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Maternal exposure to neighborhood soil Pb and eclampsia risk in new Orleans, Louisiana (USA): Evidence from a natural experiment in flooding

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ABSTRACT

Background: Previous studies link maternal blood lead (Pb) levels and pregnancy-related hypertensive disorders.
Objective: Assess the relationship between neighborhood soil Pb and maternal eclampsia risk.
Methods: Zip code summarized high density soil survey data of New Orleans collected before and after Hurricanes Katrina and Rita (HKR) were merged with pregnancy outcome data on 75,501 mothers from the Louisiana office of public health. Cross-sectional logistic regression analyses are performed testing the association between pre-HKR accumulation of Pb in soils in thirty-two neighborhoods and eclampsia risk. Then we examine whether measured declines in soil Pb following the flooding of the city resulted in corresponding reductions of eclampsia risk.
Results: Cross-sectional analyses show that a one standard deviation increase in soil Pb increases the odds of eclampsia by a factor of 1.48 (95% CI: 1.31, 1.66). Mothers in zip code areas with soil Pb > 333 mg/kg were 4.00 (95% CI: 3.00, 5.35) times more likely to experience eclampsia than mothers residing in neighborhoods with soil Pb < 50 mg/kg. Difference-in-differences analyses capturing the exogenous reduction in soil Pb following the 2005 flooding of New Orleans indicate that mothers residing in zip codes experiencing decrease in soil Pb (−387.9 to −33.6 mg/kg) experienced a significant decline in eclampsia risk (OR=0.619; 95% CI: 0.397, 0.963).
Conclusions: Mothers residing in neighborhoods with high accumulation of Pb in soils are at heightened risk of experiencing eclampsia.

1. Introduction

In this paper we investigate the association between soil Pb exposure and risk of eclampsia in New Orleans.[1] Many epidemiologic studies show that pregnancy-induced hypertensive disorders (chronic and gestational hypertension, preeclampsia, and eclampsia) increase significantly with maternal exposure to Pb (Chen et al., 2006; Dawson et al., 2000; Motawei et al., 2013; Rothenberg et al., 2002; Sowers et al., 2002; Troesken 2006; Yazbeck et al., 2009). The pathogenesis of Pb-induced hypertensive disorders remains uncertain, but the modulation of several vasoactive, volume-regulatory and cell-signaling systems are implicated (Vaziri and Sica 2004).

The flow of Pb into urban environments decreased significantly with the elimination of Pb in paint and gasoline. With the exception of the deposition of leaded aviation gasoline from piston-engine aircraft and emissions from toxic release inventory facilities, contemporary exposure risk is from legacy uses of the pollutant. The stock of historic Pb use is reflected in urban soils. Urban soils are repositories of prior period Pb use, collecting dust sources of Pb from haphazardly removed lead-based paint (Farfel

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[1] Suspicion of a link between eclampsia and Pb exposure dates to Norman Porritt's (1934) The Menace and Geography of Eclampsia in England and Wales. Porritt found that eclampsia mortality rates were ~10 times higher in towns with high lead water content versus towns with low lead water content. According to Troesken (2006: 396), lead levels in the tap water of towns in northern England and Wales examined by Porritt eclipsed the modern EPA standard (0.015 ppm) by factors of 95 to 467.

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et al., 2003; Farfel et al., 2005; Rabito et al., 2007), and the sum of fuel and point-source industrial Pb emissions from the past (Mielke and Reagan 1998; Mielke 1999; Mielke et al., 2005; Mielke et al., 2007; Mielke et al., 2011). Soil Pb is an analytically useful spatial indictor of cumulative Pb use and deposition (Mielke et al., 1999; Zahran et al., 2013b).

Moreover, Pb at or near the surface of soils is a contemporary exposure risk to humans through direct contact or inhalation of re-suspended dust (Filippelli et al., 2005; Laidlaw et al., 2005; Laidlaw et al., 2012; Zahran et al., 2013a). With respect to the soil Pb re-suspension pathway, research shows that blood Pb levels in children oscillate seasonally with measured levels of soil particles in the atmosphere (Zahran et al., 2013a). Also, the uneven deposition of Pb across neighborhood soils in various cities predicts children's health outcomes (Johnson and Bretsch, 2002; Laidlaw et al., 2005; Mielke et al., 1989; Zahran et al., 2011; Zahran et al. 2013b). In New Orleans, for instance, neighborhoods with high levels of Pb accumulated in surface soils are home to large fractions of children with elevated blood Pb levels (Mielke et al., 2007; Mielke et al., 2013; Zahran et al. 2011). Evidence of the association between blood Pb and soil Pb suggests that soil Pb is both a repository of prior period Pb use and a medium of contemporary exposure.

By extension, we explore whether the non-random accumulation of Pb in neighborhood soils also predicts eclampsia risk, a hypertensive disorder linked to Pb exposure in medical studies. To test the association between soil Pb and eclampsia, we merge zip code summarized high density soil surveys of New Orleans, conducted before and after Hurricanes Katrina and Rita (HKR), with pregnancy outcome data on 75,501 mothers with residential zip code information from the Louisiana office of public health. Analytically, exploiting spatial variation in soil Pb quantities throughout New Orleans, we begin with cross-sectional regressions analyzing whether the odds of eclampsia increase with measured levels of pre-HKR soil Pb across thirty-two zip code areas. Insofar as eclampsia is associated with Pb exposure risk, our expectation is that the odds of maternal eclampsia ought to increase dose-responsively in neighborhood soil Pb.

Before HKR, neighborhood soils in New Orleans were known to carry large concentrations of Pb, with five of the 22 zip code areas surveyed in both periods having median soil Pb levels $\geq$ 400 mg/kg. After HKR, only one of the 22 zip code areas observed in both periods had a median soil Pb level $\geq$ 400 mg/kg.[2] The catastrophic failure of the levee system and inundation of New Orleans with cleaner sediment from the Mississippi river accounts for measured declines in soil Pb levels (Zahran et al., 2010a). The exogenous decline in soil Pb presents an additional opportunity to test the association of eclampsia risk and soil Pb exposure. In the second section of our analysis, we examine whether measured changes in soil Pb in New Orleans resulted in corresponding changes in eclampsia risk for mothers. If eclampsia risk is dose-responsive in soil Pb exposure risk, then we expect the odds of eclampsia to co-vary with soil Pb change.

2. Methods and materials

The dataset includes: 1) pregnancy outcome, health, and demographic data on 75,501 mothers with residential zip code information from the Louisiana office of Public Health, state center for health statistics; and 2) zip code summarized soil Pb data from the New Orleans Soil Pb Survey II and III (Mielke et al., 2005; Zahran et al., 2010a).

2.1. Natality birth data

Natality birth data are from the Louisiana's office of Public Health, state center for health statistics from January 1, 1999 to December 31, 2009. Each fertility record contains information on maternal health behaviors, demographic characteristics, and medical outcomes, as well as information on the zip code tabulation area of maternal residence during pregnancy that was used to match zip code summarized soil Pb data.

Our response variable, eclampsia,[3] is measured as a binary outcome (1= condition present; 0=condition not present). In data documentation, eclampsia is defined as “the occurrence of convulsion and/or coma unrelated to other cerebral conditions in women with signs and symptoms of pre-eclampsia.” Seizures may occur antepartum, intrapartum, or post-partum, with proximate mechanisms involving cerebral edema, ischemia, hemorrhage, or transient vasospasm (Longo et al., 2003). Four maternal conditions known to influence eclampsia are controlled for in statistical models including diabetes, chronic hypertension, pregnancy-related hypertension, and cardiac disease (Longo et al., 2003). Each maternal condition is coded as 1 if the condition is present and 0 otherwise.[4]

Two gestational variables are analyzed: maternal weight gain (in pounds) and gestational length (in weeks). Eclampsia typically occurs in the third trimester of a pregnancy. Four other known risk factors of eclampsia (Coghill et al., 2011) are assessed: maternal race, maternal age, maternal education, and tobacco use. Maternal race/ethnicity is coded in three categories: non-hispanic white, non-hispanic black, and other race (reference category). Consistent with prior research on eclampsia risk, maternal age is divided into two categories (1= < 20 years of age; 0= $\geq$ 20 years of age). Maternal education is measured by four categories: less than high school (11 years of reported education or less), high school (12 years of education), some college (13–15 years of education), and college educated (16 years of education or more). Mother's with < high school education constitute our reference group. Tobacco use is coded as 1 if a mother smoked during pregnancy and 0 if not.

2.2. Soil Pb data

Pre-HKR soil data are from the New Orleans Soil Lead Survey II completed in 2000 (Mielke et al., 2005). The post- HKR soil data are from the New Orleans Soil Lead Survey III, completed in 2006 (Zahran et al., 2010a). Samples were collected from the top 2.5 cm surface of residential soils in metropolitan New Orleans. The extraction procedure involved room temperature leachate using 1 M nitric acid (HNO_3), a scheme that correlates with total methods. The extraction procedure more closely resembles physiological conditions compared with extraction methods based on high temperatures and concentrated HNO_3. The soil collection methodology and extraction protocol was identical for survey II and survey III, requiring the mixing 0.4 g of dry and sieved (#10USGS-2 mm) soils with 1 M HNO_3, and agitated at slow speed on an Eberbach shaker for two hours at room temperature (~22 °C). The extract was then centrifuged (10 min at 1600 × g) and filtered using Fisherbrand® P4 paper. The extract was stored in 20 mL of polypropylene scintillation vials until analyzed. A Spectro ® Analytical Instruments CIROS CCD Inductively Coupled Plasma Atomic Emission Spectrometer (ICP-AES) was used to analyze multiple metal contents in each soil sample (Mielke et al., 2005). The ICP-AES was calibrated with NIST traceable standards, and a laboratory reference (at a rate of 1 per 15 samples) was analyzed during each run. Internal laboratory references included one low soil Pb sample from New Orleans city park and one high soil Pb sample from the junction of Elysian fields and interstate 10 in the inner city of New Orleans. Duplicate extractions were included at the rate of one per 15 samples. A total of 6341 soil samples were analyzed for Pb content, distributed over the pre- and post-HKR periods and matched to zip code areas in metropolitan New Orleans. Descriptive statistics on soil Pb by zip code area before and after HKR are presented in Table 1. In analyses that follow, maternal exposure risk to soil Pb is operationalized as the median Pb content of sampled soils in the zip code area of maternal residence.

[2] The same decline in neighborhood soil Pb is observed at finer scales. In 29 of 46 census tract examined in both periods, we observed significant decline in median soil Pb after HKR. In the post-HKR period, only 6 of 46 census tracts had soil Pb levels exceeding the EPA regulatory standard of 400 mg/kg, as compared to15 of 46 neighborhoods eclipsing 400 mg/kg in the pre-HKR period (Zahran et al. 2010a).

[3] Natality data provided by the Louisiana's office of Public Health do not distinguish between eclampsia and pre-eclampsia.

[4] While chronic hypertension (HTN), pregnancy-related hypertension, and cardiovascular disease (Longo et al. 2003) are risk factors for eclampsia, these conditions have been independently linked to lead exposure suggesting that such conditions may be on the causal pathway of lead exposure to eclampsia. Previous research suggests that chronic and pregnancy-related HTN are unique entities (Lindheimer and Katz 1985), that pregnancy-related HTN and pre-eclampsia are distinct entities rather than two points along a continuum (Lindheimer and Katz 1985), and that eclampsia and HTN are separate diseases affecting similar organs (Villar et al. 2006). Regression models with and without adjustments for HTN and cardiovascular disease behave nearly identically, and are available from the first author on request.

Table 1
Descriptive statistics on soil Pb (in mg/kg units) by zip code tabulation area, before and after Hurricanes Katrina and Rita.

Zip code	Before Hurricanes Katrina and Rita					After Hurricanes Katrina and Rita				
	$P_{.10}$	$P_{.25}$	$P_{.50}$	$P_{.75}$	$P_{.90}$	$P_{.10}$	$P_{.25}$	$P_{.50}$	$P_{.75}$	$P_{.90}$
70001	14.3	28.8	61.8	141.6	283.6	13.2	20.2	49.6	170.0	229.8
70002	7.9	17.0	39.1	93.8	160.9	*	*	*	*	*
70003	5.2	8.3	20.9	57.1	99.5	9.5	13.6	35.3	91.5	121.5
70005	9.2	20.4	53.5	102.6	171.3	47.4	61.9	77.9	99.9	143.0
70006	8.6	14.5	37.8	73.3	128.1	16.9	23.6	47.2	79.9	101.8
70032	37.3	63.4	120.6	206.5	440.3	*	*	*	*	*
70043	10.7	17.2	46.2	102.1	181.3	28.9	39.0	78.8	135.9	177.6
70053	10.7	28.8	95.7	225.3	444.2	*	*	*	*	*
70056	7.0	14.1	33.9	60.0	132.3	5.5	8.6	22.1	50.2	242.7
70058	22.0	34.6	57.6	133.0	281.9	*	*	*	*	*
70062	9.4	21.9	40.8	81.6	166.8	5.6	13.8	35.2	81.5	159.7
70065	6.8	10.3	17.9	41.5	79.6	15.2	23.7	34.7	46.2	78.9
70072	13.9	28.5	59.0	104.4	288.6	*	*	*	*	*
70094	10.3	20.4	48.1	109.1	170.9	11.8	16.8	49.8	64.6	98.2
70112	55.2	132.6	199.5	349.7	916.0	40.9	61.0	98.9	321.3	610.0
70113	84.4	301.3	778.0	1967.0	3269.0	111.2	209.3	390.1	580.0	1044.0
70114	17.0	36.2	94.6	348.0	835.0	26.5	44.4	91.7	249.3	702.0
70115	54.6	201.9	449.9	1056.0	2830.7	54.5	148.2	271.9	461.0	1032.0
70116	151.4	362.6	714.0	1311.0	2992.9	113.2	212.9	568.0	1006.0	1440.0
70117	43.4	106.5	302.1	759.0	2020.0	34.4	56.1	152.1	481.7	950.0
70118	124.7	226.5	403.4	778.0	2077.0	57.9	156.2	322.0	709.0	966.0
70119	52.2	168.5	427.8	973.8	2319.8	111.0	238.5	394.2	772.5	1928.0
70121	29.1	53.8	110.4	196.2	306.6	*	*	*	*	*
70122	18.8	45.3	122.7	272.2	582.0	21.0	34.4	68.7	111.4	283.9
70123	8.6	21.0	39.3	79.8	145.2	*	*	*	*	*
70124	9.8	29.4	68.7	146.6	308.4	22.4	37.1	59.3	116.1	221.4
70125	66.5	150.1	333.8	625.0	1748.0	59.0	122.5	248.1	499.9	1174.0
70126	15.6	35.0	81.4	172.2	278.4	11.0	16.7	23.2	35.2	66.6
70127	18.0	27.0	57.4	109.0	185.8	15.8	23.7	46.0	89.3	116.7
70128	6.9	10.3	14.5	30.8	57.0	*	*	*	*	*
70130	75.4	194.0	573.0	1261.0	2947.0	*	*	*	*	*
70131	8.4	15.7	33.9	77.7	143.2	*	*	*	*	*

Note: * zip code area not observed in post-period.

2.3. Empirical strategy

Following prior research protocols, we restrict analysis to singleton births with plausible gestational ages (>20 weeks). Our empirical strategy involves both cross-sectional and temporal analyses. First, we analyze birth events in metropolitan New Orleans in 32 zip code tabulation areas with varying levels of median concentrations of soil Pb prior to HKR. Specifically, we analyze eclampsia as a function of maternal soil Pb exposure risk, adjusting for the known correlates of eclampsia. Soil Pb exposure risk is measured both continuously (median Pb in mg/kg units) and categorically. In models with soil Pb assessed categorically, zip code areas are divided into five quintiles (Q): Q1 < 50 mg/kg; 50 mg/kg < ∩ Q2 < 60 mg/kg; 60 mg/kg < Q3 < 95 mg/kg; 95 mg/kg < Q4 < 333 mg/kg; and > 333 mg/kg Q5. We assess soil Pb categorically to check for possible non-linear effects in the association of eclampsia risk and soil Pb exposure.

We specify the following logistic equation for the probability of eclampsia (E) for mother i before HKR:

$$Prob(E_i=1|L_i, M_i, G_i, R_i) = \Lambda[\alpha+\beta_1 L_i+\beta_2 M_i+\beta_3 G_i+\Gamma_1 R_i] \quad (1)$$

where $\Lambda[\cdot]$ is the cumulative distribution function (CDF) of the logistic distribution. The term L_i represents the median Pb accumulation in neighborhood soils of maternal residence (measured both continuously and categorically), M_i is a vector of maternal conditions, G_i is a vector of gestation variables, R_i represents maternal demographic characteristics and health behaviors associated with eclampsia, and α is a constant intercept. Again, insofar as eclampsia is associated with Pb exposure risk, our expectation is that, other things held equal, the odds of maternal eclampsia ought to increase with neighborhood soil Pb.

Our temporal analysis uses a regression-based difference-in-differences procedure. We analyze 75,501 singleton birth events across 22 zip code tabulation areas experiencing change in soil Pb levels following the exogenous flooding of the city. Our temporal analysis tests whether observed changes in soil Pb in New Orleans, over and above pre-HKR levels of soil Pb, resulted in corresponding changes of eclampsia risk.

As before, we specify the following reduced form logistic equation for the probability of eclampsia (E) for mother i,

$$Prob(E_i=1|P_i,\ D_i,\ M_i, G_i, R_i,\ L_i) = \Lambda[\alpha+\beta_1 P_i+\beta_2 D_i+\delta(P_i\times D_i)+\Gamma_1 M_i+\Gamma_2 G_i+\Gamma_3 R_i+\Gamma_4 L_i] \quad (2)$$

where, terms M_i, G_i, and R_i carry from Eq. (1) and $\Lambda[\cdot]$ is the CDF of the logistic distribution. In Eq. (2), L_i is the median Pb accumulation in neighborhood soils of maternal residence prior to HKR, capturing the baseline level of Pb exposure risk. P_i is a binary indicator equal to 1 if the pregnancy occurred in the period after HKR and 0 if the pregnancy occurred in the period before HKR. D_i is a categorical indicator reflecting the measured level of change in soil Pb after HKR, with zip code areas divided into terciles of small increase (1.77 to 32.6 mg/kg), small decrease (−20.45 to −0.25 mg/kg), or large decrease (−387.9 to −33.6 mg/kg). The exogenous impact of the flooding of New Orleans and subsequent change in soil Pb is captured by the estimated coefficients ($\hat{\delta}$) of interaction of P and D. *If* eclampsia risk is dose-responsive to soil Pb exposure risk, then we expect the magnitude of $\hat{\delta}$ to be decreasing in quantified increases of soil Pb. That is, the odds of eclampsia ought to decrease more in zip code areas experiencing greater reduction in soil Pb, adjusting for baseline levels of the pollutant. In reported results, the relative impacts of all risk factors are expressed as odds ratios computed as the exponential transformation of the estimated coefficients.

3. Results

3.1. Cross-sectional analyses

We begin with cross-sectional analyses of the association between eclampsia and soil Pb exposure risk. Table 2 lists odds ratios predicting maternal eclampsia for all and full term singleton births in New Orleans before HKR.[5] Our variable of interest, zip code area soil Pb, is standardized in all models ($\mu=0$; $\sigma=1$). In Column 1, showing results for all singleton births, we find that a

[5] Appendix Table 1 reports cross-sectional analyses of the association between soil Pb exposure risk and eclampsia after HKR, September 2005 to 2009. Cross-sectional results behave consistently across periods. With respect to all infants in the post-HKR period, we find that the odds of eclampsia increases by a multiplicative factor of 1.52 for a standard deviation increase in soil Pb.

Table 2
Odds ratios predicting Eclampsia for all and full term singleton births in New Orleans before Hurricanes Katrina and Rita, 1999 to August 2005.

	All infants OR	Full term infants OR	All infants OR	Full term infants OR
Soil Pb	1.476*** (0.0875)	1.491*** (0.0909)		
Reference (Soil Pb < 50 mg/kg)				
Soil Pb Quantile 2 (50–59 mg/kg)			1.109 (0.171)	1.027 (0.232)
Soil Pb Quantile 3 (60–94 mg/kg)			1.475** (0.231)	1.763** (0.413)
Soil Pb Quantile 4 (95–333 mg/kg)			2.166*** (0.410)	2.356*** (0.781)
Soil Pb Quantile 5 (> 333 mg/kg)			4.002*** (0.591)	3.949*** (0.905)
Log likelihood	−3054.2	−1681.9	−3037.6	−1677.8
McKelvey & Zavoina's R^2	0.224	0.241	0.263	0.263
N	68,920	56,262	68,920	56,262

Notes: clustered robust standard errors by zip code used; ***$p<0.01$, **$p<0.05$, *$p<0.1$; models control for gestation length, maternal weight gain, maternal diabetes, chronic hypertension, pregnancy related hypertension, cardiac disease, maternal race/ethnicity (non-hispanic white, non-hispanic black, with other race as reference group), marital status (married = 1), maternal tobacco use during pregnancy, maternal age (≤ 19 = 1), and maternal education (> high school as reference group, high school, some college, and college).

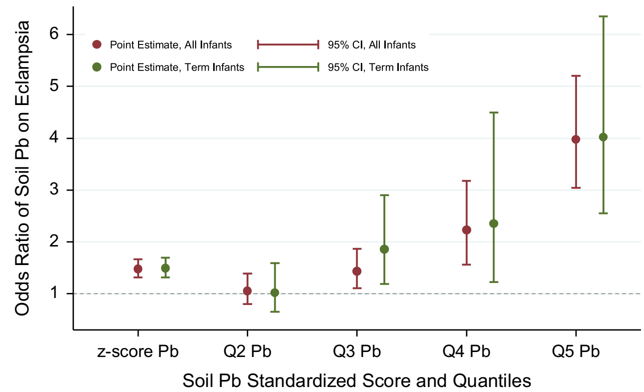

Fig. 1. Odds ratios and 95% CI corresponding to effect of soil Pb on Eclampsia before Hurricanes Katrina and Rita, 1999 to August 2005.

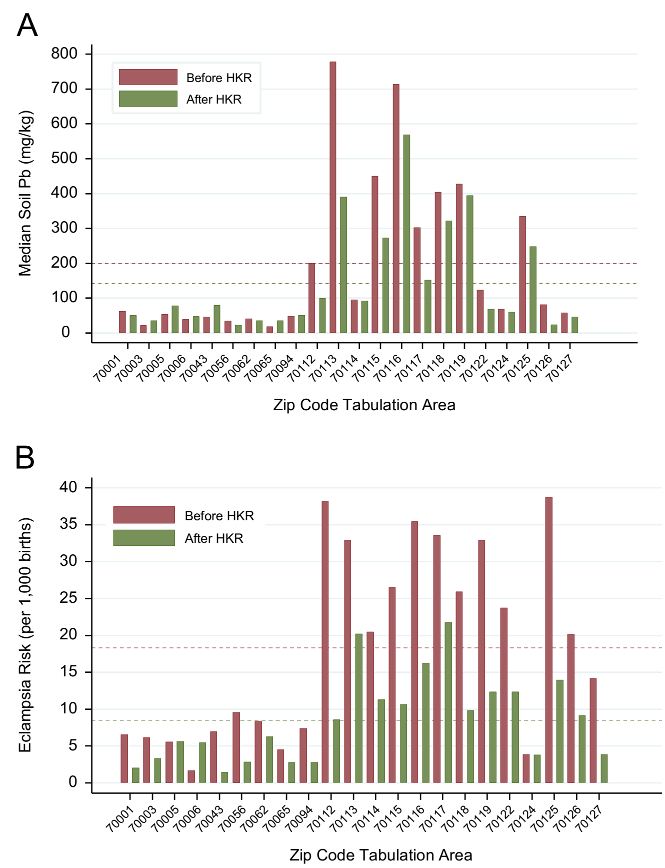

Fig. 2. Median soil Pb (mg/kg) and Eclampsia risk (per 1000 births) in New Orleans by zip code tabulation area before and after Hurricanes Katrina and Rita.

one standard deviation increase in median soil Pb (~180 mg/kg) increases the odds of an eclampsia event by a multiplicative factor of 1.48 (95% CI: 1.31, 1.66). In Column 3, zip code areas are divided into five categories (Q1 < 50 mg/kg; 50 mg/kg < Q2 < 60 mg/kg; 60 mg/kg < Q3 < 95 mg/kg; 95 mg/kg < Q4 < 333 mg/kg; and > 333 mg/kg Q5) to check if the risk of eclampsia behaves non-linearly in the accumulation of soil Pb. As compared to mothers residing in neighborhoods with median soil Pb Q1 < 50 mg/kg, results show that mothers in zip code areas with median soil Pb at Q4 (95 to 333 mg/kg) and Q5 (> 333 mg/kg) are 2.17 (95% CI: 1.49, 3.14) and 4.00 (95% CI: 3.00, 5.35) times more likely to suffer an eclampsia event, respectively. Columns 2 and 4 repeat the exercise, but restrict analysis to mothers with full-term (> 37 weeks) pregnancies. Results for full term pregnancies behave near identically with respect to continuous and categorical measures of soil Pb exposure risk.

Fig. 1 shows results in Table 1 graphically. Odds ratios and 95% CIs for all pregnancies and full term singleton birth events corresponding to the effect of soil Pb on eclampsia risk are graphed on the *y*-axis, and soil Pb quantities are plotted on the *x*-axis. Fig. 1 suggests that the risk of eclampsia increases linearly in the quantity of soil Pb exposure risk, and that the effect of soil Pb exposure risk behaves similarly for all pregnancies and full-term pregnancy restricted models.

3.2. Temporal analyses

We begin our temporal analysis with an ecological view of the data. Micro-level analyses follow. Fig. 2 shows median soil Pb (mg/kg) and eclampsia events (per 1000 births) in New Orleans by zip code area before and after HKR. As shown in Panel A, in 16 of 22 zip code areas observed before and after the flooding of New Orleans the median soil Pb levels noticeably declined. On an average, soil Pb levels declined 56 mg/kg per zip code area, constituting a 28% reduction over the pre-HKR period. Paired *t*-test results indicate that the observed decline in soil Pb after HKR is statistically significant ($t = 2.74$, $p < .01$). In Panel B, we observe that the risk of eclampsia also significantly declined after HKR, decreasing from 18.32 per 1000 births to 8.47 per 1000 births ($t = 5.38$, $p < .01$). In Fig. 3, we graph the ecological association between eclampsia risk and neighborhood soil Pb, before and after HKR. Consistent with logistic regression results in Table 2, the ecological association between eclampsia risk and soil Pb is upward sloping in both periods, with the post-HKR linear fit

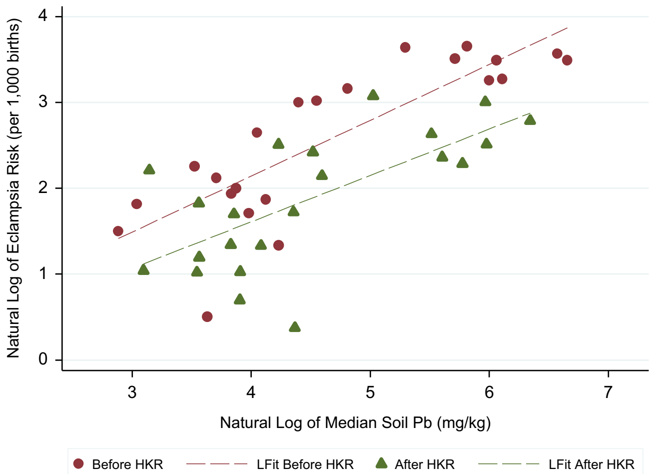

Fig. 3. Scatterplot of Eclampsia risk and soil Pb in New Orleans by zip code tabulation area and before and after Hurricanes Katrina and Rita.

Table 3
Odds ratios predicting Eclampsia for all singleton births in New Orleans before and after HKR, 1999–2009.

	All infants OR	All infants OR (Restricting to < 1 m of flood depth)	All infants OR (Restricting to < 1 m of flood depth and n-turbulent years)
Period (post = 1)	1.046	1.205	1.275
	(0.212)	(0.233)	(0.254)
Soil Pb (pre-period)	1.248***	1.027	0.962
	(0.0963)	(0.0622)	(0.049)
Reference (Soil Pb increase)			
Low soil Pb decrease	1.428*	1.608*	1.567*
	(0.291)	(0.406)	(0.388)
High soil Pb decrease	2.685***	6.284***	7.358***
	(0.680)	(1.479)	(1.510)
Low decrease X period	0.726	0.780	0.510
	(0.240)	(0.274)	(0.299)
High decrease X period	0.618**	0.413***	0.205***
	(0.140)	(0.0942)	(0.061)
Log likelihood	−3353.7	−1429.6	−1140.6
McKelvey & Zavoina's R^2	0.116	0.147	0.161
N	75,501	40,258	32,821

Notes: clustered robust standard errors by zip code used; ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$; models control for gestation length, maternal weight gain, maternal diabetes, chronic hypertension, pregnancy related hypertension, cardiac disease, maternal race/ethnicity (non-hispanic white, non-hispanic black, with other race as reference group), marital status (married = 1), maternal tobacco use during pregnancy, maternal age (≤ 19 = 1), and maternal education (> high school as reference group, high school, some college, and college).

shifting inward, reflecting the joint reduction in soil Pb and eclampsia risk observed in Fig. 2.

Returning to the micro-level, Table 3, column 1 reports odds ratios from our temporal analysis. The coefficients of interest are the interaction terms of period and categorical change in soil Pb (increase, small decrease, and large decrease). Other things held equal, we find that mothers residing in zip code areas experiencing large decreases in soil Pb (−387.9 to −33.6 mg/kg) were significantly less likely to suffer an eclampsia event (OR = 0.619; 95% CI: 0.397, 0.963) after HKR. Mothers residing in zip code areas witnessing only modest decline in soil Pb (−20.45 to −0.25 mg/kg) following the flooding of the city did not experience a reduction in eclampsia risk distinguishable from chance.

3.3. *Accounting for demographic turbulence*

Results reported in Table 3, column 1 may be biased by the demographic turbulence that followed the destruction caused HKR or by the generalized distress imposed on residential populations. By dividing zip code areas into two categories (≥ 1 m; and < 1 m) on the basis of the average flood depth incurred (as of 08-31-2005), we observe dramatic changes in the count of live births as well as the demographic composition of birth mothers across categorized areas. Fig. 4, panels A through D, summarize data with respect to four variables. In all panels time (moving at the quarterly time-step) is plotted on the *x*-axis, with a vertical short-dash line corresponding to the quarter HKR flooded New Orleans.

In panel A we see that the count of live births declined sharply with the timing of HKR. In zip code areas suffering ≥ 1 m of inundation, we observe a steeper decline in live births as compared to zip code areas visited by < 1 m of flood water, in panel B, C, and D, respectively, we see sharp reductions in the proportion of birth mothers that are African–American and < 20 years of age, as well as a spike in the proportion of married women. The decline in live births in areas with ≥ 1 m of flooding likely reflects a retreat in fertility planning in the presence of social and economic disorder caused by HKR, as well as out-migration of women of reproductive age following the disaster. The decline in the proportion of African American mothers and mothers < 20 years of age, as well as the sharp increase in the proportion of birth mothers that were married indicates that either the retreat in fertility planning and/or forced out-migration more strongly affected historically disadvantaged demographic groups in New Orleans. While these demographic dynamics following HKR are intriguing from a disaster epidemiology point of view, they challenge analytic efforts at establishing a link between soil Pb exposure risk and eclampsia in a quasi-experimental context.

To account for demographic dynamics that may compromise results from our quasi-experimental temporal investigation, we restricted analysis presented in Table 3, column 1 to zip code areas with < 1 m of flooding. These areas (with < 1 m of flooding) experienced measurable change in soil Pb levels, but did not experience massive demographic turbulence. By limiting the potential bias of demographic turbulence, the effect of observed changes in neighborhood soil Pb on the risk of eclampsia comes into sharper relief. Table 3, column 2 reports the results. Other things held equal, in zip code areas experiencing a large exogenous reduction of soil Pb (−391.7 to −33.6 mg/kg), the odds of a mother suffering an eclampsia event decreased by 59% (95% CI: 0.264, 0.646) after HKR.

As shown in Fig. 4 (panels A through D), the demographic turbulence caused by HKR noticeably subsided by 2008. In Table 3, column 3, we recapitulate models but now drop the high turbulent (or high residential mobility) years of 2006 and 2007. By dropping the turbulent years from the analysis, intervals of confidence with respect to our estimated coefficients $\left(\hat{\delta}\right)$ on the interaction of variables P and D noticeably tighten. Other things held equal, results show that mothers living in neighborhoods witnessing large reductions in soil Pb (−387.9 to −33.6 mg/kg) in the post-HKR period were significantly less likely to suffer an eclampsia

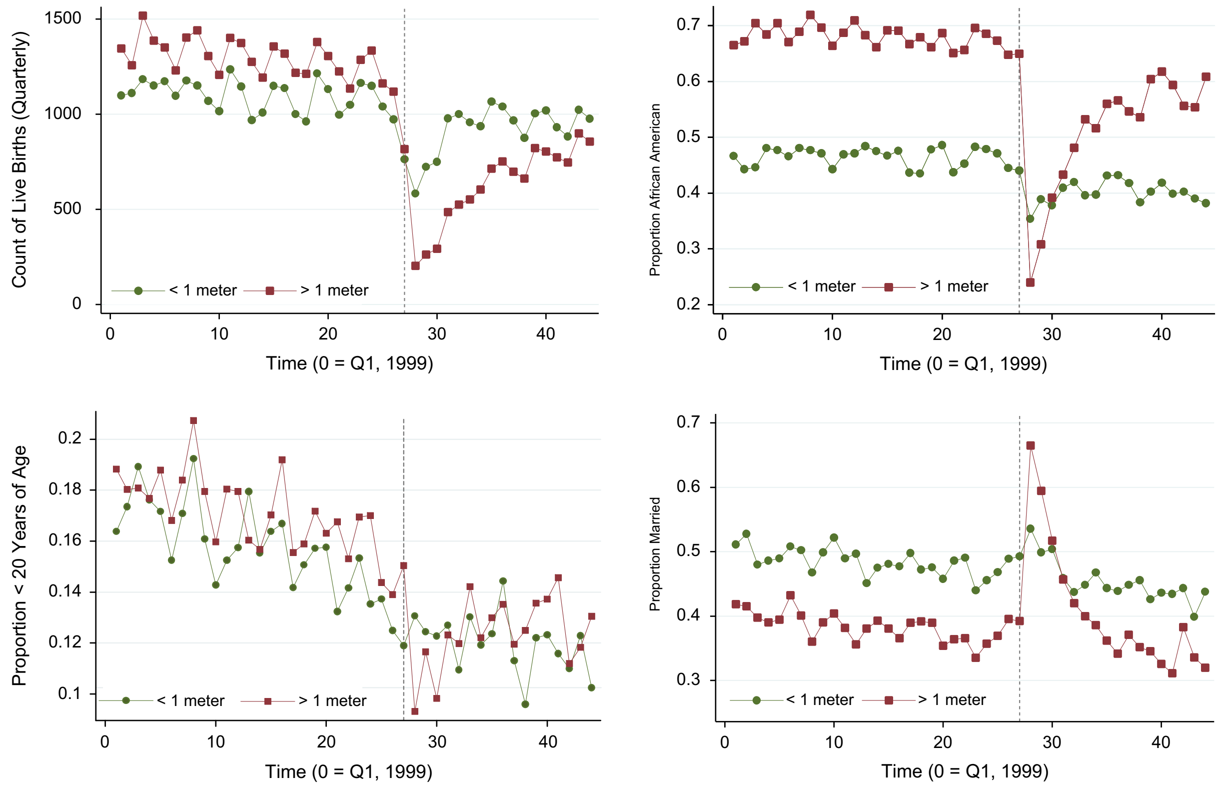

Fig. 4. Connected plots of demographic characteristics of zip code tabulations areas by flood depth in time (quarterly).

event (OR=0.21; 95% CI: 0.12, 0.37) after HKR. Overall, our temporal analyses corroborate our cross-sectional investigation.[6]

4. Discussion and conclusions

4.1. Limitations

Our investigation of the association between eclampsia risk and the soil Pb environment has limitations. First, we must acknowledge that many contaminants are strongly associated with Pb including zinc, cadmium and organic compounds such as poly aromatic hydrocarbon (PAH) and these may also influence health outcomes (Mielke et al., 2004; Mielke et al., 2005). Soil Pb may be a surrogate for multiple contaminants that also influence eclampsia. Second, because of restricted access to maternal residential information, the analytic unit used to characterize exposure risk was the zip code area. Census tracts are typically used in neighborhood soil Pb exposure studies of small children (Zahran et al., 2013b). While census tracts are preferable in risk analyses involving children, given that the activity space of adults is different from children, it is not clear what the appropriate spatial unit ought to be in analyses involving adults. Third, as shown in Fig. 4 (panel A–D), there was sizeable demographic turbulence following HKR. We addressed this demographic problem by first limiting analysis to zip code areas experiencing flooding and Pb soil change, but not a high degree of population outmigration, and then limiting analysis to post-HKR years with lower demographic turbulence. Under both sensitivity tests, we observe a significant effect on eclampsia from relatively large reductions soil Pb levels. Fourth, although the Pb exposure pathways are reasonably well established for both children as well as adults in occupational settings, the exposure routes for Pb in adults in the neighborhood settings are less clear. Studies do find that maternal residential proximity to Pb-contaminated areas strongly predicts (OR=5.1; 95% CI: 1.6, 16.7) cord blood Pb in neonates (Jones et al., 2010), implying that community measures of environmental risk are meaningfully related to health outcomes.

4.2. Disasters as natural experiments

In the developing subfield of disaster epidemiology, researchers address confounding by leveraging disasters as natural experiments and isolating the causal role of environmental variables for an array of health outcomes. Study examples include respiratory health linked to the World Trade Center disaster (Stellman et al., 2013), gastrointestinal illness as a result of massive flooding (Wade et al., 2004), neighborhood demolition activities on residents' health (Egan et al., 2013; Rabito et al., 2007), daily variation in tornado and hurricane casualties (Zahran et al., 2013d), and pregnancy complications from maternal exposure to hurricane destruction (Zahran et al., 2010b; Zahran et al., 2013c).

Hurricanes Katrina and Rita were among the costliest natural disasters in U.S. history. In addition to the nearly 2000 deaths attributed directly to the storms, HKR have been associated with multiple sequelae, including increases in psychological (Lowe et al., 2013; Lowe and Rhodes 2013; Paxson et al., 2012), alcohol abuse (Cerda et al., 2011), incidence of suicide (Straif-Bourgeois and Ratard 2012), respiratory morbidity (Rando et al., 2012), risk factors for acute myocardial infarction (Jiao et al., 2012), and declines in chronic disease management (Anderson et al., 2009; Fonseca et al., 2009; Robinson et al., 2008). Extreme weather events of the kind witnessed in New Orleans have the potential to engender both negative and beneficial changes to the ecological

[6] To provide additional confirmation that demographic turbulence was not fully responsible for the decline in preeclampsia in the post-HKR period, we stratified temporal analyses by race. We observe the same statistical patterns with respect to African American mothers, with the risk eclampsia retreating similarly in zip code areas experiencing relatively high reduction in soil Pb.

landscape of affected areas; this holds especially true for flooding events and urban soils.

In this study, pre- and post-HKR sampling of soil Pb in New Orleans facilitated a natural experiment in which a comparatively robust causal relation between Pb exposure and eclampsia could be investigated. With respect to pre-HKR cross-sectional analyses with both continuous and categorical measures of zip code summarized soil Pb accumulation, we find that the odds of eclampsia increase significantly with accumulation in Pb in neighborhood soils. The odds of eclampsia increase dose-responsively with neighborhood soil Pb. With respect to temporal analyses reported in section two of our analysis, we find that the risk of eclampsia decreased in neighborhoods experiencing relatively large reductions in soil Pb levels following the flooding of the city.

Our overall results are consistent with epidemiological research on the relationship between Pb and pregnancy-related hypertensive disorders. A systematic review of the literature identified nine studies, all observational, that evaluated the relationship between maternal Pb exposure and gestational hypertension and/or pre-eclampsia (Kennedy et al., 2012). Six of the nine studies found a significant association between blood Pb concentration and gestational hypertension or pre-eclampsia (Dawson et al., 2000; Magri et al., 2003; Sowers et al., 2002; Ugwuja et al., 2011; Vigeh et al., 2004; Yazbeck et al., 2009). Maternal blood Pb concentrations associated with the development of gestational hypertension or pre-eclampsia ranged from 1.2 μg/dL to 73.8 μg/dL (Kennedy et al., 2012). Furthermore, a cross-sectional study demonstrated an association between pre-eclampsia and maternal Pb exposure (Motawei et al., 2013), though results were not adjusted for confounding variables.

4.3. Natural disasters indicate opportunities for intervention

In industrialized nations alluvial soils have become both sinks of environmental contaminants, particularly metals, and also sources of contamination, depending on proximity to agricultural, urban and industrial locations (Cappuyns and Swennen 2007). The elevated metal content in soils of residential areas in New Orleans have been considered an important driver of health disparities in the region, particularly related to pediatric health (Mielke et al., 2007; Mielke et al., 2013; Zahran et al., 2011). A pre-HKR intervention project covered Pb contaminated residential soils in New Orleans with low Pb (< 10 mg/kg) Mississippi river alluvial soils and this action resulted in a significant decrease in outdoor soil Pb as well as indoor floor Pb dust content (Mielke et al., 2006b). The massive flooding experienced by the Gulf region during HKR caused widespread soil and sediment relocation and deposition throughout the area and previous study demonstrated a significant reduction in soil Pb in New Orleans in the post-HKR period, and a concomitant decrease in childhood blood Pb levels in the area (Mielke et al., 2006a; Zahran et al., 2010a).

Our study provides evidence that deleterious pregnancy outcomes co-vary with neighborhood levels of Pb contamination. The list of health costs associated with Pb is long (U.S. Department of Health and Human Services, 2012) and this study appends eclampsia to the body of the literature. Regarding future actions there is a need to improve understanding of community exposure routes for Pb in adults and pregnant women in particular. Importantly, this and other studies indicate the need for surveying the distribution of pollutants and intervention to prevent exposure to polluted soil in communities.[7]

[7] To prevent children's exposure to polluted soil, Norway established a National polluted soil mapping and intervention program to intervene at childcare centers, elementary schools and public parks in cities as well as in communities adjacent to industrial sites throughout Norway (Ottesen et al. 2008).

Table A1
Odds ratios predicting Eclampsia for all and full term singleton births in New Orleans after Hurricanes Katrina and Rita, August 2005 to 2009.

	All infants OR	Full term infants OR	All infants OR	Full term infants OR
Soil Pb	1.515***	1.563***		
	(0.120)	(0.184)		
Reference (Soil Pb < 50 mg/kg)				
Soil Pb Quantile 2 (50–60 mg/kg)			0.790	0.465***
			(0.122)	(0.127)
Soil Pb Quantile 3 (60–95 mg/kg)			1.750**	1.929
			(0.403)	(0.794)
Soil Pb Quantile 4 (95–333 mg/kg)			3.508***	3.618***
			(0.570)	(1.125)
Soil Pb Quantile 5 (> 333 mg/kg)			3.024***	3.391***
			(0.424)	(1.000)
Log likelihood	−1121.6	−456.0	−1109.4	−450.5
McKelvey & Zavoina's R^2	0.180	0.116	0.212	0.226
N	32,867	26,530	32,867	26,530

Notes: clustered robust standard errors by zip code used; ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$; models control for gestation length, maternal weight gain, maternal diabetes, chronic hypertension, pregnancy related hypertension, cardiac disease, maternal race/ethnicity (non-hispanic white, non-hispanic black, with other race as reference group), marital status (married=1), maternal tobacco use during pregnancy, maternal age (≤ 19=1), and maternal education (> high school as reference group, high school, some college, and college).

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Appendix

See Table A1.

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