shale formations with substantial shale gas extraction activity, generates about 24% of U.S. natural gas (U.S. Energy Information Administration 2017a). Additional conventional reserves in Texas using traditional methods also produce oil and gas, accounting for 41% of domestic crude oil production (U.S. Energy Information Administration 2019). This industry provides substantial economic activity for local communities (Brown et al. 2019; Weber 2012). When an oil and gas industry enters a community, there are measured and positioned local economic benefits, such as new job opportunities (Maniloff and Mastromonaco 2017; Weber 2012), increased regional tax revenue (Kargbo et al. 2010; Weber et al. 2016), and increased household income (Brown et al. 2019; Feyrer et al. 2017; Hardy and Kelsey 2015). For instance, the Barnett Shale in the Dallas–Fort Worth–Arlington metropolitan region of Texas was projected to yield an increased revenue of $11 billion USD and create more than 100,000 new jobs in the early years of development (Kinnaman 2011; Sovacool 2014). Although some of these benefits are distributed to local residents in Texas, much of the economic gain via royalty payments from mineral rights may go to individuals who do not reside on the leased property (Fry et al. 2015). New industry also brings substantial sociodemographic changes to the community as individuals move into the area for better employment prospects (Silva et al. 2018; Kinnaman 2011; Brown 2015; Zwickl 2019).

Recent estimates indicate that 4.5 million Texans live within 1.6 km (1 mile) of at least one oil and gas drilling site (Czolowski et al. 2017), and numerous communities are concerned about the impact of this industry on local population health (Korfhammer et al. 2014; Maule et al. 2013). Potential exposures from oil and gas sites include air pollution from drilling activities, flaring, and truck traffic; water contamination from hydraulic fracturing chemicals; noise pollution from ongoing industrial activity; light pollution from new drilling facilities; and social stressors from shifts in population dynamics and influxes of new workers (Deziel et al. 2020; HEI Energy Research Committee 2020; Korfhammer et al. 2014; Shonkoff et al. 2014). Throughout drilling processes, toxic air pollutants are emitted, including particulate matter [diesel PM, particulate matter with an aerodynamic diameter of less than or equal to 10 micrometers (PM10)]; volatile organic compounds (benzene, toluene, ethylbenzene, and xylene) polycyclic aromatic hydrocarbons (naphthalene, chlorobenzene, phenol); and other pollutants (formaldehyde, ethylene glycol, methane) (Czolowski et al. 2017; Elliott et al. 2017; Adgate et al. 2014; Korfhammer et al. 2014; HEI Energy Research Committee 2020). A synthesis of existing literature posits that the air pollution from oil and gas extraction is concentrated within 1 km of the site and generally dissipates to background levels at 3 km away from the drilling site (Czolowski et al. 2017).
Evidence also suggests that water pollution from oil and gas drilling is likely concentrated within 1 km of the drilling site (Fontenot et al. 2013; Jackson et al. 2013). This distance gradient varies based on the pollutant of interest, and the distances at which other pollution from oil and gas drilling (e.g., light, noise) dissipate to background levels are less clear (HEI Energy Research Committee 2020).

Developing fetuses are especially sensitive to environmental toxicants, including those produced from oil and gas drilling sites (Faustman et al. 2000). Existing literature reports associations between exposure to air and water pollution and adverse reproductive health outcomes, such as term birth weight and small for gestational age (SGA) (Klepac et al. 2018; Currie et al. 2013). Higher traffic-related air pollution levels are associated with increased risk of adverse birth outcomes (Stieb et al. 2012), and the large numbers of trucks required for oil and gas drilling yield substantial increases in local traffic-related air pollution (U.S. Department of Energy 2009). Although the specific biological mechanisms causing pollution-related adverse perinatal health outcomes are not fully understood, these pollutants can cause chronic inflammation and oxidative stress in the mother that can increase the risk of adverse birth outcomes (Valavanidis et al. 2013; Ghio et al. 2012; Tanner et al. 2015). Infants who are smaller than average at full term (37–42 wk gestation) may have greater risk of chronic diseases later in life including hypertension, cardiovascular disease, type 2 diabetes, impaired renal function, and learning difficulties (Albu et al. 2014; Cosmi et al. 2011; Ewing et al. 2017; Romo et al. 2009). Identifying modifiable risk factors that can reduce the burden of adverse birth outcomes and its long-term consequences is important for informing future environmental and health policy.

A growing body of literature has examined associations between residential proximity to the oil and gas industry and adverse birth outcomes (Caron-Beaudoin et al. 2021; Casey et al. 2015, 2019; Currie et al. 2017; Cushing et al. 2020; Gonzalez et al. 2020; Hill 2018; McKenzie et al. 2014; Stacy et al. 2015; Tran et al. 2020; Walker et al. 2018; Whitworth et al. 2017). Health risks associated with drilling-related exposures can be difficult to accurately characterize due to local socioeconomic and demographic shifts that occur from the industrial boom that accompanies oil and gas extraction, such as increases in minority racial and ethnic populations and needs for skilled labor at drilling sites (Brown 2015; Fry et al. 2015; Zwickl 2019). Furthermore, these socioeconomic shifts change the underlying population-level risk factors for health effects such as adverse birth outcomes. Conventional epidemiological approaches may not adequately account for this confounding by changing socioeconomic and demographic factors, which could bias the estimated health effect of drilling-related pollution for people living in close proximity to oil and gas drilling sites. To address this concern, we used a difference-in-differences (DiD) quasi-experimental design to estimate differences in term birth weight and term small for gestational age (SGA) status associated with proximity to drilling sites while also accounting for confounding by other factors that changed over time, including changes in local socioeconomic characteristics related to drilling activity.

**Methods**

**Study Population**

Our initial data included all Texas births during the period 1996–2009 with a maternal residence at birth that was geocoded to the full address level \(N = 4,569,428\) (Figure S1). We then excluded nonsingleton births \((n = 131,880)\), records with unlikely values for birth weight \((\leq 500 \text{ and } \geq 5,000 \text{ g}; n = 10,797)\), and births \(\leq 36 \text{ wk or } \geq 43 \text{ wk} (n = 393,192)\). We also planned to exclude records with unlikely values for maternal age at birth \((\leq 10 \text{ y or } \geq 65 \text{ y})\), but no records were excluded for this reason. We also excluded 369,254 records with missing data for continuous covariates on the birth certificates, but we retained records with missing birth certificate data for important categorical covariates only, which were assigned to missing data categories for each variable. Finally, we excluded all birth records with maternal residences >10 km from a drilling site that was active or permitted between 1 January 1985 and 28 June 2019 \((n = 1,066,280)\), leaving 2,598,025 singleton term births in the analytical sample.

This research has been approved by the Texas State Department of Health and Human Services (#15-063) and the Oregon State University Institutional Review Board (#6692). Informed consent was waived because the data is from administrative records, and no participant contact was required for this study.

**Difference-in-Differences (DiD) Study Design**

We used a DiD quasi-experimental design to compare before drilling and during drilling changes in risk of adverse birth outcomes to a temporal control group where drilling never occurred (Figure 1). An advantage of the DiD framework is that it accounts for the secular trends in birth weight and SGA that are happening over time that are unrelated to our oil and gas drilling exposures of interest. Births were defined as exposed if there was a drilling site within 3 km of the maternal address prior to birth. Births were defined as a part of the control groups if they were born prior to drilling within 10 km of the maternal address or if the closest drilling site active at the time of birth was beyond 3 km of the maternal address.

**Oil and Gas Drilling Exposures**

We received academic access to a proprietary database of all oil and gas sites drilled in the United States from Enverus DrillingInfo (https://www.enverus.com/). We define unique drilling sites using the American Petroleum Institute (API) identifiers, which correspond to a one-to-one ratio with drilling site boreholes, and we include all drilling sites that were spudded (date that drilling began) between 1 January 1985 and 28 June 2019. In our exposure assessment, we focus on the earliest recorded date at which drilling activity is recorded for a site. In most cases, this date is the first day on which drilling began (spud date), but some records show production dates that occur long before the spud date, in which case we used the production date to determine active drilling site status. Approximately 12% of records contain a first production date that precedes the spud date, which is partially driven by some first production dates sometimes being reported on a monthly scale (i.e., 1 June 2005) and the spud dates being reported on a daily scale (i.e., 12 June 2005). In addition, drilling sites that ceased production before the end of the study period (28 June 2019) were excluded from the study after the final month of reported production, and subsequent births within 10 km of such sites were not included in analyses (unless another drilling site was within 10 km). Maternal addresses were available only for the residence on the date of delivery; therefore, exposures were assigned based only on proximity and drilling activity on the day of birth. In addition to classifications based on any drilling activity, we also classified each drilling site according to the primary resource type (oil or natural gas) and drilling type (conventional or unconventional) and classified each eligible birth according to the primary resource and drilling characteristics of the active or future drilling site.

**Neighborhood Exposures**

Residential address at delivery was linked to census tract sociodemographic information to characterize neighborhood context.
Figure 1. Schematic of spatial and temporal components of the difference-in-differences analytical design. Key assumptions that are made for the difference-in-differences study design to be valid are: a) similar composition in our near (e.g., 0–1 km) and far groups (e.g., 3–10 km) before and during drilling (e.g., no spillover effects where drilling differentially impacts the demographics of our far distance group); and b) parallel trends in our near (e.g., 0–1 km) and far groups (e.g., 3–10 km) prior to drilling exposures (e.g., term birth outcomes were not differentially changing in areas without oil and gas drilling exposure.). (A) Near and Before = residence is located 0–3 km of an active or future drilling site, and there are no active drilling sites within 10 km; (B) Near and During = residence is located 0–3 km of an active future drilling site, and there are active drilling sites within 10 km; (C) Far and Before = residence is located 3–10 km of an active or future drilling site, and there are no active drilling sites within 10 km; (D) Far and During = residence is located 3–10 km of an active or future drilling site, and there are active drilling sites within 10 km. Note: DiD, difference-in-differences.

(Daoud et al. 2015; van Vuuren et al. 2014). The time frame included in this analysis spanned two census surveys. For births prior to 2005, we used the 2000 census information to derive neighborhood context; and for births in and after 2005, we used 2010 census information. Neighborhood-level covariates included median household income, unemployment percentage, proportion of non-White population, and population count. We also calculated the distance between each maternal residential address at delivery to the nearest primary or secondary road (e.g., highways, interstate) using the 2010 census road shapefile (Federal Highway Administration 2017). Because there had been minimal new roads built during our study period (Texas Department of Transportation 2019), we use this metric to account for potential traffic-related air pollution exposures that may confound associations between drilling and infant health (Klepac et al. 2018; Stieb et al. 2012; Willis et al. 2021). We accounted for differences between urban and rural communities by including an indicator variable for births occurring outside of a census place boundary (i.e., births in nonincorporated communities) (U.S. Census Bureau 2000).

**Term Birth Outcomes**

Data collected by Texas Vital Statistics was used to assess birth outcomes. Term birth weight was defined as a continuous outcome for the recorded birth weight of infants born between 37 and 42 weeks of gestation. SGA was defined as a binary indicator birth weight below the 10th percentile by sex, gestational age, and birth year among the full set of contemporaneous births in Texas, and we also restricted this outcome to infants born between 37 and 42 weeks of gestation. This restriction to term births limited the applicability of our results for births outside of this gestational range.

**Descriptive Statistics**

We tested the key assumptions required to pursue a DiD analysis (Abadie 2005; Kahn-Lang and Lang 2020; Wing et al. 2018): a) similar composition in our near (e.g. 0–1 km) and far groups (e.g., 3–10 km) before and during drilling (e.g., no spillover effects where drilling differentially affects the demographics of our far distance group); and b) parallel trends in our near (e.g., 0–1 km) and far groups (e.g., 3–10 km) prior to the commencement of drilling (e.g., term birth outcomes were not differentially changing in areas without oil and gas drilling exposure.). To test the stable population assumption, we showed descriptive statistics for each of our population characteristics in the near and far groups before and after drilling begins to examine differences among groups. We also graphed the monthly means of key population sociodemographic characteristics of our near and far groups by year. Ideally, the proportions of each characteristic do not change in a meaningful way with the introduction of drilling. To test the parallel trends assumption, we graphed the mean term birth weight and proportion of term SGA infants for each year in our birth cohort with respect to each component of the DiD interaction term (e.g., maternal residence 0–1 km of active drilling; maternal residence 0–1 km of future drilling; maternal residence 3–10 km of active drilling; maternal residence 3–10 km of future drilling). In addition, we examined the spatial distribution of our
population that contributes to each component of the DiD interaction term to ensure that our sample selection was not driven by location-specific dissimilarities. For all assumptions listed above, we could test only the data that were measured in our data set, which did not preclude the possibility that there were important unmeasured confounding factors that could be relevant to our exposure-outcome relationship. This issue must be carefully considered when interpreting the results of any study that uses a DiD study design.

**Main Model**

We implemented a series of regression models to examine associations of residential proximity to oil and gas drilling during pregnancy and adverse birth outcomes. Each model included an indicator term for residential proximity (e.g., 0–1 km vs. 3–10 km from an active or future drilling site for our primary models), an indicator term for time period (i.e., whether the birth occurred before drilling began or during the drilling and production phases), and a product interaction term between proximity and time period. The primary estimate of interest was the coefficient for the product term, which represents the difference in the association between proximity and the outcome during drilling vs. the association between proximity and the outcome before drilling. We used separate models to estimate interactions with proximity defined as 1–2 km vs. 3–10 km, or 2–3 km vs. 3–10 km, respectively.

We selected covariates *a priori* based on a review of the literature. A new birth certificate was implemented across Texas in 2005; thus three key covariates contain subtly different questions for 1996–2004 vs. 2005–2009. Educational attainment switched from asking for how many years of education a mother has completed in 1996–2004 as opposed to requesting the highest degree obtained in 2005–2009, and we harmonized years of education to align with the degree obtained. Maternal weight gain during pregnancy changed from a single field reporting the total weight gain during pregnancy in 1996–2004 to a pair of fields that asked for prepregnancy and delivery weight in 2005–2009, so we used subtraction to align on a single weight gain during pregnancy covariate. Smoking during pregnancy changed from a binary variable (yes if indicated; no otherwise) in 1996–2004 to number of cigarettes and/or packs per day during pregnancy in 2005–2009, and we harmonized to create a single covariate of any cigarettes or packs to indicate yes to smoking during pregnancy. In all analyses, we used the harmonized covariates as described here.

All term birth weight models are linear regressions with robust standard errors, and all SGA models are logistic regressions with robust standard errors. Model 1 was our unadjusted model. Model 2 was adjusted for individual covariates that are self-reported on the Texas birth certificate, including birth year (categorical), infant sex (male, female), maternal age (continuous), maternal race and ethnicity (White non-Hispanic, Black non-Hispanic, Hispanic, other/unknown/missing) (Texas Department of State Health Services 2015), maternal educational attainment (less than high school, high school graduate, some college education, bachelor’s degree, postgraduate education, missing), nulliparous (yes, no), reported prenatal care received (yes, no, missing), smoking during pregnancy (yes, no, missing), maternal weight gain during pregnancy (continuous), diabetes diagnosis (yes if indicated; otherwise no—includes gestational and chronic diabetes due to data limitations), gestational hypertension diagnosis (yes if indicated; otherwise no), eclampsia diagnosis (yes if indicated; otherwise no), and infant gestational age (continuous—term birth weight models only). Model 3 adjusted for the same individual covariates as Model 2 and regional location (county of maternal residence at delivery), census tract median household income (continuous), census tract unemployment (continuous), census tract percent White population (continuous), census tract population (continuous), distance from residence to nearest highways in meters (continuous), and residence outside the boundaries of a census place (yes, no).

**Exposure and Population Subgroups**

We used separate models to estimate associations for drilling sites that were subgrouped according to the resource being extracted (oil or gas) and the type of drilling (conventional or unconventional), respectively. Each analysis was limited to births with residences within 10 km of drilling sites with the characteristic being assessed. To assess potential differences between population subgroups we used separate models to estimate associations according to maternal race/ethnicity (White non-Hispanic or Hispanic/Latina, with Black non-Hispanic and other/unknown/missing births excluded), education (≤high school or >high school), and residence in a large metropolitan area (Austin, Dallas–Fort Worth–Arlington, Houston, San Antonio) vs. residence outside of these metropolitan areas based on boundaries in the census place file (U.S. Census Bureau 2000).

**Sensitivity Analyses**

We implemented several sensitivity analyses. To assess the potential influence of within-year secular trends, we added birth month as a covariate to the fully adjusted model and included birth month in a second model without the census tract covariates. Although we could have adjusted for conception month, because our analysis is restricted to term births (gestational range of 37–42 wk), conception and birth months yield functionally similar categorical variables because gestational age ranges only by 5 weeks. Furthermore, we repeated the primary analysis without the gestational hypertension, eclampsia, and diabetes covariates to ensure that these potential mediators are not overadjusting our estimates. Likewise, we repeated the primary analysis with all missing data categories excluded from the sample (i.e., a complete case framework) to confirm that including births with missing data are not biasing our results. In addition, to assess the potential influence of the Great Recession, we repeated the primary analysis after excluding births in 2008 and 2009.

To facilitate comparisons with previous studies, and between findings based on DiD vs. other approaches, we estimated associations between birth outcomes and residential proximity to active drilling sites (0–1 km, 1–2 km, and 2–3 km vs. 3–10 km) and compared birth outcomes during vs. before active drilling among mothers living within the same distance (0–1 km, 1–2 km, or 2–3 km) of a current or future drilling site.

Data analysis was conducted in Stata (version 16.1; StataCorp).

**Results**

**Descriptive Statistics**

The spatial distribution of drilling by resource and drilling type across Texas from 1985 to 2019 are shown in Figure 2. Each dot represents a single oil or gas drilling site that was spudded in this period. A total of 356,527 drilling sites were spudded in Texas between 1 January 1985 and 28 June 2019. The overall distribution of drilling sites varied by the primary resource extracted, with gas extraction predominant in the areas around Dallas–Fort Worth–Arlington and oil extraction predominant in the western part of the state. The distribution of sites according to the type of drilling activity reflects the primary resource extracted at each site, with sites...
that primarily extracted oil being more likely to use conventional drilling methods than sites that primarily extracted gas. For illustrative purposes, the temporal distribution of oil and gas production over the same time period are shown in Figure 3.

The study sample included a total of 2,598,025 term births (Table 1). Most of the mothers identified as White non-Hispanic (37.7%) or Hispanic (46.9%), and a large proportion (31.3%) had less than a high school education. Only 13.2% of birth residences were classified as rural based on location outside of a census place boundary. Most of the birth residences (77%) were 3–10 km from a drilling site, whereas 8.7%, 8.6%, and 6.0% of residences were 0–1, 1–2, or 2–3 km from a drilling site, respectively. In total, 77% of births were associated with an active drilling site, whereas 23% were associated with a future drilling site.

Among births to mothers living within 0–1 km of a drilling site at the time of delivery, average term birth weight was 30 g lower for births that occurred during vs. before drilling activity. At the same time, average term birth weight among births to mothers living 3–10 km from a drilling site was 14 g lower for births during vs. before drilling activity. When we subtracted the results of the 3–10 km average term birth weight from the 0–1 km average term birth weight, we found a difference of 16 g (30 g – 14 g) in the unadjusted association between birth weight with drilling activity between the near and far births. Term SGA was 0.2% higher during vs. before drilling activity among mothers living within 0–1 km of a drilling site and 0.1% higher during vs. before drilling among mothers living within 3–10 km of a drilling site, for a difference-in-differences of 0.1% (0.2% – 0.1%).

We examined the assumption of time-invariant confounding between near and far exposure groups by comparing population characteristics before and during drilling. Proportions of Black non-Hispanic mothers decreased from 14% before to 9% during drilling in the 0–1 km group but increased from 9% to 12% in the 3–10 km group, whereas the opposite pattern was evident for Hispanic mothers (increasing from 34% to 40% vs. decreasing from 50% to 48%, respectively) (Table 1). Proportions of Hispanic mothers also increased from before to during drilling in the 1–2 km and 2–3 km groups (35% to 44% and 39% to 48%, respectively), whereas proportions of White non-Hispanic mothers decreased in both groups (53% to 40% and 50% to 35%, respectively) (Tables S1 and S2), compared with 36% before and during drilling for the 3–10 km group and 47% during both time periods for the 0–1 km group (Table 1). The proportion of births to mothers residing in rural locations (geocoded address outside of a census place boundary) increased from 10% before drilling to 32% during...
Mean term birth weight was lower during vs. before drilling for each population characteristic. Births in the near/before drilling subgroup were concentrated in the Dallas–Fort Worth and Houston areas, whereas births in the near/during, far/before, and far/during subgroups were more widely distributed throughout the state as well (Figure 4).

### Main Model Results

Mean term birth weight was lower during vs. before drilling based on models for all three “near” proximity groups. The fully adjusted mean difference in term birthweight during vs. before drilling in the 0–1 km group but was relatively stable before and during drilling in the 3–10 km group (11% and 12%, respectively) (Table 1). The proportions of rural residences also increased in the 0–1 km group (8% to 18%) and the 2–3 km group (10% to 13%) (Tables S1 and S2). Secular trends in maternal race/ethnicity and education were similar between 0 and 1 (Table 1). The proportions of rural residences also increased in the 0–1 km group but was relatively stable before and during drilling in the 3–10 km group (11% and 12%, respectively) (Table 1). The proportions of rural residences also increased in the 0–1 km group but was relatively stable before and during drilling in the 3–10 km group (11% and 12%, respectively) (Table 1).
Figure 4. Spatial distribution of population subgroups in the difference-in-differences modeling framework for term infants in Texas, USA, 1996–2009 (n = 2,598,025). Note: Each graph is a separate spatial distribution in deciles of the inverse distance weighted (IDW) density of where maternal addresses at delivery are located in our analysis. Deciles are determined within each sample. (A) Near and Before = residence is located 0–3 km of an active or future drilling site, and there are no active drilling sites within 10 km (n = 201,750); (B) Near and During = residence is located 0–3 km of an active or future drilling site, and there are active drilling sites within 10 km (n = 401,920); (C) Far and Before = residence is located 3–10 km of an active or future drilling site, and there are no active drilling sites within 10 km (n = 401,069); (D) Far and During = residence is located 3–10 km of an active or future drilling site, and there are active drilling sites within 10 km (n = 1,593,286).
drilling between 0–1 km and 3–10 km groups was −7.3 g (95% CI: −11.6, −3.0) (Table 2). Estimated mean differences based on unadjusted models were larger when 1–2 km and 2–3 km births were compared with the 3–10 km group but were similar to corresponding estimates for the 0–1 km group when adjusted (fully adjusted model estimates of −8.9 g; 95% CI: −13.1, −4.8 and −9.3 g; 95% CI: −14.1, −4.5, respectively). Odds ratios (OR) for relative differences in term SGA during drilling vs. before drilling between near and far groups indicated significant positive associations when adjusted for individual-level covariates only (e.g., OR = 1.08 [OR equals 1.08]; 95% CI: 1.04, 1.11 for 0–1 km vs. 3–10 km), but ORs were close to the null for all three proximity groups after additional adjustment for county- and neighborhood-level covariates (e.g., OR = 1.02 [OR equals 1.02]; 95% CI: 0.98, 1.06 for the 0–1 km vs. 3–10 km comparison).

### Exposure and Population Subgroup Results

There were no clear or consistent differences in associations with term birth weight for proximity to oil drilling vs. gas drilling activity (Table 3). Associations were stronger for oil drilling when proximity was defined as 0–1 km or 2–3 km, but stronger for gas drilling for the 1–2 km “near” group, with complete or substantial overlap in corresponding CIs. Inverse DID associations were stronger for conventional vs. unconventional drilling in all models, with the 2–3 km vs. 3–10 km comparison providing the strongest evidence of a difference according to type of drilling (fully adjusted estimates of −13.1 g; 95% CI: −18.5, −7.8 and −0.7 g; 95% CI: −7.2, 5.7, respectively.) Term SGA showed no associations by drilling type at the 1-km buffer, but elevated risks of term SGA were observed at the 1–2 and 2–3 km buffers for gas, conventional, and unconventional drilling.

In restricted models by race/ethnicity, estimated mean differences during vs. before activity were greater for near vs. far births to Hispanic mothers compared with White non-Hispanic mothers. However, all associations were inverse, and the difference between the two groups was more pronounced (i.e., greater than might be expected due to random error) only for the 0–1 km proximity group (−16.3 g; 95% CI: −23.4, −9.2 vs. −5.2 g; 95% CI: −11.7, 1.2, respectively). For SGA, there was a positive association for Hispanic mothers, but not White non-Hispanic mothers based on the 0–1 km vs. 3–10 km comparison (OR = 1.07 [OR equals 1.07]; 95% CI: 1.01, 1.13 vs. OR = 1.01 [OR equals 1.01; 95% CI: 0.95, 1.08]). Nevertheless, associations were similar and positive for both groups based on the 1–2 km and 2–3 km comparisons. Differences between White non-Hispanic and Hispanic women were only clearly delineated in the 0–1 km buffer distance. In models restricted by maternal educational attainment, associations with term birth weight were inverse for both groups in all models, but these estimates were consistently stronger for births to women with less education, where we estimate most pronounced difference for the 0–1 km models. For SGA, associations are positive for women with less education and null for women with more education based on the 0–1 km and 1–2 km models, but comparable for both groups based on the 2–3 km model. (Table 3).

In additional restricted models by metropolitan (Austin, Dallas–Fort Worth–Arlington, Houston, San Antonio) vs. nonmetropolitan residence, we noted that the larger magnitude of association for oil- and gas drilling-related exposures and adverse term birth outcomes is concentrated among the population residing in metropolitan areas but largely dissipates (and shows potential protective associations in the 1-km buffer) in the nonmetropolitan areas (Table 3). For instance, infants whose mothers resided 0–1 km from at least one drilling site in metropolitan areas had decreased term birth weight (−12.8; 95% CI: −18.8, −6.8) and increased term SGA (1.07; 95% CI: 1.02, 1.13). In contrast, infants whose mothers resided 0–1 km from at least one drilling site in nonmetropolitan areas, had increased term birth weight (8.0; 95% CI: 0.5, 15.5) and decreased term SGA (0.92; 95% CI: 0.86, 0.98).

### Sensitivity Analyses

Estimates from models with additional adjustment for birth month (categorical); models adjusted for birth month but not census tract median household income, percent unemployment, percent White population, or population count; fully adjusted models excluding births after 2007; fully adjusted models without gestational hypertension, eclampsia, or diabetes; and fully adjusted model with no missing data (i.e., complete case analysis) (Table S3) were similar to primary model estimates (Table 3). We also tested models in a traditional epidemiological framework to examine differences and potential sources of bias. In the before drilling vs. during drilling models, we see similar magnitude results in comparison with our DiD models (Table S4). For instance, when comparing before and during drilling activity, the fully adjusted regression estimates for term birth weight are

| Exposure groups (a) | Difference-in-differences estimate (95% CI) |
|---------------------|------------------------------------------|
| Term birth weight   |                                          |
| Near and before     | Mean difference                        |
| 0–1 km              | 80.101                                  |
| 1–2 km              | 75.726                                  |
| 2–3 km              | 45.923                                  |
| Far and after       | Mean difference                        |
| 0–1 km              | 144.831                                  |
| 1–2 km              | 147.949                                  |
| 2–3 km              | 109.140                                  |
| Far and during      | Mean difference                        |
| 0–1 km              | 401.069                                  |
| 1–2 km              | 1,593,286                                |
| 2–3 km              | 1,593,286                                |

Note: All models include robust standard errors. Model 1: Unadjusted. Model 2: Adjusted for birth year (categorical), infant sex (male, female), maternal age (continuous), maternal race and ethnicity (White non-Hispanic, Black non-Hispanic, Hispanic, other), maternal educational attainment (less than high school, high school graduate, some college education, bachelor’s degree, postgraduate education, missing), multiparous (yes, no), prenatal care received (yes, no, missing), smoking during pregnancy (yes, no, missing), maternal weight gain during pregnancy (continuous), diabetes (yes, no), eclampsia (yes, no), and gestational hypertension (yes, no). Term birth weight models are also adjusted for gestational age in weeks (continuous). Model 3: Adjusted for Model 2 covariates plus county of maternal residence at delivery, neighborhood median household income (continuous), neighborhood unemployment (continuous), neighborhood percent White population (continuous), neighborhood population count (continuous), neighborhood total population (continuous), distance to nearest highways in meters (continuous), and unincorporated residential location (yes, no).

(a) Numbers of observations included in Model 3 for term SGA are reduced due to a lack of variation in the outcome in certain counties. Numbers of observations classified as near and before and far and during are 401,060 and 1,593,269, respectively. Numbers of observations classified as near and before and far and during, respectively, are 80,101 and 144,831 for 0–1 km, 75,275 and 147,948 for 1–2 km, and 45,922 and 109,138 for 2–3 km.
births during vs. before drilling activity according to residence proximity to a current or future drilling site (near = 0–1 km, 1–2 km, or 2–3 km vs. far 3–10 km), stratified by the resource extracted (oil or gas) and type of drilling activity (conventional, unconventional) at each current or future drilling site, and by maternal race/ethnicity, maternal education, or residential location in a metropolitan region.

Our analysis of singleton live births to mothers living within 10 km by maternal race/ethnicity, maternal education, or residential location in a metropolitan region.

Term birth weight

| Resource extractiona | Births 3–10 km (n) | Births 0–1 km (n) | Estimate (95% CI) | Births 1–2 km (n) | Estimate (95% CI) | Births 2–3 km (n) | Estimate (95% CI) |
|----------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Oil                  | 1,685,685         | 69,384            | −7.2 (−16.9, 2.5) | 105,391           | −4.1 (−11.0, 2.7) | 107,800           | −10.0 (−15.8, −4.1) |
| Gas                  | 1,244,665         | 167,253           | −3.8 (−9.0, 1.3)  | 181,416           | −8.9 (−14.0, −3.8) | 133,162           | −4.2 (−10.6, 2.1) |

Drilling typeb

- Conventional
- Unconventional
- Maternal race/ethnicityc
- Hispanic
- White non-Hispanic

| Maternal educationd | ≤High school diploma | >High school | Metropolitan residencee | Nonmetropolitan regionf |
|--------------------|-----------------------|--------------|------------------------|-------------------------|
| Oil                | 1,228,110             | 750,829      | 1,007,728              | 986,627                 |
| Gas                | 135,100               | 88,802       | 107,927                | 127,874                 |
| Conventional       | 115.0                | −2.2 (−9.0, 4.6) | 90,918                | 66,210                  |
| Unconventional     | 107.9                | −3.4 (−9.8, 3.0) | 120,506               | −15.2 (−18.8, −6.2)    |
| Hispanic           | 103,014               | 92,389       | 103,485                | −13.6 (−19.1, −8.0)    |
| White non-Hispanic | 92,904                | 89,908       | 90,918                 | −12.5 (−18.8, −6.2)    |
| Maternal race/ethnicity | Hispanic | White non-Hispanic | 103,485 | −13.6 (−19.3, −7.9) |
| Metropolitan region | Nonmetropolitan region | Metropolitan Region | Nonmetropolitan Region |

Table 3. Difference-in-differences estimates of associations between term birth weight (mean difference, grams) and small-for-gestational-age (odds ratios) for births during vs. before drilling activity according to residence proximity to a current or future drilling site (near = 0–1 km, 1–2 km, or 2–3 km vs. far 3–10 km), stratified by the resource extracted (oil or gas) and type of drilling activity (conventional, unconventional) at each current or future drilling site, and by maternal race/ethnicity, maternal education, or residential location in a metropolitan region.

Note: Unless otherwise indicated, linear regression models (for term birth weight) and logistic regression models (for term SGA) include robust standard errors and are adjusted for

- Birth year (categorical), infant sex, maternal age (continuous), maternal race/ethnicity (White non-Hispanic, Black non-Hispanic, Hispanic, other), maternal educational attainment (less than high school, high school graduate, some college education, bachelor degree, postgraduate education, missing), nulliparous (yes, no), prenatal care received (yes, no, missing), smoking during pregnancy (yes, no, missing), maternal weight gain during pregnancy (continuous), diabetes (yes, no), eclampsia (yes, no), and gestational hypertension (yes, no),
- county of maternal residence at delivery (indicators), neighborhood median household income (continuous), neighborhood percent unemployed (continuous), neighborhood percent White population (continuous), neighborhood total population (continuous), distance of the birth residence to nearest highway (in meters, continuous), and unincorporated residential location (yes, no),
- Term birth weight models are also adjusted for gestational age in weeks (continuous). CI, confidence interval; SGA, small for gestational age.

- Stratified models restricted to mothers identified as White non-Hispanic or Hispanic. Models are not adjusted for maternal race/ethnicity.
- Stratified by maternal educational attainment, restricted to mothers that reported a specific educational attainment level (e.g., attained up to a high school education; attained more than a high school education.) Models not adjusted for maternal education. Women who were missing the educational attainment covariate were not included in these models.
- Stratified models restricted to births with maternal residences in a metropolitan region (within the boundaries of Austin, Dallas–Fort Worth–Arlington, Houston, or San Antonio) or births with residences outside of these areas. Models are not adjusted for unincorporated residential location.
- Models for term SGA include smaller numbers of observations in some groups due to a lack of variation in the outcome within specific counties.

Discussion

Our analysis of singleton live births to mothers living within 10 km of an active vs. future oil or gas drilling site in Texas during 1996–2009 suggests that oil and gas activity may pose increase the risks of adverse birth outcomes. Specifically, living near an active vs. future drilling site was associated with lower term birth weight when the mother’s residence was closer to the site, with an estimated mean decrease of −7.3 g (95% CI: −11.6, −3.0 g) for residences within 0–1 km compared with 3–10 km of an active site. In contrast, there was little evidence of an association between term SGA and proximity to an active drilling site. Associations with term birth weight were similar in magnitude to the summary estimate from a recent meta-analysis of the association between birth weight and a 10-μg/m3 increase in average fine particulate matter with aerodynamic diameter less than or equal to 2.5 μm [PM2.5] exposure during pregnancy (−15.9 g; 95% CI: −26.8, −5.0 g) (Sun et al. 2016). However, the associations we find are smaller in magnitude than what is estimated for maternal exposure to environmental tobacco smoke during pregnancy (−33.0 g; 95% CI: −51.0, −16.0 g) based on a different meta-analysis (Leonardi-Bee et al. 2008). We hypothesize that a complex interplay of exposure mechanisms may be playing a role, such as drilling-related pollution from the site itself, traffic-related air pollution from new diesel truck traffic, groundwater contamination from hydraulic fracturing chemicals, noise or light pollution from increased permanent infrastructure, or new chronic social stressors from the influx of community fracturing changes (Adgate et al. 2014; Colborn et al. 2011; Czolowski 2010).
Importantly, we note that we are unable to directly test these specific exposure pathways in this current analysis, and our proximity measures likely capture a combination of exposures. We did not observe consistent differences in associations with term birth weight for proximity to oil drilling vs. gas drilling activity. Multiple populations—such as infants born to Hispanic women, infants born to women with the lowest educational attainment, and infants born to women living in cities—show higher reductions in term birth weight and increased odds of term SGA compared with our main model results. In contrast, other populations—such as infants born to White women, infants born to women with higher educational attainment, and infants born to women living outside of cities—show lower to no reductions in term birth weight and lower to no odds of term SGA compared with our main model results.

Our results provide a new dimension to previous literature on oil and gas drilling and infant health by incorporating multiple exposure scenarios (e.g., conventional vs. unconventional drilling site and primary resource extraction), fine scale exposure areas (e.g., 1 km from a drilling site), and future drilling sites as a counterfactual control group (e.g., spudding sites from 2010 to 2019.) Most of the studies in the epidemiological literature used spatial study designs (as opposed to spatial temporal designs with quasi-experimental components), where the main comparison groups are close to drilling in comparison with far away from drilling. For instance, Casey et al. used an electronic medical records cohort in eastern Pennsylvania and observed no association between a drilling activity index and term birth weight after accounting for birth year (Casey et al. 2015). Their main unconventional natural gas drilling exposure metric is an activity index incorporating proximity, stage of activity (including fracking vs. drilling), and production volume, which makes it difficult to directly compare with our present study. In contrast, Stacy et al. used birth certificate records in southwestern Pennsylvania and demonstrated that increasing tertiles in their inverse distance weighted drilling site count metric is associated with increased odds of SGA and a small inverse association with birth weight (Stacy et al. 2015). Outside Pennsylvania, other areas of the country have been less frequently studied. In California, Tran et al. found reduced term birth weight and increased odds of low birth weight and SGA infants for high-production oil and gas sites using birth records data (Tran et al. 2020). In Texas, Whitworth et al. used Dallas–Fort Worth area birth records, where they observed no clear associations between drilling activity and odds of an SGA infant and inverse but not significant associations for drilling activity and decreased term birth weight (Whitworth et al. 2017). Cushing et al. also used Texas birth records and demonstrated that some of the association between residential proximity to drilling and reduced term birth weight is attributed to natural gas flaring (Cushing et al. 2020), the process by which economically nonviable natural gas is extracted and combusted (Elvidge et al. 2009; Franklin et al. 2019). In Colorado, McKenzie et al. used birth records and observed small protective associations with preterm birth and term low birth weight for infants whose mothers resided near natural gas drilling during pregnancy (McKenzie et al. 2014). We hypothesize that the inverse distance weighted drilling activity metric that they used could leave residual confounding that is related to industrial economic growth and demographic changes (Brown 2015; Fry et al. 2015; Weber et al. 2016), which could partially explain why some of our near vs. far models showed small protective effects of drilling exposure. In addition, we find that the effect estimates in the before drilling vs. during drilling activity framework are much larger than what we find in the DiD analysis, which we hypothesize is due to socioeconomic shifts (e.g., responses to environmental injustices) as opposed to the drilling-related environmental exposures. Our study period also encompasses an earlier time period, during the drilling boom in Texas, compared with the existing epidemiological work (other than McKenzie et al.), so there is the potential that our dissimilar results are the product of changing drilling practices over time.

In the economics literature, Currie et al. and Hill separately leverage quasi-experimental DiD designs in Pennsylvania birth records (Currie et al. 2017; Hill 2018). These studies estimated much larger magnitudes of associations between residential proximity to drilling activity and term birth weight at \(-49.6 \text{ g (95\% CI: } -77.1, -22.1\text{)}\) relative to permitted (but not yet active) drilling sites by Hill and with all birth weight \(-36.7 \text{ g (95\% CI: } -67.1, -6.2\text{)}\) relative to no drilling activity within 0–1 km and births with residences 3–15 km from any drilling activity by Currie et al. In comparison with Pennsylvania, Texas is the largest energy-producing state in the nation with extensive historical drilling, leading to a unique oil and gas drilling exposure profile (U.S. Energy Information Administration 2019, 2021a). The rural Pennsylvania setting provides lower ambient air pollution exposures, such as traffic or industrial facilities, in comparison with our Texas setting, a factor that may have contributed to our dissimilar results.

When we examine variation in metropolitan and nonmetropolitan areas, we estimate that maternal residence near oil and gas development shows decreased term birth weight and increased odds of term SGA in the metropolitan regions. However, we also estimate increased term birth weight and reduced odds of term SGA in the nonmetropolitan regions in the group that resides within 0–1 km of the oil and gas industry before and during drilling activity relative to before and during drilling activity in 3–10 km group. This result provides an interesting view into potential differential economic–pollution tradeoffs between these regions (Kimman 2011; Sovacool 2014). In nonmetropolitan regions, the substantial economic stimulation from an oil and gas industry boom may provide local residents with benefits that are different from what their urban counterparts are experiencing, resulting in weaker associations between oil and gas industries on term birth weight and term SGA in rural communities. These results contrast the findings by Tran et al. in California, where their analysis showed evidence for stronger reductions in term birth weight and SGA in the rural population in comparison with the urban population (Tran et al. 2020). However, the protective effect estimates in rural regions are similar to those in previous work on birth outcomes among rural populations in Colorado and southwestern Pennsylvania (McKenzie et al. 2014; Stacy et al. 2015). Future studies should disentangle this distinct urban–rural phenomenon in more depth.

Our study has several strengths that provide important new insights into the associations between residential proximity to oil and gas drilling and population health outcomes. First, Texas has the largest population with potential exposure to oil and gas development shows decreased term birth weight and increased odds of term SGA in the metropolitan regions. However, we also estimate increased term birth weight and reduced odds of term SGA in the nonmetropolitan regions in the group that resides within 0–1 km of the oil and gas industry before and during drilling activity relative to before and during drilling activity in 3–10 km group. This result provides an interesting view into potential differential economic–pollution tradeoffs between these regions (Kimman 2011; Sovacool 2014). In nonmetropolitan regions, the substantial economic stimulation from an oil and gas industry boom may provide local residents with benefits that are different from what their urban counterparts are experiencing, resulting in weaker associations between oil and gas industries on term birth weight and term SGA in rural communities. These results contrast the findings by Tran et al. in California, where their analysis showed evidence for stronger reductions in term birth weight and SGA in the rural population in comparison with the urban population (Tran et al. 2020). However, the protective effect estimates in rural regions are similar to those in previous work on birth outcomes among rural populations in Colorado and southwestern Pennsylvania (McKenzie et al. 2014; Stacy et al. 2015). Future studies should disentangle this distinct urban–rural phenomenon in more depth.
Despite the many strengths of our analysis, we acknowledge that there are some important limitations to consider when interpreting our results. First, birth certificate data contains only maternal address at delivery, so we could not capture any residential changes that occurred during pregnancy. Inherently, our exposure metric is therefore only considering drilling activity that was occurring at the time of delivery. We also do not have access to a unique maternal identifier that could distinguish among siblings in our analysis or account for nonindependent observations resulting from multiple births to the same mother. Given the self-reported nature of birth certificates, there is also substantial missing data on some questions (e.g., maternal weight gain during pregnancy). By using term birth weight and SGA as infant health end points, our approach incorporates gestational age and gestation length as components of these outcomes. This minimizes the potential for bias but also means we cannot interpret these results with respect to gestational age or gestation length (Neophytou et al. 2020; Wilcox 2001). Second, many other components of drilling infrastructure (e.g., pipelines, compressor stations, retention ponds) (U.S. Department of Energy 2009) may have been present in our study area that could have produced air pollution that affects infant health that are beyond the scope of this project. Third, differences in maternal race/ethnicity between near and far proximity groups were not consistent before and during drilling activity, which suggests that the DiD comparison of time-invariant confounders may not have been fully met. Although we adjusted for individual- and neighborhood-level risk factors, we cannot rule out the possibility of residual confounding due to unmeasured characteristics. Fourth, although we adjusted for census tract-level characteristics and county, residual confounding due to spatial variation in risk factors is possible. Finally, given the need for a definitive before-and-after time in the counterfactual group for a DiD analysis (Abadie 2005), it is difficult to apply more complex oil and gas drilling exposure metrics (e.g., inverse distance weighting, activity index) that would be comparable to existing work (Casey et al. 2015; McKenzie et al. 2014) and align better with estimated pollution exposure gradients.

Our study adds important new information for residential proximity to active oil and gas extraction sites during pregnancy and adverse birth outcomes. We leveraged a large population birth cohort from 1996 to 2009 in Texas, a state where oil and gas extraction using both conventional and unconventional approaches was common throughout the study period. Residing near oil and gas drilling sites during pregnancy was associated with a small reduction in term birth weight, with less evidence for associations with term SGA. Future work is necessary to determine whether associations are related to specific aspects of oil and gas drilling activities and inform the development of health-protective policies.

Acknowledgments

This work is partially funded by the National Institute of Environmental Health Sciences, National Institutes of Health (NIH) (Award Number: F31 ES029801), the National Center for Advancing Translational Sciences, NIH (Award Number: TL1 TR00237), and Office of the Director, NIH (Award Number: DP5 OD021338). The content is solely the responsibility of the authors and does not necessarily represent the official views of the NIH.

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