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RESEARCH ARTICLE

Industrial air pollution and low birth weight: a case-control study in Texas, USA

Xi Gong[1] · Yan Lin[1] · F. Benjamin Zhan[2]

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Abstract

Many studies have investigated associations between maternal residential exposures to air pollutants and low birth weight (LBW) in offspring. However, most studies focused on the criteria air pollutants ($PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2, CO, and Pb), and only a few studies examined the potential impact of other air pollutants on LBW. This study investigated associations between maternal residential exposure to industrial air emissions of 449 toxics release inventory (TRI) chemicals and LBW in offspring using a case-control study design based on a large dataset consisting of 94,106 LBW cases and 376,424 controls in Texas from 1996 to 2008. Maternal residential exposure to chemicals was estimated using a modified version of the emission-weighted proximity model (EWPM). The model takes into account reported quantities of annual air emission from industrial facilities and the distances between the locations of industrial facilities and maternal residence locations. Binary logistic regression was used to compute odds ratios measuring the association between maternal exposure to different TRI chemicals and LBW in offspring. Odds ratios were adjusted for child's sex, birth year, gestational length, maternal age, education, race/ethnicity, and public health region of maternal residence. Among the ten chemicals selected for a complete analysis, maternal residential exposures to five TRI chemicals were positively associated with LBW in offspring. These five chemicals include acetamide (adjusted odds ratio [aOR] 2.29, 95% confidence interval [CI] 1.24, 4.20), *p*-phenylenediamine (aOR 1.63, 95% CI 1.18, 2.25), 2,2-dichloro-1,1,1-trifluoroethane (aOR 1.41, 95% CI 1.20, 1.66), tributyltin methacrylate (aOR 1.20, 95% CI 1.06, 1.36), and 1,1,1-trichloroethane (aOR 1.11, 95% CI 1.03, 1.20). These findings suggest that maternal residential proximity to industrial air emissions of some chemicals during pregnancy may be associated with LBW in offspring.

Keywords Air pollution · GIS · Health · Toxic release inventory (TRI) chemicals · Low birth weight (LBW) · Exposure assessment

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✉ F. Benjamin Zhan
zhan@txstate.edu

Xi Gong
xigong@unm.edu

Yan Lin
yanlin@unm.edu

[1] Department of Geography & Environmental Studies, University of New Mexico, Albuquerque, NM 87131, USA

[2] Texas Center for Geographic Information Science, Department of Geography, Texas State University, San Marcos, TX 78666, USA

Introduction

Ambient air pollution (AAP), also known as outdoor air pollution, is ubiquitous (Polichetti et al. 2013) and has become a global public health problem (Brunekreef and Holgate 2002; Kampa and Castanas 2008). It has been well documented that exposure to AAP was associated with a number of adverse health outcomes, such as respiratory and cardiovascular diseases (Brook et al. 2004; Dominici et al. 2006; Polichetti et al. 2009), and even mortality (Hoek et al. 2013). Because developing fetuses are more vulnerable than children and adults, many studies have investigated possible adverse influences of AAP on birth outcomes since the mid-1990s (Li et al. 2017; Ritz and Wilhelm 2008; Shah et al. 2011; Srám et al. 2005), including low birth weight (LBW, newborn weighted less than 2500 g or 5.5 lb at birth), small for gestational age (SGA), preterm birth, and birth defects.

Because LBW infants may experience higher risk of mortality and/or morbidity in childhood (McCormick 1985; McIntire et al. 1999; Watkins et al. 2016), and are more susceptible for other diseases than normal-weight infants, including stroke (Lawlor et al. 2005), coronary heart disease, hypertension, type II diabetes (Whincup et al. 2008), delayed motor/social development (Hediger et al. 2002), and learning disabilities (Litt et al. 2005), LBW is considered as an important predictor of an infant's health. Statistics suggested that 2.6% of live term singleton births were LBW births in the United States (U.S.) during 2000–2015 (U.S. CDC 2018).

Pollutants in the air can be divided into two categories: (1) six criteria air pollutants (CAPs) designated by the Clean Air Act and subsequent amendments (including particulate matter ($PM_{2.5}$, PM_{10}), ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), and lead (Pb)) (U.S. EPA 2017) and CAPs-related air pollutants, and (2) other air pollutants (non-criteria air pollutants). Based on publication records related to birth weight from the Web of Science database covering years 1904–2017 (Table 1), most studies reported in the literature focused on CAPs rather than non-criteria air pollutants (Wilhelm et al. 2012).

Table 1 Ambient air pollutants in publications related to birth weight as of December, 2017

Categories	Air pollutants	No. of studies	Examples of studies
Criteria air pollutants (CAPs) and related air pollutants (430 studies)	$PM_{2.5}$	99	(Ebisu and Bell 2012; Hyder et al. 2014; Li et al. 2017)
	NO_2	75	(Darrow et al. 2011; Dedele et al. 2017; Estarlich et al. 2011)
	PM_{10}	66	(Balsa et al. 2016; Xu et al. 2011)
	SO_2	46	(Cho et al. 2013; Jacobs et al. 2017; Williams et al. 2007)
	CO	44	(Bell et al. 2007; Merklinger-Gruchala et al. 2017)
	O_3	42	(Chen et al. 2002; Díaz et al. 2016; Geer et al. 2012)
	PM	14	(Ha et al. 2017; Siddiqui et al. 2008)
	Nitrogen oxides (NO_x)[a]	13	(Bobak 2000; Malmqvist et al. 2017)
	Nitric oxide (NO)	9	(Coker et al. 2016; Ghosh et al. 2012)
	Total suspended particulate (TSP)	8	(Bobak 2000; Lee et al. 2002; Wang et al. 1997)
	Lead	6	(Berkowitz et al. 2006; Govarts et al. 2016)
	Black carbon[b]	5	(Brauer and Lencar 2008; Paciorek 2010)
	Black smoke[c]	2	(Pearce et al. 2012; Stankovic et al. 2011)
	Pollutant Standard Index (PSI)[d]	1	(Janghorbani and Piraei 2013)
Other air pollutants (non-criteria air pollutants) (40 studies)	Polycyclic aromatic hydrocarbons (PAHs)	11	(Jedrychowski et al. 2017; Perera et al. 2003; Wilhelm et al. 2012)
	Benzene, Toluene, Ethyl benzene, and Xylene (BTEX)	9	(Aguilera et al. 2009; Estarlich et al. 2011; Zahran et al. 2012)
	Benzo [*a*] pyrene (B[*a*]P)	4	(Gladen et al. 2000; Veleminsky et al. 2016)
	Ammonia (NH_3)	2	(Dimitriev et al. 2006)
	Arsenic	2	(Govarts et al. 2016; Laurent et al. 2014)
	Cadmium	2	(Currie and Schmieder 2009; Govarts et al. 2016)
	Polycyclic organic matter (POM)	2	(Vassilev et al. 2001a, 2001b)
	Air pollution index based on coal consumption	1	(Bobak et al. 2001)
	Chlorine	1	(Dimitriev et al. 2006)
	Epichlorohydrin	1	(Currie and Schmieder 2009)
	Hydrogen sulfide (H2S)	1	(Harrath et al. 2015)
	Phenol	1	(Dimitriev et al. 2006)
	Polychlorinated biphenyls (PCB)	1	(Nieuwenhuijsen et al. 2013)
	Soot	1	(Gehring et al. 2011)
	Welding fumes (WF) and Metal dusts or fumes (MD/F)	1	(Quansah and Jaakkola 2009)

[a] NO_x is a generic term for mono-nitrogen oxides NO and NO_2

[b] A component of fine particulate matter (http://www.epa.gov/blackcarbon/basic.html)

[c] A historic measure of airborne particulate matter

[d] PSI for five major pollutants (CO, O_3, NO_2, SO_2, PM_{10}). PSI converts air pollution concentrations to a simple number between 0 and 500 and assigns descriptive terms such as "good" or "moderate" to that value

The associations between maternal exposure to the six CAPs and LBW have been investigated in a large number of studies (430 studies in total as of the end of 2017). For example, Salam et al. (2005) found that O_3 exposure during the second and third trimesters and CO exposure during the first trimester were associated with increased LBW levels; Xu et al. (2011) discovered that exposure to PM_{10} during pregnancy might increase the risk of LBW. Ebisu and Bell (2012) identified associations between $PM_{2.5}$ components and LBW in the northeastern and mid-Atlantic regions of the U.S. Dedele et al. (2017) showed that increased maternal exposure to NO_2 tended to increase LBW risk in offspring. Around 12% of these studies have also examined components or combination of the CAPs (CAPs-related air pollutants), including total suspended particle (TSP) (Bobak 2000; Lee et al. 2002; Wang et al. 1997), black carbon (Brauer and Lencar 2008; Paciorek 2010), black smoke (Pearce et al. 2012; Stankovic et al. 2011), among others.

However, the examination of association between maternal exposure to non-criteria air pollutants and LBW in offspring has been reported in a limited number of studies (only 40 studies as of the end of 2017). Among these studies, 9 of them investigated benzene, toluene, ethyl benzene, and xylene (BTEX) and 11 of them studied polycyclic aromatic hydrocarbons (PAHs). For example, airborne benzene exposure was found to be associated with increasing odds of a LBW event (Slama et al. 2009; Zahran et al. 2012). Jedrychowski et al. (2017) found that exposure to PAH was inversely associated with birth weight. Aguilera et al. (2009) linked an increase in BTEX exposure levels to reductions in birth weight for women who spent < 2 h/day in nonresidential outdoor environments. However, other non-criteria pollutants were hardly mentioned.

One possible explanation for the unbalanced number of studies on the two categories of air pollutants was the lack of high-quality air monitoring data covering non-criteria air pollutants. The extensive monitoring network of CAPs with finer spatial-temporal sampling resolution has significantly facilitated the estimation of exposure to CAPs (Gong et al. 2016). Although 18 non-criteria air pollutants have been studied (Table 1), these pollutants only accounted for a limited portion of the total non-criteria pollutants released into the air. Based on information from the databases maintained by the toxic release inventory (TRI) program of the U.S. Environmental Protection Agency (U.S. EPA), there have been over 650 non-criteria pollutants from industrial facilities in the U.S. and 449 in Texas (U.S. EPA 2013). It is hypothesized that some of these pollutants (TRI chemicals) could possibly exert a negative impact on birth weight. Therefore, this study attempts to identify associations between maternal residential exposure to TRI chemicals during pregnancy and LBW in offspring using a case-control study design based on the analysis of massive georeferenced data over a 13-year period in Texas from 1996 to 2008.

Study area, data, and methods

Study area

This study chose the state of Texas in the U.S. as the study area (Fig. 1). Among the 48 states in the contiguous U.S., Texas is the largest by area and second largest by population. Two datasets in Texas were used, including air emission data from industrial facilities and birth data.

Air emission data of industrial facilities

This study obtained air emission data of Texas industrial facilities from the U.S. EPA TRI program. The TRI program, a mandatory program established by Section 313 of the Emergency Planning and Community Right-to-Know Act (EPCRA), requires industrial facilities in the U.S. to report annual information about their names, locations, reporting years, types of chemicals released, and estimated quantity of a chemical released into the environment (U.S. EPA 2013). Based on reports during 1996–2008, 1286 to 1635 Texas industrial facilities reported air emissions to TRI program each year. Industrial facility addresses were geocoded and maintained at Texas State University (Zhan et al. 2015). During 1996–2008, 89.66% of the TRI facilities were successfully geocoded on average (Fig. 1). A TRI air emission geodatabase was constructed for the purpose of this study, containing both geographic locations of TRI facilities (Fig. 1) and non-spatial data summarizing the annual air emission amount of the 449 TRI chemicals released from industrial facilities in Texas during 1996–2008.

Birth data

This study obtained birth certificate data for all registered births during 1996–2008 in Texas from the Center for Health Statistics in the Texas Department of State Health Services (DSHS). Each birth certificate record contained information of maternal residential address at delivery; birth weight; birth year; plurality; child's sex; gestational age in weeks; mother's characteristics (age, race/ethnicity, education, marital status, and tobacco use during pregnancy); and father's characteristics (age, race/ethnicity, and education). This study excluded births of weight > 5500 g or < 1000 g (0.1%), births with gestational age > 44 weeks or < 37 weeks (17.8%), births with incomplete location information (10.9%), plural deliveries (2.7%), or births given by non-Texas residents or occurred outside of Texas (0.2%). Only births with weight < 2500 g were considered as the LBW cases and used in this study. This study matched LBW cases and controls by year of birth (1996–2008) and selected four controls for each case to ensure sufficient study power. Control births from the same birth year were randomly selected from the birth certificate data. The

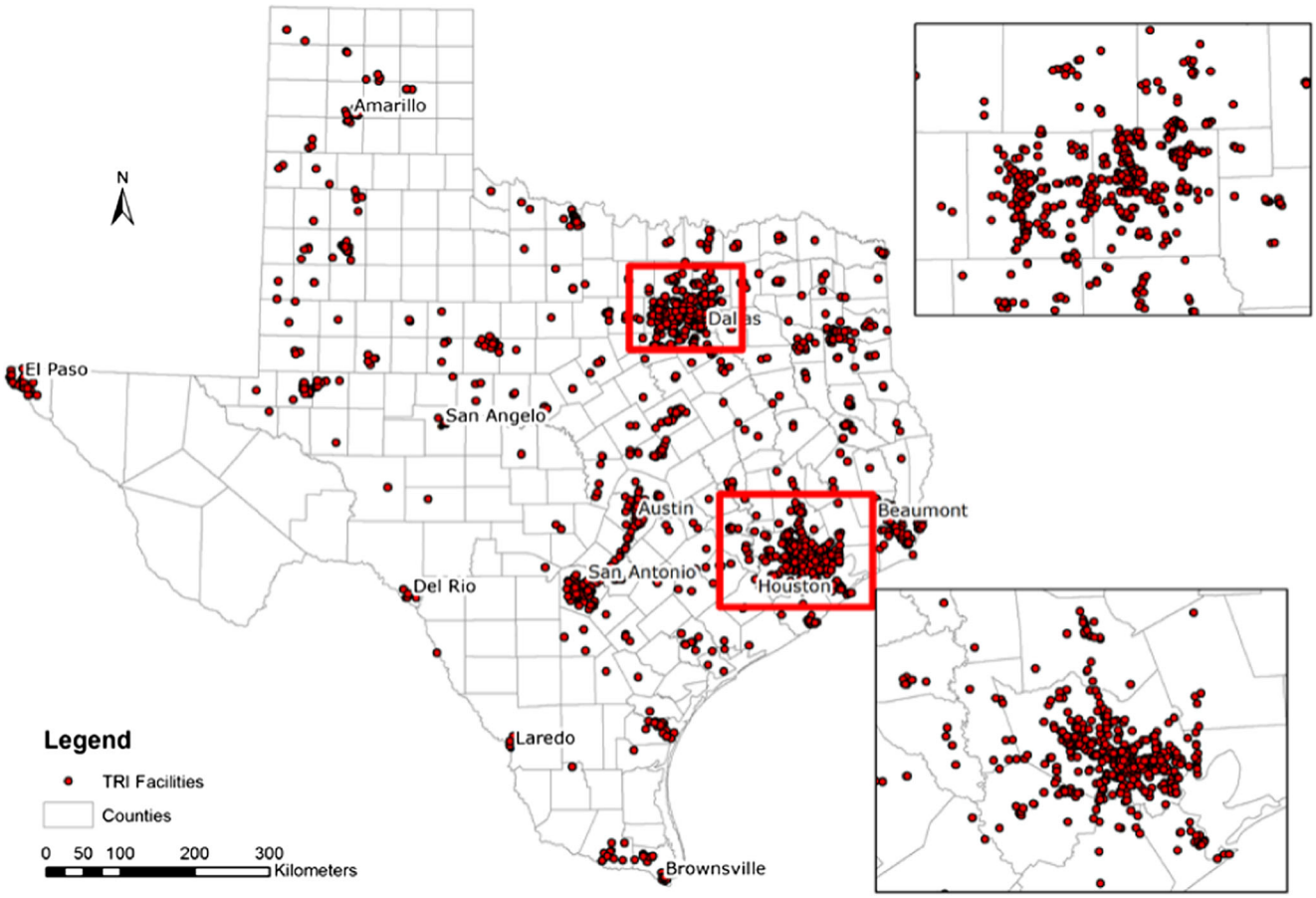

Fig. 1 Geographic distribution of toxic release inventory (TRI) facilities in Texas that reported emissions during 1996–2008

maternal addresses of all cases and controls were geocoded to their exact geographic locations (latitudes and longitudes) by the Texas DSHS.

Air pollution exposure assessment

A modified version of the emission-weighted proximity model (EWPM) (Gong et al. 2016; Zou et al. 2009b) was used to estimate exposure intensities to a given TRI chemical at the location of a maternal residence for each case and control. This modified version of the EWPM model takes into account both the distances between the location of a maternal residence and industrial facilities within an effective distance as well as the rate and duration of a specific chemical released into the air by each facility annually. The formula for the EWPM model is given by Expression (1) below.

$$A^{\theta}{}_{i} = \sum_{j=1}^{m} E^{\theta}{}_{ij} \times T^{\theta}{}_{ij} \times \left(\left(k^{\theta} - D_{ij}\right)/k^{\theta}\right), \quad \text{for} \quad \left(D_{ij} \le k^{\theta}\right) \quad (1)$$

where $A^{\theta}{}_{i}$ is the estimated exposure intensity to chemical θ of a person at residence location i, represented by the quantity of chemical θ reaching location i from all emission sources ($j, j = 1, 2, \ldots \ldots, m$) within an effective distance (k^{θ}); $E^{\theta}{}_{ij}$ and $T^{\theta}{}_{ij}$ are the emission rate and duration of emission of chemical θ from emission source j that is within the effective distance (k^{θ}) of location i; D_{ij} is the distance between location i and emission source j; k^{θ} is the effective distance beyond which chemical θ is considered to have no harm on an individual (Gong et al. 2016; Zou et al. 2009b). This study used an effective distance (k^{θ}) of 10 km.

Identification of the most likely potential risk factors

This study used odds ratios (ORs) from a logistic regression to assess the associations between exposure to different TRI chemicals and LBW in offspring first, and then identified chemicals with the highest positive statistically significant ORs as the most likely risk factors associated with LBW. For each TRI chemical, cases and controls were divided into two groups: exposed (cases and controls with estimated exposure intensity value to a given chemical greater than zero) or unexposed (cases and controls with estimated exposure intensity value to a given chemical equal to zero). The binary logistic regression analysis used the unexposed group as the reference group. The logistic regression analysis was adjusted for several covariates, including child's sex, gestational weeks (37–44 weeks), maternal age (11–19, 20–24, 25–29, 30–34,

35–39, > 39 years), education (< high school, high school, > high school), race/ethnicity (non-Hispanic white, non-Hispanic black, Hispanic, other non-Hispanic), the public health service region of maternal residence (11 regions in Texas as 11 categories), and year of birth (1996–2008 as 13 categories). We selected these covariates for the analyses based on recommendations in the literature (Bell et al. 2007; Brender et al. 2014; Valero De Bernabé et al. 2004). In the next phase of the analysis, this study used values of adjusted odds ratios (aORs) to rank the TRI chemicals. Ten chemicals with the highest positive statistically significant aORs from the 449 TRI chemicals were selected for additional epidemiological analysis.

Additional epidemiological analysis

For each of the ten identified TRI chemicals, this study categorized the estimated exposure intensity values for all cases and controls into four levels: one unexposed group and three exposed groups. The cases and controls in the unexposed group were those with zero estimated exposure intensity for a given chemical. The ones with estimated exposure intensity value greater than zero were divided into three intervals in such way that each interval contained approximately the same number of controls. In epidemiology, it is common to categorize exposure levels based on the distribution of exposure levels in controls because controls are thought to most closely represent the underlying population. The four levels of exposure are called zero, low, medium, and high exposure in the rest of this article. In the next step, binary logistic regressions were used to estimate the associations (aOR and 95% confidence interval (CI)) between maternal residential exposure to these ten chemicals and LBW in offspring. The unexposed groups were considered as the reference groups in the analyses. The aORs were adjusted for the same covariates listed in the previous section. In addition, a multiple comparison correction was conducted to evaluate the results from the regression analysis.

Results

There were a total of 94,106 term LBW cases and 376,424 controls that were frequency-matched to cases by year of birth in this study. Table 2 compares the LBW cases and controls by child's sex, mother's age at delivery, mother's race/ethnicity, gestational length, year of birth, mother's education, and public health service region of maternal residence at the time of delivery. In this study population, LBW cases were more likely to be female and have shorter gestational length than controls. The mothers of the LBW cases were also more likely to be non-Hispanic black, younger at age of delivery, or less educated when compared to the control-mothers.

Estimated exposure intensities to the 449 TRI chemicals were calculated at the maternal residence location of each LBW case and control. To protect confidentiality, we use maps showing the estimated exposure densities at the locations of the centroids of census tracts, instead of maternal residential locations, to illustrate the geographic distribution of exposure intensity to a specific chemical. We used a four-step procedure to produce these maps (Fig. 2). First, centroids of the 4388 census tracts in Texas in 2000 were considered as hypothetical point receptors of air pollution exposure. Second, we used EWPM to estimate exposure intensities to a given chemical at the locations of these 4388 centroids. Third, the estimated exposure intensity at the centroid of a specific census tract was used to represent the exposure intensity of the whole census tract, assuming that the exposure distribution in the census tract is homogenous. Fourth, exposure intensities in the 4388 census tracts were categorized into seven levels (exposure intensity at zero and greater than zero divided into six equal-interval groups).

Figure 2 shows an example distribution of estimated exposure intensities to chemical 1,1,1-trichloroethane (chemical abstracts service (CAS) number 71556) among census tracts in Texas during 1996–2008. The highest exposure intensity level was observed in northeastern Texas (Dallas-Fort Worth area) in 1996. However, the exposure intensity level of this area decreased every year after 1996 and reached zero in year 2001. The southeastern Texas (Houston area) had a mid-level exposure intensity consistently during the 13 years. In 1996 and 1998, two areas in central Texas also showed mid-level exposure intensities.

Table 3 shows 78 TRI chemicals with statistically significant aORs greater than 1 when exposure intensities were dichotomized into exposed and unexposed groups. Compared with the unexposed reference groups, the LBW risks in exposed groups of the 78 chemicals increased by 2 to 60% (aOR 1.02–1.60). Then, 10 chemicals with the largest positive aORs were chosen from the 78 chemicals as the potential risk factors for LBW in additional epidemiology analysis. The ten chemicals were acetamide (aOR 1.60, 95% CI 1.09, 2.34), *p*-phenylenediamine (aOR 1.32, 95% CI 1.07,1.63), 2,2-dichloro-1,1,1-trifluoroethane (aOR 1.21, 95% CI 1.10, 1.34), 1,2-phenylenediamine (aOR 1.20, 95% CI 1.02, 1.41), resmethrin (aOR 1.14, 95% CI 1.01, 1.30), toluene-2,6-diisocyanate (aOR 1.14, 95% CI 1.02, 1.28), tributyltin methacrylate (aOR 1.14, 95% CI 1.05, 1.23), propetamphos (aOR 1.11, 95% CI 1.01, 1.23), 1,1,1-trichloroethane (aOR 1.10, 95% CI 1.05, 1.15), and creosote (aOR 1.09, 95% CI 1.02, 1.16).

Table 4 shows the results from the additional analyses of the above ten identified chemicals, where estimated exposure intensities were divided into four levels (zero, low, medium, and high exposure). Without multiple comparison correction, seven of the ten chemicals had statistically significant aORs larger than 1.0 in at least one of the three exposure levels.

Table 2 Descriptive statistics of low birth weight cases and frequency-matched controls, Texas, 1996–2008

Characteristic		Cases (n = 94,106)		Controls (n = 376,424)		Total (n = 470,530)	
		n	%	n	%	n	%
Child's sex	Male	39,787	42.3	192,170	51.1	231,957	49.3
	Female	54,319	57.7	184,254	48.9	238,573	50.7
Mother's age at delivery (years)	11–19	18,791	20.0	51,840	13.8	70,631	15.0
	20–24	28,850	30.7	104,253	27.7	133,103	28.3
	25–29	22,139	23.5	103,103	27.4	125,242	26.6
	30–34	14,898	15.8	76,662	20.4	91,560	19.5
	35–39	7470	7.9	34,021	9.0	41,491	8.8
	>39	1957	2.1	6543	1.7	8500	1.8
	Unknown	1	<0.1	2	<0.1	3	<0.1
Mother's race/ethnicity	Non-Hispanic White	27,642	29.4	142,220	37.8	169,862	36.1
	Non-Hispanic black	18,344	19.5	39,968	10.6	58,312	12.4
	Hispanic	43,366	46.1	179,051	47.6	222,417	47.3
	Others, non-Hispanic	4754	5.1	15,185	4.0	19,939	4.2
Gestational length (weeks)	37	29,089	30.9	39,432	10.5	68,521	14.6
	38	25,426	27.0	83,900	22.3	109,326	23.2
	39	18,488	19.6	107,832	28.6	126,320	26.8
	40	10,578	11.2	80,679	21.4	91,257	19.4
	41	5307	5.6	38,516	10.2	43,823	9.3
	42	2830	3.0	14,717	3.9	17,547	3.7
	43	1634	1.7	7805	2.1	9439	2.0
	44	754	0.8	3543	0.9	4297	0.9
Year of birth	1996	5739	6.1	22,956	6.1	28,695	6.1
	1997	5750	6.1	23,000	6.1	28,750	6.1
	1998	5910	6.3	23,640	6.3	29,550	6.3
	1999	5974	6.3	23,896	6.3	29,870	6.3
	2000	6333	6.7	25,332	6.7	31,665	6.7
	2001	6433	6.8	25,732	6.8	32,165	6.8
	2002	7023	7.5	28,092	7.5	35,115	7.5
	2003	7166	7.6	28,664	7.6	35,830	7.6
	2004	7535	8.0	30,140	8.0	37,675	8.0
	2005	8451	9.0	33,804	9.0	42,255	9.0
	2006	9071	9.6	36,284	9.6	45,355	9.6
	2007	9236	9.8	36,944	9.8	46,180	9.8
	2008	9485	10.1	37,940	10.1	47,425	10.1
Education	< High school	33,963	36.1	113,301	30.1	147,264	31.3
	High school	30,200	32.1	108,392	28.8	138,592	29.5
	> High school	29,082	30.9	151,886	40.3	180,968	38.5
	Unknown	861	0.9	2845	0.8	3706	0.8
Public health service region	1	3855	4.1	11,866	3.2	15,721	3.3
	2	1992	2.1	7692	2.0	9684	2.1
	3	24,253	25.8	106,683	28.3	130,936	27.8
	4	3230	3.4	11,551	3.1	14,781	3.1
	5	2561	2.7	8306	2.2	10,867	2.3
	6	23,094	24.5	93,920	25.0	117,014	24.9
	7	9236	9.8	41,031	10.9	50,267	10.7
	8	10,324	11.0	37,836	10.1	48,160	10.2
	9	2565	2.7	8306	2.2	10,871	2.3
	10	4183	4.4	14,944	4.0	19,127	4.1
	11	8813	9.4	34,289	9.1	43,102	9.2

These seven chemicals are acetamide, *p*-phenylenediamine, 2,2-dichloro-1,1,1-trifluoroethane, resmethrin, toluene-2,6-diisocyanate, tributyltin methacrylate, and 1,1,1-trichloroethane. Five chemicals survived a multiple comparisons correction using the Benjamini-Hochberg procedure with false discovery rate (FDR) at the level of 0.05. These five chemicals are acetamide, *p*-phenylenediamine, 2,2-dichloro-1,1,1-trifluoroethane, tributyltin methacrylate, and 1,1,1-trichloroethane.

The largest aOR value was noted in the case of low exposure to acetamide (aOR 2.29, 95% CI 1.24, 4.20), indicating that mothers with low exposure to acetamide had a 129% higher chance of delivering LBW babies when compared with mothers who had no exposure to air emissions of acetamide from industrial facilities. Chemical 1,1,1-trichloroethane showed statistically significant aORs among mothers within two exposure levels (low and medium). Monotonically increasing trends were noted between maternal residential

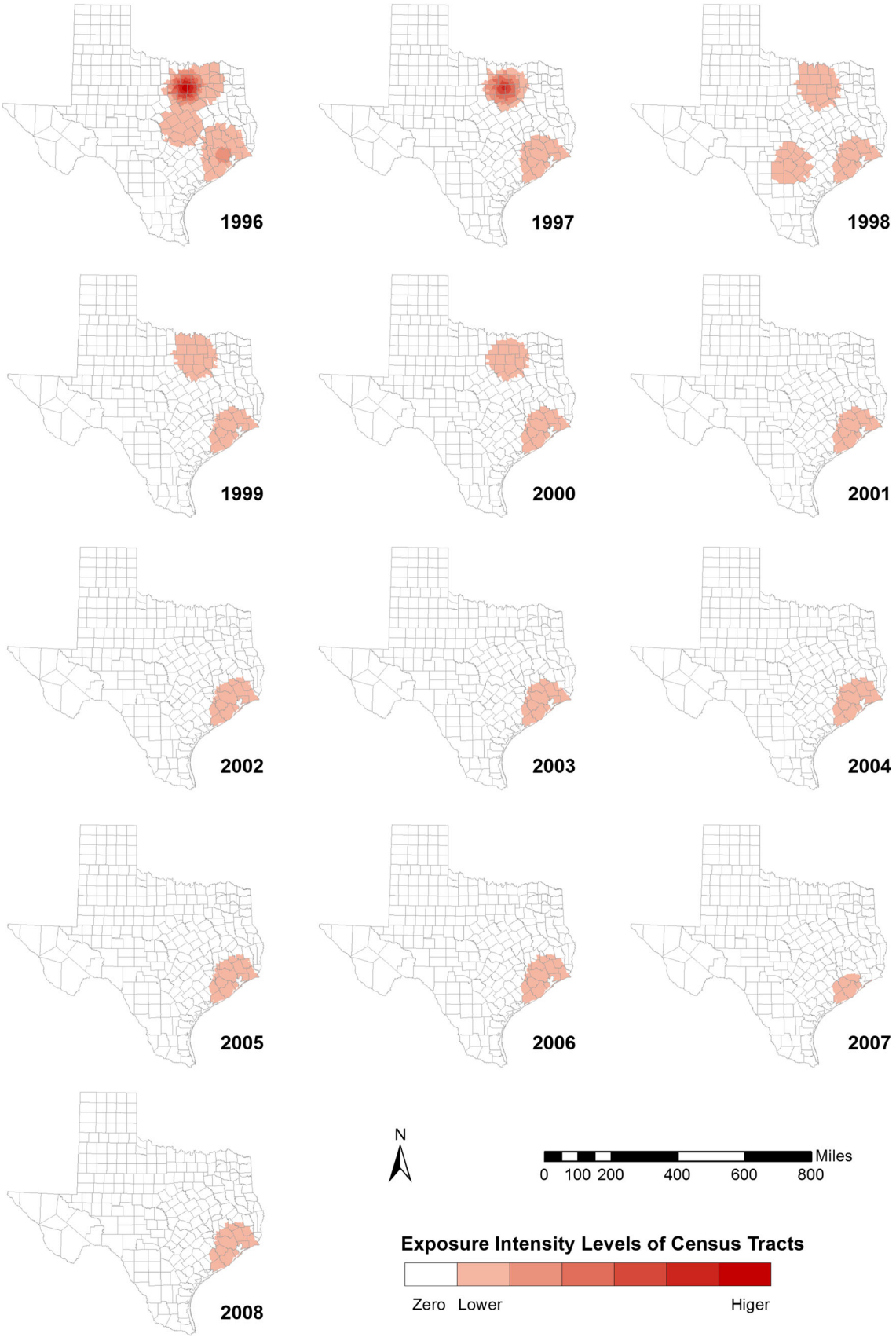

Fig. 2 Distribution of estimated 1,1,1-trichloroethane exposure intensities, Texas, 1996–2008

Table 3 Maternal exposure to selected chemicals and low birth weight in offspring, Texas, 1996–2008

Pollutant (CAS number)	Exposure intensity[a]	Cases		Controls		Adjusted OR[b] (95% CI)[c]
		n	%	*n*	%	
Acetamide (60355)	0	94,062	99.95	376,321	99.97	1.00 (Referent)
	> 0	43	0.05	101	0.03	1.60 (1.09, 2.34)
P-Phenylenediamine (106503)	0	93,958	99.84	376,064	99.90	1.00 (Referent)
	> 0	147	0.16	358	0.10	1.32 (1.07, 1.63)
2,2-Dichloro-1,1,1-trifluoroethane (306832)	0	93,456	99.31	374,733	99.55	1.00 (Referent)
	> 0	649	0.69	1689	0.45	1.21 (1.10, 1.34)
1,2-Phenylenediamine (95545)	0	93,853	99.73	375,739	99.82	1.00 (Referent)
	> 0	252	0.27	683	0.18	1.20 (1.02, 1.41)
Resmethrin (10453868)	0	93,779	99.65	375,155	99.66	1.00 (Referent)
	> 0	326	0.35	1267	0.34	1.14 (1.01, 1.30)
Toluene-2,6-diisocyanate (91087)	0	93,666	99.53	374,917	99.60	1.00 (Referent)
	> 0	439	0.47	1505	0.40	1.14 (1.02, 1.28)
Tributyltin methacrylate (2155706)	0	93,146	98.98	373,247	99.16	1.00 (Referent)
	> 0	959	1.02	3175	0.84	1.14 (1.05, 1.23)
Propetamphos (31218834)	0	93,578	99.44	374,080	99.38	1.00 (Referent)
	> 0	527	0.56	2342	0.62	1.11 (1.01, 1.23)
1,1,1-Trichloroethane (71556)	0	91,070	96.77	364,653	96.87	1.00 (Referent)
	> 0	3035	3.23	11,769	3.13	1.10 (1.05, 1.15)
Creosote (8001589)	0	92,560	98.36	371,124	98.59	1.00 (Referent)
	> 0	1545	1.64	5298	1.41	1.09 (1.02, 1.16)
Carbon disulfide (75150)	0	87,775	93.27	354,743	94.24	1.00 (Referent)
	> 0	6330	6.73	21,679	5.76	1.09 (1.05, 1.12)
Asbestos (Friable) (1332214)	0	92,719	98.53	371,799	98.77	1.00 (Referent)
	> 0	1386	1.47	4623	1.23	1.08 (1.02, 1.16)
Vanadium (except when contained in an alloy) (7440622)	0	92,110	97.88	369,205	98.08	1.00 (Referent)
	> 0	1995	2.12	7217	1.92	1.08 (1.03, 1.14)
1,4-Dioxane (123911)	0	90,411	96.07	363,170	96.48	1.00 (Referent)
	> 0	3694	3.93	13,252	3.52	1.08 (1.04, 1.13)
Mixture (mixture)	0	92,102	97.87	369,266	98.10	1.00 (Referent)
	> 0	2003	2.13	7156	1.90	1.08 (1.02, 1.14)
N-Hexane (110543)	0	56,317	59.84	236,226	62.76	1.00 (Referent)
	> 0	37,788	40.16	140,196	37.24	1.08 (1.06, 1.09)
Benzene (71432)	0	63,707	67.70	265,864	70.63	1.00 (Referent)
	> 0	30,398	32.30	110,558	29.37	1.08 (1.06, 1.09)
Sec-butyl alcohol (78922)	0	89,343	94.94	357,950	95.09	1.00 (Referent)
	> 0	4762	5.06	18,472	4.91	1.07 (1.04, 1.11)
Biphenyl (92524)	0	89,350	94.95	358,987	95.37	1.00 (Referent)
	> 0	4755	5.05	17,435	4.63	1.07 (1.04, 1.11)
Carbonyl sulfide (463581)	0	88,876	94.44	358,038	95.12	1.00 (Referent)
	> 0	5229	5.56	18,384	4.88	1.07 (1.03, 1.11)
Phenol (108952)	0	82,363	87.52	333,803	88.68	1.00 (Referent)
	> 0	11,742	12.48	42,619	11.32	1.07 (1.05, 1.10)
Zinc (fume or dust) (7440666)	0	83,591	88.83	336,610	89.42	1.00 (Referent)
	> 0	10,514	11.17	39,812	10.58	1.07 (1.04, 1.10)
Tetrachloroethylene (127184)	0	82,771	87.96	331,299	88.01	1.00 (Referent)
	> 0	11,334	12.04	45,123	11.99	1.07 (1.04, 1.10)
Phthalic anhydride (85449)	0	87,016	92.47	350,960	93.24	1.00 (Referent)
	> 0	7089	7.53	25,462	6.76	1.07 (1.04, 1.10)
Cyclohexane (110827)	0	73,182	77.77	300,903	79.94	1.00 (Referent)
	> 0	20,923	22.23	75,519	20.06	1.07 (1.05, 1.09)
Ethylene (74851)	0	84,205	89.48	341,216	90.65	1.00 (Referent)
	> 0	9900	10.52	35,206	9.35	1.07 (1.04, 1.10)
Methyl *tert*-butyl ether (1634044)	0	74,238	78.89	303,602	80.65	1.00 (Referent)
	> 0	19,867	21.11	72,820	19.35	1.07 (1.05, 1.09)
Chromium (7440473)	0	73,593	78.20	298,570	79.32	1.00 (Referent)
	> 0	20,512	21.80	77,852	20.68	1.07 (1.05, 1.09)
Propylene (115071)	0	82,796	87.98	336,664	89.44	1.00 (Referent)
	> 0	11,309	12.02	39,758	10.56	1.07 (1.04, 1.09)
Polycyclic aromatic compounds (N590)	0	70,007	74.39	287,925	76.49	1.00 (Referent)
	> 0	24,098	25.61	88,497	23.51	1.06 (1.04, 1.08)
Toluene (108883)	0	43,059	45.76	181,344	48.18	1.00 (Referent)
	> 0	51,046	54.24	195,078	51.82	1.06 (1.05, 1.08)
N-butyl alcohol (71363)	0	61,571	65.43	252,392	67.05	1.00 (Referent)

Table 3 (continued)

Pollutant (CAS number)	Exposure intensity[a]	Cases		Controls		Adjusted OR[b] (95% CI)[c]
		n	%	*n*	%	
	> 0	32,534	34.57	124,030	32.95	1.06 (1.04, 1.08)
O-xylene (95476)	0	87,570	93.06	351,576	93.40	1.00 (Referent)
	> 0	6535	6.94	24,846	6.60	1.06 (1.03, 1.10)
Chlorine (7782505)	0	81,320	86.41	329,427	87.52	1.00 (Referent)
	> 0	12,785	13.59	46,995	12.48	1.06 (1.04, 1.09)
Styrene (100425)	0	49,818	52.94	207,156	55.03	1.00 (Referent)
	> 0	44,287	47.06	169,266	44.97	1.06 (1.04, 1.08)
Barium (7440393)	0	91,861	97.62	368,601	97.92	1.00 (Referent)
	> 0	2244	2.38	7821	2.08	1.06 (1.01, 1.12)
1,2,4-Trimethylbenzene (95636)	0	55,915	59.42	233,482	62.03	1.00 (Referent)
	> 0	38,190	40.58	142,940	37.97	1.06 (1.04, 1.08)
Hydrogen cyanide (74908)	0	89,882	95.51	360,972	95.90	1.00 (Referent)
	> 0	4223	4.49	15,450	4.10	1.06 (1.02, 1.10)
Nickel (7440020)	0	72,425	76.96	293,476	77.96	1.00 (Referent)
	> 0	21,680	23.04	82,946	22.04	1.06 (1.04, 1.08)
Ethylbenzene (100414)	0	53,782	57.15	224,116	59.54	1.00 (Referent)
	> 0	40,323	42.85	152,306	40.46	1.06 (1.04, 1.08)
Methyl isobutyl ketone (108101)	0	67,392	71.61	272,718	72.45	1.00 (Referent)
	> 0	26,713	28.39	103,704	27.55	1.06 (1.04, 1.08)
Naphthalene (91203)	0	63,897	67.90	264,855	70.36	1.00 (Referent)
	> 0	30,208	32.10	111,567	29.64	1.06 (1.04, 1.08)
Methyl ethyl ketone (78933)	0	71,908	76.41	290,050	77.05	1.00 (Referent)
	> 0	22,197	23.59	86,372	22.95	1.06 (1.03, 1.08)
Cobalt (7440484)	0	87,674	93.17	351,060	93.26	1.00 (Referent)
	> 0	6431	6.83	25,362	6.74	1.06 (1.02, 1.09)
Diisocyanates (N120)	0	79,385	84.36	318,964	84.74	1.00 (Referent)
	> 0	14,720	15.64	57,458	15.26	1.05 (1.03, 1.08)
Xylene (mixed isomers) (1330207)	0	39,953	42.46	167,276	44.44	1.00 (Referent)
	> 0	54,152	57.54	209,146	55.56	1.05 (1.04, 1.07)
Manganese (7439965)	0	82,118	87.26	330,175	87.71	1.00 (Referent)
	> 0	11,987	12.74	46,247	12.29	1.05 (1.03, 1.08)
Chromium compounds (except chromite ore mined in the Transvaal region) (N090)	0	71,478	75.96	291,475	77.43	1.00 (Referent)
	> 0	22,627	24.04	84,947	22.57	1.05 (1.03, 1.07)
Carbon tetrachloride (56235)	0	91,596	97.33	366,841	97.45	1.00 (Referent)
	> 0	2509	2.67	9581	2.55	1.05 (1.00, 1.10)
Benzo (*g,h,i*) perylene (191242)	0	81,549	86.66	330,263	87.74	1.00 (Referent)
	> 0	12,556	13.34	46,159	12.26	1.05 (1.03, 1.08)
M-xylene (108383)	0	86,863	92.30	348,651	92.62	1.00 (Referent)
	> 0	7242	7.70	27,771	7.38	1.05 (1.02, 1.08)
Dicyclopentadiene (77736)	0	88,089	93.61	354,556	94.19	1.00 (Referent)
	> 0	6016	6.39	21,866	5.81	1.05 (1.02, 1.09)
Dichloromethane (75092)	0	77,881	82.76	312,778	83.09	1.00 (Referent)
	> 0	16,224	17.24	63,644	16.91	1.05 (1.03, 1.07)
Mercury (7439976)	0	88,029	93.54	354,603	94.20	1.00 (Referent)
	> 0	6076	6.46	21,819	5.80	1.05 (1.02, 1.08)
Cumene (98828)	0	76,251	81.03	309,285	82.16	1.00 (Referent)
	> 0	17,854	18.97	67,137	17.84	1.05 (1.03, 1.07)
Zinc compounds (N982)	0	58,445	62.11	236,635	62.86	1.00 (Referent)
	> 0	35,660	37.89	139,787	37.14	1.05 (1.03, 1.07)
P-xylene (106423)	0	88,534	94.08	355,325	94.40	1.00 (Referent)
	> 0	5571	5.92	21,097	5.60	1.05 (1.01, 1.08)
Copper (7440508)	0	75,134	79.84	302,226	80.29	1.00 (Referent)
	> 0	18,971	20.16	74,196	19.71	1.05 (1.03, 1.07)
Methanol (67561)	0	60,497	64.29	247,135	65.65	1.00 (Referent)
	> 0	33,608	35.71	129,287	34.35	1.05 (1.03, 1.07)
Toluene diisocyanate (mixed isomers) (26471625)	0	88,676	94.23	355,332	94.40	1.00 (Referent)
	> 0	5429	5.77	21,090	5.60	1.04 (1.01, 1.08)
Acetonitrile (75058)	0	90,395	96.06	362,306	96.25	1.00 (Referent)
	> 0	3710	3.94	14,116	3.75	1.04 (1.00, 1.09)
Ethylene glycol (107211)	0	65,540	69.65	265,824	70.62	1.00 (Referent)
	> 0	28,565	30.35	110,598	29.38	1.04 (1.02, 1.06)
Methyl acrylate (96333)	0	89,510	95.12	358,117	95.14	1.00 (Referent)
	> 0	4595	4.88	18,305	4.86	1.04 (1.01, 1.08)

Table 3 (continued)

Pollutant (CAS number)	Exposure intensity[a]	Cases		Controls		Adjusted OR[b] (95% CI)[c]
		n	%	*n*	%	
Butyl acrylate (141322)	0	84,248	89.53	337,025	89.53	1.00 (Referent)
	> 0	9857	10.47	39,397	10.47	1.04 (1.02, 1.07)
Formaldehyde (50000)	0	77,921	82.80	314,531	83.56	1.00 (Referent)
	> 0	16,184	17.20	61,891	16.44	1.04 (1.02, 1.06)
Tert-butyl alcohol (75650)	0	87,708	93.20	352,663	93.69	1.00 (Referent)
	> 0	6397	6.80	23,759	6.31	1.04 (1.01, 1.07)
Lead (7439921)	0	59,037	62.74	237,194	63.01	1.00 (Referent)
	> 0	35,068	37.26	139,228	36.99	1.04 (1.02, 1.06)
Certain glycol ethers (N230)	0	55,200	58.66	223,084	59.26	1.00 (Referent)
	> 0	38,905	41.34	153,338	40.74	1.04 (1.02, 1.06)
Diethanolamine (111422)	0	83,874	89.13	339,011	90.06	1.00 (Referent)
	> 0	10,231	10.87	37,411	9.94	1.04 (1.01, 1.06)
1,3-Butadiene (106990)	0	83,291	88.51	337,164	89.57	1.00 (Referent)
	> 0	10,814	11.49	39,258	10.43	1.04 (1.01, 1.06)
Acrylonitrile (107131)	0	87,189	92.65	349,410	92.82	1.00 (Referent)
	> 0	6916	7.35	27,012	7.18	1.03 (1.00, 1.06)
Copper compounds (N100)	0	79,028	83.98	319,653	84.92	1.00 (Referent)
	> 0	15,077	16.02	56,769	15.08	1.03 (1.01, 1.05)
Methyl methacrylate (80626)	0	83,114	88.32	332,518	88.34	1.00 (Referent)
	> 0	10,991	11.68	43,904	11.66	1.03 (1.00, 1.06)
Antimony compounds (N010)	0	85,086	90.42	339,902	90.30	1.00 (Referent)
	> 0	9019	9.58	36,520	9.70	1.03 (1.00, 1.06)
Nickel compounds (N495)	0	82,042	87.18	331,040	87.94	1.00 (Referent)
	> 0	12,063	12.82	45,382	12.06	1.03 (1.00, 1.05)
Vinyl acetate (108054)	0	82,474	87.64	331,318	88.02	1.00 (Referent)
	> 0	11,631	12.36	45,104	11.98	1.03 (1.00, 1.05)
Lead compounds (N420)	0	63,217	67.18	253,655	67.39	1.00 (Referent)
	> 0	30,888	32.82	122,767	32.61	1.03 (1.01, 1.04)
Ammonia (7664417)	0	59,005	62.70	238,116	63.26	1.00 (Referent)
	> 0	35,100	37.30	138,306	36.74	1.02 (1.01, 1.04)

[a] Exposure intensity value based on maternal residential proximity to source (s) of air emissions and estimated pounds of chemical emitted annually

[b] Adjusted for birth year, public health region, child's sex, maternal race/ethnicity, age, education, and gestational length

[c] Sorted by descending adjusted odds ratios

exposure to tributyltin methacrylate and LBW in offspring (highest aOR in high exposure: 1.20, 95% CI 1.06, 1.36). Statistically significant association was also observed in medium exposure to *p*-phenylenediamine and 2,2-dichloro-1,1,1-trifluoroethane (Table 4).

Discussions

Adverse health outcomes of exposure to the ten chemicals in Table 4 (acetamide, *p*-phenylenediamine, 2,2-dichloro-1,1,1-trifluoroethane, 1,2-phenylenediamine, resmethrin, toluene 2,6-diisocyanate, tributyltin methacrylate, propetamphos, 1,1,1-trichloroethane, and creosote) have been documented in various studies reported in the literature. Inhalation of tributyltin methacrylate and propetamphos might cause serve injury or death (U.S. NOAA 2016). Short-term exposure to the other eight chemicals might cause irritation to the eyes, skin, mucous membranes, and respiratory tract, while long-term exposure to these chemicals was reported to yield other adverse health effects, including skin sensitization, asthma, narcosis, cardiac disorders, anemia, dermatitis, and hyperpigmentation of skin (U.S. CDC 2015). Long-term exposure to *p*-phenylenediamine and 2,2-dichloro-1,1,1-trifluoroethane might also have effects on kidney and liver respectively (U.S. CDC 2015). Chemical 1,1,1-trichloroethane, also known as methyl chloroform, was reported to be associated with neural tube defects in a study conducted in Texas investigating the associations between chlorinated solvent exposures and birth defect in offspring (Brender et al. 2014). However, no study has examined the associations between maternal residential exposure to these chemicals and LBW in offspring. The identified association between LBW and the five TRI chemicals in this study created new opportunities for further epidemiological, biological, and toxicological research. It is important to note that some other significant pollutants from this exploratory analysis might also be important risk factors for LBW, despite that they did not survive multiple testing correction reported in this paper.

Table 4 Maternal exposure to different levels (low, medium, and high) of intensities to selected chemicals (with top ten aORs in Table 3) and low birth weight in offspring, Texas, 1996–2008

Pollutant (CAS number)	Exposure intensity[a]	Cases		Controls		Adjusted OR[b] (95% CI)
		n	%	*n*	%	
Acetamide (60355)	0	94,062	99.95	376,321	99.97	1.00 (Referent)
	0.01–18.74	19	0.02	34	0.01	2.29 (1.24, 4.20)*
	18.75–83.10	16	0.02	33	0.01	1.44 (0.76, 2.71)
	> 83.10	8	0.01	34	0.01	1.09 (0.49, 2.42)
P-phenylenediamine (106503)	0	93,958	99.84	376,064	99.90	1.00 (Referent)
	0.01–0.31	39	0.04	119	0.03	1.25 (0.85, 1.84)
	0.32–0.58	69	0.07	120	0.03	1.63 (1.18, 2.25)*
	> 0.58	39	0.04	119	0.03	1.06 (0.72, 1.56)
2,2-Dichloro-1,1,1-trifluoroethane (306832)	0	93,456	99.31	374,733	99.55	1.00 (Referent)
	0.01–32.98	193	0.21	563	0.15	1.11 (0.94, 1.33)
	32.99–83.01	237	0.25	563	0.15	1.41 (1.20, 1.66)*
	> 83.01	219	0.23	563	0.15	1.13 (0.95, 1.33)
1,2-Phenylenediamine (95545)	0	93,853	99.73	375,739	99.82	1.00 (Referent)
	0.01–0.80	87	0.09	228	0.06	1.17 (0.90, 1.53)
	0.81–2.24	101	0.11	227	0.06	1.29 (1.00, 1.66)
	>2.24	64	0.07	228	0.06	1.14 (0.85, 1.53)
Resmethrin (10453868)	0	93,779	99.65	375,155	99.66	1.00 (Referent)
	0.01–0.01	106	0.11	422	0.11	1.06 (0.84, 1.33)
	0.02–0.02	108	0.11	423	0.11	1.13 (0.90, 1.41)
	> 0.02	112	0.12	422	0.11	1.25 (1.01, 1.56)
Toluene-2,6-diisocyanate (91087)	0	93,666	99.53	374,917	99.60	1.00 (Referent)
	0.01–1.18	105	0.11	501	0.13	0.98 (0.78, 1.22)
	1.19–7.07	141	0.15	503	0.13	1.17 (0.96, 1.43)
	> 7.07	193	0.21	501	0.13	1.25 (1.05, 1.50)
Tributyltin methacrylate (2155706)	0	93,146	98.98	373,247	99.16	1.00 (Referent)
	0.01–0.90	276	0.29	1057	0.28	1.07 (0.93, 1.23)
	0.91–1.84	306	0.33	1065	0.28	1.13 (0.99, 1.29)
	> 1.84	377	0.40	1053	0.28	1.20 (1.06, 1.36)*
Propetamphos (31218834)	0	93,578	99.44	374,080	99.38	1.00 (Referent)
	0.01–1.05	162	0.17	780	0.21	1.06 (0.88, 1.26)
	1.06–2.11	178	0.19	782	0.21	1.14 (0.96, 1.35)
	> 2.11	187	0.20	780	0.21	1.15 (0.97, 1.36)
1,1,1-Trichloroethane (71556)	0	91,070	96.77	364,653	96.87	1.00 (Referent)
	0.01–43.80	1021	1.08	3919	1.04	1.11 (1.03, 1.20)*
	43.81–530.15	1009	1.07	3931	1.04	1.10 (1.03, 1.19)*
	> 530.15	1005	1.07	3919	1.04	1.09 (1.01, 1.17)
Creosote (8001589)	0	92,560	98.36	371,124	98.59	1.00 (Referent)
	0.01–0.18	500	0.53	1764	0.47	1.07 (0.96, 1.19)
	0.19–0.64	509	0.54	1770	0.47	1.10 (0.99, 1.22)
	> 0.64	536	0.57	1764	0.47	1.10 (0.99, 1.22)

*Statistically significant after multiple comparisons correction using the Benjamini-Hochberg procedure with FDR at level 0.05

[a] Exposure intensity value based on maternal residential proximity to source (s) of air emissions and estimated pounds of chemical emitted annually

[b] Adjusted for birth year, public health region, child's sex, maternal race/ethnicity, age, education level, and gestational length

As shown in Table 4, with the increase of maternal residential exposure intensities to acetamide, *p*-phenylenediamine, 2,2-dichloro-1,1,1-trifluoroethane, and 1,1,1-trichloroethane, the risk of having LBW newborns did not necessarily increase

monotonically in that the highest aORs were not noted in mothers who were categorized in the level of high exposure. Brender et al. (2014) also found similar trends in their studies examining associations between maternal chlorinated solvent exposures and birth defect in Texas. The non-monotonic trends may be due to the fact that data used in this study contained live births only. One possible explanation is that higher maternal residential exposure intensities to certain chemicals could have severely affected weight gain in the fetus during some pregnancies and resulted in induced terminations or fetal deaths. However, data about these pregnancies were not available in the present study. Therefore, the groups categorized as high exposure in this study might have odds ratios biased toward null.

The emission-weighted proximity model (EWPM) was used in this study to estimate maternal residential exposure to the TRI chemicals during pregnancy. Compared to other exposure assessment methods, the EWPM is simpler to implement and more cost-effective when many air pollutants are considered (Gong et al. 2016). Different types and magnitudes of exposure misclassifications are expected in different exposure assessment models, the EWPM might also introduce some degree of exposure misclassifications (Zou et al. 2009a). To assess the performance of EWPM in estimating exposure intensities, a study was conducted to examine how the EWPM estimated exposure intensities correlated with air monitoring data of 27 non-criteria air pollutants at 48 monitoring sites in Texas in 2005 (Gong et al. 2016). The study concluded that the EWPM is a valid and useful approach for exposure assessment when analyses involve data covering a large geographic area over multiple years (Gong et al. 2016). This study used a consistent effective distance (k^{θ} = 10 km) for all chemicals, meaning exposure to a given chemical was only considered to be affected by sources within 10 km from the location of interest. However, the best effective distance (k^{θ}) for each chemical may be related to chemical properties, meteorological conditions, and terrain surrounding the location of interest. Therefore, future studies should consider finding the best effective distance for a specific chemical before using the EWPM model in order to improve the accuracy of the estimated exposure.

Air emission data used in this study had several limitations. First, because only annual-level TRI air emission data were available, this study could only estimate annual exposure to the TRI chemicals. It was not possible to estimated exposure variations at finer temporal scales to reflect daily, monthly, and seasonal variations. Second, industrial facilities self-reported their annual air emission quantities to the TRI program, which may lead to some uncertainties in the data. Third, only industrial air emissions from point sources (stacks of TRI industrial facilities) were used for exposure assessment in this study, future studies should consider integrating more emission source types (linear, areal, and mobile sources) for more accurate measures. Fourth, based on the observation that a small portion of the study population resided in areas near the Texas state boundaries to other states or Mexico (8.92% (n = 41,957) within 10 km of the border, and 6.67% (n = 31,392) within 10–50 km of the border), we performed analyses to examine how the removal of the cases and controls within 10 km of the Texas state boundaries may affect the results. Among the five significant chemicals reported in Table 4, only acetamide did not survive the multiple comparison correction after those cases and controls were removed. The results are summarized in a table in the supplementary materials (Table S-1). The results suggest that the "edge effect" of geographic boundaries does affect the results to some degree, and it should be considered when interpreting the results of the type of analysis similar to the ones reported in this article.

Maternal residential addresses at delivery were used in this study to estimate exposure during pregnancy, assuming that each maternal residence was the same from conception to delivery. Therefore, exposure misclassifications might exist if there were maternal residential movements during pregnancy in the study population (Canfield et al. 2006; Lupo et al. 2010). To overcome this limitation, data with maternal residential history are needed to more accurately estimate and categorize exposure. For a large-scale study based on birth registry data such as the one reported in this paper, data with detailed residential history were simply not available. It is worth noting that the impact might be limited because the change of residences during pregnancy tends to involve only short distances in most cases (Lupo et al. 2010). In addition, there has been a number of studies suggesting an association between maternal food restriction (MFR) with reduced birth weight (Godfrey et al. 1996). It would be ideal to include data about MFR into the analyses of this study, but again data about MFR were simply not available for this large-scale study. We used maternal education level as a covariate in the analysis. Because education level is a good indicator for socioeconomic status, we hope this covariate will partly take care of this limitation.

Conclusion

This large population-based, case-control study examined whether maternal residential proximity to some of the 449 TRI air pollutants could be potential risk factors associated with LBW in offspring. This number of 449 chemicals far exceeded the number of non-criteria air pollutants examined by studies reported in the literature. Maternal residential exposure to the TRI chemicals during pregnancy was estimated using the EWPM model. The model takes into account reported quantities of annual air emission from industrial facilities and the distances between the locations of industrial facilities

and maternal residence locations. This study concluded that maternal residential proximity to industrial air emissions of some TRI chemicals during pregnancy may be associated with LBW in offspring. These chemicals included acetamide, *p*-phenylenediamine, 2,2-dichloro-1,1,1-trifluoroethane, tributyltin methacrylate, and 1,1,1-trichloroethane. For most of these five pollutants, the exposure-response function does not seem to be monotonically increasing when the estimated exposure is categorized into low, medium, and high levels.

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Compliance with ethical standards

Competing interest The authors declare that they have no competing interest.

Abbreviations AAP, ambient air pollution; aOR, adjusted odds ratio; CAP, criteria air pollutant; CDC, Centers for Disease Control and Prevention; CI, confidence interval; DSHS, Texas Department of State Health Services; EWPM, emission weighted proximity model; LBW, low birth weight; NOAA, National Oceanic and Atmospheric Administration; OR, odds ratio; TRI, toxic release inventory; U.S. EPA, United States Environmental Protection Agency

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