



Original Contribution

Associations Between Residential Proximity to Power Plants and Adverse Birth Outcomes

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Few studies have assessed the associations between residential proximity to power plants and adverse birth outcomes including preterm delivery (PTD), very preterm delivery (VPTD), and term low birth weight (LBW). We geocoded 423,719 singleton Florida births born from 2004 to 2005 and all active power plants and determined residential proximity to the nearest power plant for each birth. Prenatal exposure to particulate matter less than 2.5 μm in diameter for women living near different types of power plants was also determined by using National Environmental Public Health Tracking Network data. Logistic regression models were used to test the hypothesized associations. Women who lived closer to coal and solid waste power plants were exposed to higher levels of particulate matter less than 2.5 μm in diameter compared with other types. We observed a 1.8% (95% confidence interval (CI): 1.3, 2.3) increased odds for PTD, 2.2% (95% CI: 1.0, 3.4) for VPTD, and 1.1% (95% CI: 0.2, 2.0) for term LBW for each 5 km closer to any power plant. When stratifying by different fuel type, we found that only solid waste had an association with term LBW, whereas oil, gas, and solid waste all had an association with PTD and VPTD. Results were consistent when exposure was categorized by number of power plants. Our study found evidence of increasing odds of adverse birth outcomes among infants born to pregnant women living closer to power plants. More research is warranted to better understand the causal relationship.

birth outcomes; environment; low birth weight; pollution; power plants; preterm delivery

Abbreviations: CI, confidence interval; LBW, low birth weight; OR, odds ratio; $\text{PM}_{2.5}$, particulate matter less than 2.5 μm in diameter; PTD, preterm delivery; SD, standard deviation; VPTD, very preterm delivery.

Air pollution has been extensively linked to many negative health outcomes ranging from cardiorespiratory diseases (1–3) to hospitalizations (4–6) and mortality (7, 8). A recent risk analysis estimated that particulate matter less than 2.5 μm in diameter ($\text{PM}_{2.5}$) and ozone, estimated from the 2005 air quality level, were responsible for 130,000 and 4,700 excess deaths, respectively (9). These mortality estimates were significantly higher for the older population. In populous cities, the percentage of deaths attributable to $\text{PM}_{2.5}$ and ozone ranges from 3.5% in San Jose to 10% in Los Angeles (both in California) (9). Exposure to various air pollutants has also been linked to adverse pregnancy-related and birth outcomes including gestational hypertension, premature delivery, and low birth weight (10–13).

The American Lung Association has estimated that pollution specifically from power plants is responsible for approximately

13,000 excess deaths annually in the United States (14). Because living near power plants may expose people to additional sources of air pollution, this proximity may increase their risk of having negative health endpoints. According to the US Environmental Protection Agency, power plants release toxic chemicals into the air including mercury, heavy metals, and acid gases, all of which are known to be deleterious to human health, especially that of the unborn fetus (15). Moreover, there is recent evidence suggesting that harmful emissions from power plants may be increasing (16).

Because of accumulating evidence of a negative relationship between power plants and human health, a few studies have assessed the association between proximity to nuclear power plants and adverse birth outcomes, but no association was found (17–19). To our knowledge, few existing studies

Table 1. Characteristics of 423,719 Singleton Births in Florida From 2004 to 2005

Characteristic	Term LBW			PTD			VPTD			Controls		
	Mean (SD)	No.	%	Mean (SD)	No.	%	Mean (SD)	No.	%	Mean (SD)	No.	%
Total participants		9,320	2.4		33,402	8.2		5,680	1.5		375,317	
Distance from plant, km												
Continuous	14.5 (11.8)			14.4 (11.6)			14.1 (11.5)			15.0 (12.1)		
Categorical												
<5		1,497	16.1		5,288	15.8		943	16.6		56,016	14.9
5–9.9		2,441	26.2		8,900	26.7		1,531	27.0		97,167	25.9
10–19.9		3,393	36.4		12,400	37.1		2,080	36.6		138,917	37.0
≥20		1,989	21.3		6,814	20.4		1,126	19.8		83,217	22.2
Maternal age, years	26.7 (7.1)			27.6 (6.9)			27.4 (7.3)			27.5 (6.4)		
Gestational age, weeks	38.0 (1.0)			35.1 (1.2)			27.9 (2.6)			39.0 (1.1)		
Mother's education												
Less than high school		2,560	27.8		7,730	23.4		1,397	25.2		77,011	20.7
High school/some college		4,749	51.6		16,674	50.5		2,942	53.1		183,225	49.3
College degree		1,504	16.4		6,896	20.9		984	17.8		88,270	23.7
Graduate school		394	4.3		1,710	5.2		215	3.9		23,343	6.3
Maternal race												
White		3,344	36.4		14,615	44.1		1,864	33.3		176,354	47.4
Black		2,756	30.0		7,710	23.3		1,932	34.5		62,419	16.8
Hispanic		1,881	20.5		6,451	19.5		1,155	20.6		83,470	22.4
Asian/Pacific Islander		324	3.5		902	2.7		124	2.2		10,605	2.9
Others		894	9.6		3,430	10.4		522	9.3		39,483	10.6
Census block group annual income, US dollars												
<29,643.00 (first quartile)		3,026	32.5		9,174	27.5		1,892	33.3		92,338	24.6
29,643.00 to <38,095.00 (second quartile)		2,401	25.8		8,287	24.8		1,461	25.7		94,213	25.1
38,095.00 to <49,457.00 (third quartile)		2,152	23.1		8,288	24.8		1,320	23.2		94,303	25.1
≥49,457.00 (fourth quartile)		1,741	18.7		7,653	22.9		1,007	17.7		94,463	25.2

Table continues

have evaluated the association between residential proximity to different types of power plants and adverse birth outcomes (20). Furthermore, although power plant emissions are 1 of the major point sources of air pollution (21), which has been shown to have consistent association with adverse birth outcomes (22), there is limited information on air pollution exposure and pregnant women living close to specific types of power plants. Such information would be valuable in public health efforts to reduce adverse birth outcomes. Given that PM_{2.5} is a measurable air pollutant and a major component of power plant emissions (21), as well as its consistent associations with adverse birth outcomes (22, 23), PM_{2.5} can serve as a good indicator for air pollution from power plants. Florida has relatively high power plant emissions (16, 24) that provide a unique opportunity to investigate the potential association between power plant emissions and adverse birth outcomes. Thus, the primary purpose of this retrospective cohort study is to estimate the association between residential proximity to power plants and risk of adverse birth outcomes including term low birth

weight (LBW), preterm delivery (PTD), and very preterm delivery (VPTD) among singleton births in Florida from 2004 to 2005. We further stratify these associations by fuel type. Second, we use PM_{2.5} as a surrogate for "pollution" from power plants to determine 1) the level of "pollution" exposure during pregnancy for women living close to power plants and 2) whether the amount of pollution depends on fuel type.

METHODS

Setting and participants

The source population was all livebirths recorded by the Florida Department of Health, Office of Vital Statistics (Florida Vital Records), from January 1, 2004, through December 31, 2005 ($n = 445,028$). After exclusion of births that had addresses outside Florida ($n = 4,672$); births that were missing address ($n = 423$), unable to geocode (e.g., only post office box available, $n = 563$), missing gestational age ($n = 937$),

Table 1. Continued

Characteristic	Term LBW			PTD			VPTD			Controls		
	Mean (SD)	No.	%	Mean (SD)	No.	%	Mean (SD)	No.	%	Mean (SD)	No.	%
Urban neighborhood		8,160	87.6		28,972	86.7		4,986	87.8		323,992	86.3
Infant's sex, female		5,578	59.9		15,910	47.6		2,655	46.7		182,823	48.7
Marital status, married		4,408	47.4		18,549	55.6		2,631	46.4		224,450	59.8
Prenatal care, yes		9,055	97.2		32,214	96.4		5,224	92.0		370,271	98.7
Tobacco use												
Yes, <10/day		1,519	16.3		4,960	14.9		1,031	18.2		51,941	13.8
Yes, ≥10/day		1,128	12.1		2,586	7.5		472	8.3		22,611	6.0
Quit		190	2.0		548	1.7		99	1.7		5,952	1.6
No		6,483	69.6		25,308	75.8		4,078	71.8		294,813	78.6
Alcohol, yes		69	0.7		160	0.5		32	0.6		1,180	0.3
Season of conception												
Warm (May–October)		4,382	47.0		16,221	48.6		2,743	48.3		182,090	48.5
Cold (November–April)		4,938	53.0		17,181	51.4		2,937	51.7		193,227	51.5
Year of conception												
2003		3,243	34.8		10,772	32.3		1,448	25.5		135,717	36.2
2004		4,664	50.0		16,924	50.7		2,866	50.5		189,748	50.6
2005		1,413	15.2		5,706	17.1		1,366	24.1		49,852	13.3
Type of nearest power plant												
Coal		634	6.8		2,555	7.7		403	7.1		27,160	7.2
Gas		4,024	43.2		14,447	43.3		2,416	42.5		164,909	43.9
Nuclear		63	0.7		222	0.7		37	0.7		2,913	0.8
Oil		1,611	17.3		5,519	16.5		1,032	18.2		62,212	16.6
Solid waste		2,818	30.2		10,148	30.4		1,718	30.3		112,135	29.9
Other		170	1.8		511	1.5		74	1.3		5,988	1.6

Abbreviations: LBW, low birth weight; PTD, preterm delivery; SD, standard deviation; VPTD, very preterm delivery.

and multiple births ($n = 13,686$); and those with birth weight out of range (i.e., <500 and $>5,000$ g) ($n = 903$) and those with gestational age out of range (i.e., <140 days and >320 days) ($n = 125$), 423,719 births remained for analyses.

Exposure assessment

The exposure for this study was proximity to a nonrenewable-source power plant. All active power plants during the study period and eligible births were geocoded and mapped using ArcGIS V10.1 (ESRI, Redlands, California). Distance from the nearest power plants was measured in kilometers. The type of nearest power plant was also identified by fuel type. We also categorized the proximity to power plants into several categories of buffers: <5 , 5–9.9, 10–19.9, and ≥ 20 km. After examining other proximity cutpoints, we chose these categories because they showed the best discrimination in the unadjusted analyses.

To describe prenatal exposures to $PM_{2.5}$, we estimated average daily residential exposures to $PM_{2.5}$ during pregnancy for each birth using data from the Centers for Disease Control and Prevention's National Environmental Public Health Tracking Network. These data are based on the US Environmental Protection Agency's Hierarchical Bayesian Prediction Model

output (25). Briefly, this model uses hierarchical Bayesian methods to combine data from observed air quality data measured at air monitors, the National Emission Inventory, and meteorological and photochemical data to produce 12×12 km gridded estimates of daily average $PM_{2.5}$ concentrations. We overlaid geocoded residential addresses over the 12×12 km grids. Prenatal exposure was assigned to each birth as the average daily $PM_{2.5}$ concentration over the first trimester for the grid in which it falls. We chose first trimester because 1) first trimester exposure to $PM_{2.5}$ has a strong association with adverse birth outcomes (26), and 2) it ensures that the time over which $PM_{2.5}$ is averaged is similar for cases and controls. The first trimester was defined as the first 13 weeks of gestation. A detailed description of this method was reported elsewhere (23). In addition, we also overlaid geocoded active power plants and the 12×12 km grids to determine the daily $PM_{2.5}$ concentrations near the power plants during the study period.

Outcome assessment

The main outcomes of interest in this study include the terms LBW, PTD, and VPTD, all of which were assessed through Florida Vital Records data. The term LBW was defined as a birth weighing less than 2,500 g at birth and born at

or after 37 weeks of gestation. PTD was defined as a birth that occurred before 37 but at or after 32 weeks of gestation. VPTD was defined as a birth that occurred before 32 weeks of gestation. On Florida birth certificates, the gestational age in weeks is typically determined by ultrasound measurements. When ultrasound is not available, fundal height (determined by clinical examination) or menstrual history is used to estimate gestational age. For controls, we used eligible births that had none of the 3 outcomes we assessed.

Covariates

Covariates were chosen on the basis of a directed acyclic graph (Web Figure 1 available at <http://aje.oxfordjournals.org/>). They included mother’s age (continuous), maternal education (less than high school, high school graduate and/or some college, college graduate, graduate school), maternal race (white, black, Hispanic, Asian/Pacific Islander, and others), and marital status (married, unmarried). We also used Census 2000 data to determine census block group income as a proxy for neighborhood socioeconomic status and urbanity.

Statistical analyses

To describe exposures to PM_{2.5} during pregnancy and throughout the study period according to nearest power plants, we used scatterplots with locally weighted scatterplot smoothing (LOESS) functions (smooth = 0.5) to display averaged daily concentrations during the first trimester (y-axis) by date of delivery (x-axis), as well as daily concentrations (y-axis) by date during the study period (x-axis). We stratified the plots by fuel type for comparison. To compare continuous and categorical characteristics for participants with and without the 3 adverse birth outcomes, we performed *t* tests and χ^2 tests. We used logistic regression models to investigate the association between proximity to a power plant and the adverse birth outcomes. Two logistic regression models were used for each outcome: The first model was unadjusted, and the second model was a parsimonious model adjusted for potential confounders on the basis of our directed acyclic graph (Web Figure 1). We obtained the odds ratios and 95% confidence intervals for the increase in odds of having adverse birth outcomes for each 5 km closer to any power plant. We also compared the odds for different buffer sizes of <5, 5–9.9, 10–19.9, and ≥ 20 km from a power plant. We further stratified analyses for different types of plants. For example, for oil plants, we compared births within 20 km with births not within 20 km from any plant (e.g., excluding those who were closer to any other types of plant). We were unable to perform analyses for more refined proximity categories because of low sample size for certain cells. Data analyses were performed by using SAS, version 9.3, software (SAS Institute, Inc., Cary, North Carolina).

RESULTS

Table 1 shows participants’ characteristics by term LBW, PTD, and VPTD. The sample prevalence was 2.4% for term LBW, 8.2% for PTD, and 1.5% for VPTD. Overall, the

Table 2. Association Between Proximity to Power Plants and Adverse Birth Outcomes in Florida From 2004 to 2005

Distance From Power Plant, km	Term LBW			PTD			VPTD			
	OR	95% CI	aOR ^a	OR	95% CI	aOR ^a	OR	95% CI	aOR ^a	
Continuous (for each 5 km closer)	1.018	1.009, 1.027	1.011	1.020	1.002, 1.020	1.018	1.031	1.019, 1.043	1.022	1.010, 1.034
Categorical										
<5	1.118	1.045, 1.197	1.038	1.153	0.968, 1.113	1.126	1.244	1.140, 1.357	1.160	1.060, 1.270
5–9.9	1.051	0.990, 1.116	1.026	1.119	0.965, 1.092	1.114	1.164	1.078, 1.258	1.138	1.050, 1.233
10–19.9	1.022	0.966, 1.081	1.059	1.090	1.000, 1.121	1.106	1.107	1.029, 1.190	1.147	1.064, 1.236
≥ 20	1.00	Referent	1.00	1.00	Referent	1.00	1.00	Referent	1.00	Referent

Abbreviations: aOR, adjusted odds ratio; CI, confidence interval; LBW, low birth weight; OR, odds ratio; PTD, preterm delivery; VPTD, very preterm delivery.
^a Adjusted for maternal age, maternal race, education, marital status, census block group income, and urban neighborhood.

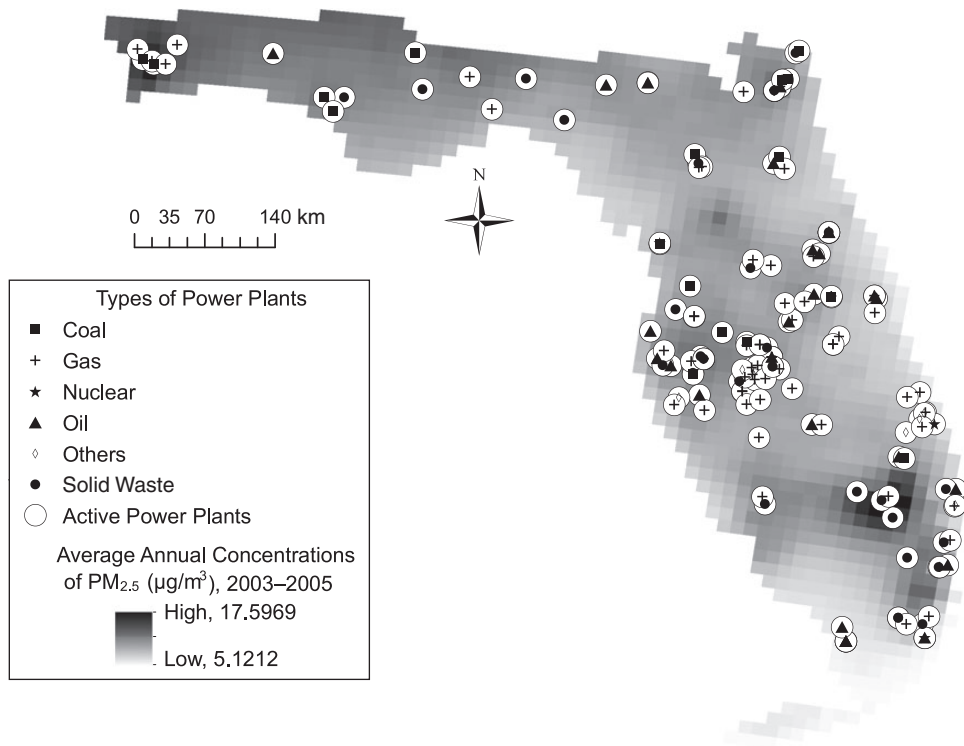


Figure 1. Geographical distribution of power plants and average annual levels of particulate matter less than 2.5 µm in diameter (PM_{2.5}) in Florida during the study period from 2003 to 2005.

percentages of people living closer to power plants were higher among those with adverse birth outcomes compared with those among controls. For example, among those with term LBW, the percentage of those who lived within 5 km

of any power plant (16.1%) was higher than that of controls (14.9%). Furthermore, among the case groups, the percentages of women who had lower education, were black, lived in neighborhoods with lower income, were unmarried, had no prenatal

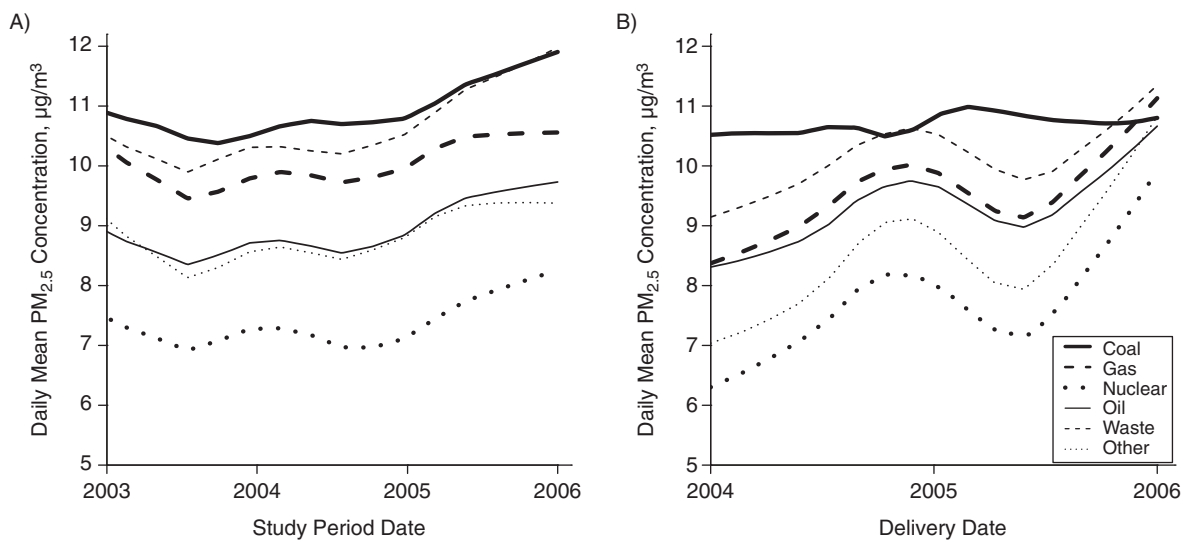


Figure 2. Exposures to levels of particulate matter less than 2.5 µm in diameter (PM_{2.5}) stratified by power plant type in Florida from 2003 to 2005. A) Daily concentrations of PM_{2.5} during the study period 2003–2005 at power plants; B) mean daily PM_{2.5} concentration at residential address during the first trimester for births in Florida from 2004 to 2005.

Table 3. Association Between Proximity to Power Plants, by Fuel Type, and Adverse Birth Outcomes in Florida From 2004 to 2005

Type of Power Plants	Term LBW		PTD		VPTD	
	aOR ^a	95% CI	aOR ^a	95% CI	aOR ^a	95% CI
<i>Continuous (for Each 5 km Closer in Distance)</i>						
Coal plant (n = 17)	1.02	0.98, 1.06	1.01	0.99, 1.03	1.03	0.98, 1.09
Gas plant (n = 66)	1.00	0.99, 1.02	1.02	1.01, 1.03	1.01	0.99, 1.03
Nuclear plant (n = 3)	1.07	0.96, 1.20	0.90	0.86, 0.95	0.99	0.87, 1.14
Oil plant (n = 28)	1.00	0.99, 1.02	1.02	1.01, 1.03	1.03	1.01, 1.06
Solid waste plant (n = 29)	1.03	1.01, 1.04	1.02	1.02, 1.03	1.02	1.00, 1.05
Other (n = 7)	1.05	0.96, 1.15	1.01	0.96, 1.06	1.03	0.91, 1.18
<i>Categorical (≤20 km Away vs. >20 km Away From All Plants)</i>						
Coal plant (n = 16)	1.19	0.98, 1.45	1.07	0.97, 1.18	1.19	0.93, 1.51
Gas plant (n = 67)	0.96	0.89, 1.04	1.09	1.04, 1.13	1.09	0.99, 1.20
Nuclear plant (n = 3)	1.37	0.81, 2.31	0.82	0.60, 1.11	0.88	0.39, 2.00
Oil plant (n = 28)	1.04	0.91, 1.19	1.14	1.06, 1.24	1.27	1.07, 1.52
Solid waste plant (n = 30)	1.10	1.00, 1.22	1.16	1.09, 1.22	1.15	1.01, 1.32
Other (n = 7)	1.16	0.68, 1.98	1.23	0.89, 1.70	1.39	0.61, 3.17

Abbreviations: aOR, adjusted odds ratio; CI, confidence interval; LBW, low birth weight; PTD, preterm delivery; VPTD, very preterm delivery.

^a Adjusted for maternal age, maternal race, marital status, census block group income, and urban neighborhood.

care, smoked, or drank alcohol during pregnancy were higher compared with those in the control group (Table 1).

Figure 1 shows a map of the spatial distribution of active power plants and the average annual PM_{2.5} concentrations in Florida during 2003–2005. There were 150 active nonrenewable power plants with different fuel types including 17 coal plants, 66 gas plants, 3 nuclear plants, 28 oil plants, 29 solid waste plants, and 7 plants with other types of fuel (e.g., coke, etc.). In general, PM_{2.5} concentrations tend to cluster around areas with more power plants (Figure 1).

Figure 2A and 2B illustrate PM_{2.5} exposure by types of power plants. In general, the concentrations of PM_{2.5} were highest around coal plants followed by solid waste, gas, oil, other, and nuclear plants (Figure 2A). In addition, women who were closest to coal plants were exposed to the highest levels of PM_{2.5} (mean = 10.7 (standard deviation (SD), 2.7) µg/m³) during the first trimester, followed by those living close to solid waste plants (mean = 10.1 (SD, 1.8) µg/m³), gas plants (mean = 9.5 (SD, 2.1) µg/m³), and oil plants (mean = 9.3 (SD, 1.8) µg/m³). Those who were closest to nuclear plants (mean = 7.7 (SD, 1.9) µg/m³) and “other” plants (mean = 8.5 (SD, 2.0) µg/m³) were exposed to the lowest levels of PM_{2.5} (Figure 2B; Web Table 1).

Table 2 provides the unadjusted and adjusted odds ratios for the association between proximity to power plants and term LBW, PTD, and VPTD. Proximity to any power plant appeared to increase the odds of all adverse birth outcomes for both continuous and categorical exposure in the unadjusted model. Moreover, these associations showed an exposure-response relationship with closer residents having the higher odds. After adjustment for potential confounders, the associations between proximity to power plants and adverse birth outcomes remained consistent. Specifically, for each 5-km

decrease in the distance to any power plant, the odds of term LBW, PTD, and VPTD increased by 1.1% (odds ratio (OR) = 1.011, 95% confidence interval (CI): 1.002, 1.020), 1.8% (OR = 1.018, 95% CI: 1.013, 1.023), and 2.2% (OR = 1.022, 95% CI: 1.010, 1.034), respectively. These associations remained consistent for PTD and VPTD when exposures were categorized (Table 2). For term LBW, only those living between 10 and 20 km away from any power plant had increased odds.

Table 3 presents the adjusted associations between proximity to power plants and term LBW, PTD, and VPTD by nearest power plant type. Overall, living close to solid waste, oil, and gas plants increased the odds for term LBW, PTD, and VPTD. In the continuous exposure analyses, only solid waste plants (OR = 1.03, 95% CI: 1.01, 1.04) had an association with term LBW for each 5-km decrease in distance. All types of plants had a slightly elevated association with PTD, except nuclear plants, which had a negative association (OR = 0.90, 95% CI: 0.86, 0.95), and “others” and coal plants with no associations. For VPTD, only oil and solid waste plants had significant associations. The results remained consistent when exposure was categorized (Table 3).

Because there was evidence of spatial clustering of power plants, distance from power plants may not be the best measure of exposure. We also created 20 km buffers around each birth and determined the total number of power plants within this buffer (Table 4). The association between adverse birth outcomes and total number of power plants within 20 km was determined. Compared with pregnant women who lived with no power plants within a 20 km radius, women living near ≥2 power plants had a 7% increased odds of term LBW (OR = 1.07, 95% CI: 1.01, 1.12), 12% increased odds of PTD (OR = 1.12, 95% CI: 1.09, 1.15), and 17% increased odds of VPTD (OR = 1.17, 95% CI: 1.09, 1.25). When stratified for different

Table 4. Association Between Number of Plants Within 20 km, by Fuel Type, and Adverse Birth Outcomes in Florida From 2004 to 2005

Type and No. of Power Plants Within 20 km	Term LBW		PTD		VPTD	
	aOR ^a	95% CI	aOR ^a	95% CI	aOR ^a	95% CI
All plants						
0	1.00	Referent	1.00	Referent	1.00	Referent
1	0.93	0.86, 1.01	1.08	1.04, 1.13	1.06	0.95, 1.17
≥2	1.07	1.01, 1.12	1.12	1.09, 1.15	1.17	1.09, 1.25
Coal plant						
0	1.00	Referent	1.00	Referent	1.00	Referent
1	0.93	0.87, 1.00	1.09	1.05, 1.13	0.99	0.91, 1.08
≥2	1.12	1.03, 1.22	1.20	1.14, 1.25	1.23	1.10, 1.36
Gas plant						
0	1.00	Referent	1.00	Referent	1.00	Referent
1	1.07	1.02, 1.13	1.05	1.02, 1.08	1.13	1.06, 1.21
≥2	1.06	1.00, 1.12	1.13	1.10, 1.17	1.13	1.06, 1.21
Oil plant						
0	1.00	Referent	1.00	Referent	1.00	Referent
1	1.07	1.02, 1.12	1.10	1.07, 1.12	1.18	1.12, 1.25
≥2	0.97	0.89, 1.06	0.99	0.95, 1.04	0.83	0.74, 0.94
Nuclear plant ^b						
0	1.00	Referent	1.00	Referent	1.00	Referent
≥1	1.03	0.93, 1.15	0.92	0.86, 0.98	0.88	0.75, 1.02
Solid waste plant						
0	1.00	Referent	1.00	Referent	1.00	Referent
1	1.08	1.04, 1.13	1.06	1.03, 1.09	1.13	1.06, 1.20
≥2	1.00	0.93, 1.07	1.09	1.06, 1.13	1.13	1.04, 1.22
Other plant						
0	1.00	Referent	1.00	Referent	1.00	Referent
1	0.94	0.87, 1.02	1.03	0.99, 1.08	1.07	0.98, 1.19
≥2	0.95	0.80, 1.14	0.86	0.78, 0.96	0.77	0.60, 0.99

Abbreviations: aOR, adjusted odds ratio; CI, confidence interval; LBW, low birth weight; PTD, preterm delivery; VPTD, very preterm delivery.

^a Adjusted for maternal age, maternal race, maternal education, marital status, census block group income, and urban neighborhood.

^b Nuclear plants are categorized differently because there are no births with 2 or more nuclear plants within 20 km.

types of power plants, the results remained generally consistent. Coal was strongly associated with all adverse birth outcomes (Table 4).

DISCUSSION

This study found that women with residential proximity to coal and solid waste plants were exposed to the highest concentrations of PM_{2.5} during the first trimester, and those closest to nuclear plants were exposed to the lowest concentrations. This pattern remained consistent when daily PM_{2.5} concentrations near different types of power plants were examined. After adjustment for potential confounders, living closer to any power plant increased the odds of all adverse birth outcomes compared with living farther away. We further identified that solid

waste plants had the strongest association with term LBW, while oil, gas, and solid waste plants all had strong associations with PTD and VPTD. The study also found that women living near 1 or more power plants located within a 20 km radius from their residence had higher odds of adverse birth outcomes. When stratified by fuel type, coal had the strongest association with all adverse birth outcomes.

Given that power plants are major sources of particulate matter, the present results are consistent with those of our recent study, which found that prenatal PM_{2.5} exposure was positively associated with LBW, PTD, and VPTD (23). During the study period, power plants in the United States emitted an estimated annual average of 2,491,971 metric tons of carbon dioxide, 10,431 metric tons of sulfur dioxide, and 4,212 metric tons of nitric oxides (27). These pollutants have been

linked to adverse birth outcomes in many studies. For example, higher exposure to sulfur dioxide has been linked to PTD among singleton births (28) and decreased term birth weight (29). In addition, nitric oxides have also been linked to term LBW and PTD (30, 31). Given the high emission of sulfur dioxide and nitric oxides from power plants and the positive association between these pollutants and adverse birth outcomes, it is plausible that proximity to power plants was associated with adverse birth outcomes. This finding has also been observed in Taiwan by Tsai et al. (20), who reported that the odds of PTD were 14 times higher among women who lived within 3 km of a thermal power plant compared with those who lived farther than 3 km.

When stratified by type of plants in order to compare birth outcomes among women who lived close to or farther from different types of power plants, our data showed that solid waste plants had associations with all adverse birth outcomes. In addition, when exposure was changed to number of plants within 20 km, coal plants had the highest association with all adverse birth outcomes. These findings are consistent with the fact that coal and solid waste power plants produce relatively larger amounts of particulate emissions compared with other types of power plants. Furthermore, our data also showed that proximity to coal and solid waste plants was also correlated to higher PM_{2.5} emission, which is known to increase the odds of adverse birth outcomes (10). With coal combustion accounting for approximately 45% of electricity produced in the United States, it may pose a serious public health issue. This is especially true because the by-products of coal plants also include toxic components including sulfur dioxide and nitric oxides, all of which are also associated with negative health outcomes (32). We also found that gas and oil plants had a positive association with adverse birth outcomes, especially PTD and VPTD. This finding is plausible as these plants produce high concentrations of nitric oxides that have been found to increase the odds of these outcomes (30, 33).

Our continuous exposure analysis showed that proximity to nuclear plants was protective against PTD, but not term LBW or VPTD. In categorical exposure analyses, no association was found. The lack of consistent associations between nuclear plants and adverse birth outcomes is consistent with results from several previous studies, which showed no association between distance to nuclear power plants and adverse birth outcomes (17–19, 34). The lack of a positive association could be explained by the fact that, compared with other types of plants, nuclear plants do not emit as many atmospheric pollutants in high concentrations (e.g., PM_{2.5}, sulfur dioxide, and nitric oxides) (35). This association is also consistent with our data that showed, on average, that women close to nuclear plants and other plants were exposed to lower levels of PM_{2.5}.

Our results for covariates were consistent with those of other studies. For example, the fact that our study showed an increased proportion of females among the term LBW group and a decreased proportion of females among the PTD and VPTD groups confirmed previous findings. On average, males weigh 150 and 200 g more than females (36) given term birth, and they have a 9%–24% increased risk for PTD (37). In addition, our observation that pregnant women who had a lower level of education, were racial minorities and unmarried, had no prenatal care, used tobacco, and smoked

during pregnancy were more likely to be in the adverse birth outcome groups is also consistent with the literature (38–40). It is possible that socioeconomic status confounded the association that we observed in this study. However, in addition to adjustment for maternal education, which serves as a proxy for socioeconomic status, we also adjusted for census-tract-level median household income from the US Census 2000 to control for ecological (or population-level) socioeconomic status factors.

Like most retrospective studies, this study has several limitations. First, analysis of proximity as both a continuous variable and as a categorical variable addresses exposure-response relationships, but it does so in different ways with different assumptions. In the categorical exposure analyses, we made a fundamental assumption that each power plant has a uniform effect on participants within a certain buffer. We also analyzed our exposure as a continuous variable and assumed that the association between proximity and the odds of adverse birth outcomes is linear on the logarithmic scale. When the results for both analyses were compared, the conclusions were consistent, although those for categorical exposure are stronger. One of the reasons for the differences may be a result of the spatial clustering of power plants. To ensure that clustering was not influencing our results, we performed a sensitivity analysis using the number of power plants within 20 km as exposure. This analysis yielded results consistent with proximity to power plants as a measure of exposure.

Although we chose PM_{2.5} to “validate” our exposure, power plants also emit other gaseous pollutants including carbon oxides, sulfur dioxide, and nitric oxides (41), all of which are highly correlated (30). Because of the use of proximity and the unavailability of specific pollutant data from the US Environmental Protection Agency’s Hierarchical Bayesian Prediction Model, we were unable to disentangle the specific pollutant. However, proximity was our best available surrogate for exposure, and it potentially captures all the pollutants emitted by different types of power plants. Additionally, we were not able to identify critical windows of exposure that underlie these associations. Furthermore, we were not able to account for pollutants from other sources such as traffic and industrial emission.

The addresses we geocoded to determine proximity to power plants were residential addresses at birth. This method assumes that pregnant women stayed at those same addresses throughout their pregnancy. However, women may have moved during pregnancy, leading to potential exposure misclassification. We unfortunately did not have residential mobility information to address this issue. However, studies on residential mobility and its effects on air pollution assessment suggest a very low degree of misclassification (42, 43).

We were also unable to adjust for daily activities patterns. Some women may spend most of their time outside their residential home; therefore, their exposure may be different from that estimated. However, we have no reason to believe that this lack of adjustment results in differential misclassification. Therefore, this discrepancy is likely to bias our results toward the null. Consequently, daily activity patterns cannot entirely explain the increased risk that we found.

One may argue that potential confounding may be caused by other variables that we did not adjust for. However, we have

also used a fully adjusted model with all covariates in our directed acyclic graph. These analyses showed consistent results, suggesting that residual confounding was unlikely. Finally, the Hierarchical Bayesian Prediction Model data that we used to describe PM_{2.5} exposures were available at only 12 × 12 km resolution. Therefore, we were not able to account for local variation smaller than this spatial resolution.

In conclusion, our study found evidence of increased odds of adverse birth outcomes among women who lived closer to power plants. This association remained consistent in our analyses for total number of power plants within a 20 km radius and stratified analyses for different types of power plants. These results call for further investigation to confirm our results and to investigate the specific pollutants generated from power plants that are responsible for this association.

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