



Determining the relative importance of soil sample locations to predict risk of child lead exposure

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ABSTRACT

Soil lead in urban neighborhoods is a known predictor of child blood lead levels. In this paper, we address the question where one ought to concentrate soil sample collection efforts to efficiently predict children at-risk for soil Pb exposure. Two extensive data sets are combined, including 5467 surface soil samples collected from 286 census tracts, and geo-referenced blood Pb data for 55,551 children in metropolitan New Orleans, USA. Random intercept least squares, random intercept logistic, and quantile regression results indicate that soils collected within 1 m adjacent to residential streets most reliably predict child blood Pb outcomes in child blood Pb levels. Regression decomposition results show that residential street soils account for 39.7% of between-neighborhood explained variation, followed by busy street soils (21.97%), open space soils (20.25%), and home foundation soils (18.71%). Just as the age of housing stock is used as a statistical shortcut for child risk of exposure to lead-based paint, our results indicate that one can shortcut the characterization of child risk of exposure to neighborhood soil Pb by concentrating sampling efforts within 1 m and adjacent to residential and busy streets, while significantly reducing the total costs of collection and analysis. This efficiency gain can help advance proactive *upstream, preventive methods* of environmental Pb discovery.

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1. Introduction

During the 20th century, lead (Pb) was widely used as a constituent in commercial products, including canned goods, plumbing, folk remedies, lead-based paints and gasoline. With respect to U.S. paint and gasoline, an estimated twelve million metric tons of Pb was used (Clark et al., 1991; Mielke and Reagan, 1998). The legacy of Pb used is reflected in the accumulation of Pb in urban soils. Soil integrates all dust sources of Pb including lead-based paint (either deteriorated, haphazardly removed by power sanding, sand blasted, scraped without capture, or released by building demolition), lead additives in vehicle fuel emissions, and incinerator or industrial Pb emissions (Farfel et al., 2005; Mielke, 1999; Mielke and Reagan, 1998; Mielke et al., 2011a; Rabito et al., 2007). While prevention is the key for protecting children

from environmental toxins (Lanphear et al., 2005), concern has been raised about the effectiveness of traditional intervention methods which focus on household environments for reducing children's blood Pb (Yeoh et al., 2012). A major purpose of this study is to evaluate a process for economically discovering community Pb contamination in a manner that supports proactive intervention and prevents childhood Pb exposure.

Soil Pb at or near the surface is an exposure risk to humans through direct contact or re-suspension of Pb in contaminated soils during summer periods (Filippelli et al., 2005; Laidlaw et al., 2005, 2012; Reagan and Silbergeld, 1990; Zahran et al., 2013). Soil lead as a cause for community health concern has been documented by many empirical studies showing strong associations between neighborhood soil Pb, children's blood Pb, and learning or behavioral outcomes (Johnson and Bretsch, 2002; Mielke et al., 1997, 2007; Zahran et al., 2011).

Given that soil Pb is recognized as an important source and predictor of child blood Pb, and assuming that environmental scientists interested in the question of soil Pb risk have fixed budgets, an important soil sampling question arises: *Given scarce resources, where should scientists concentrate soil sample collection efforts to efficiently predict children at-risk for Pb exposure?* To pursue this question of efficient sampling of the soil

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environment, two metropolitan New Orleans datasets were analyzed; one with over 5000 surface soil samples measured for Pb content and stratified by census tracts (Mielke et al., 2005), and the other with geo-referenced blood Pb data for over 55,000 children also stratified by census tracts.

The conventional approach for detecting Pb in the lived environment of at-risk children is by application of a *medical model*, involving routine measurement of children's blood for Pb content. This approach can be characterized as a *downstream methodology* of environmental Pb discovery. If a child records elevated Pb in their bloodstream, then parents, guardians, and authorities follow-up with a search of the lived environment of the child for the source of exposure. By investigating the question of how to efficiently sample neighborhood soils to characterize Pb risk, our study helps advance *upstream or preventive methods* of environmental Pb discovery. In May 2012, the U.S. Centers for Disease Control and Prevention restated a conclusion reached in 1991 that *there is no known safe level of lead exposure* (U.S. CDC Advisory Committee, 2012; U.S. CDC Response to Advisory Committee, 2012; U.S. DHHS, 2012). With no safe level of lead exposure, our investigation can help economize urban soil sampling and mapping efforts to anticipate interventions that minimize the health and developmental costs of elevated blood Pb in children.

2. Materials and methods

2.1. Soil lead (Pb) data

The soil Pb dataset was assembled from samples collected from the upper 2.5 cm of the soil surface within residential metropolitan New Orleans (Mielke et al., 2005). The soil samples were stratified by the census tracts of metropolitan New Orleans ($n = 286$) (U.S. Census Tracts and Block Number Areas, 1993). Because of relative uniformity in population size and demographic composition, census tracts (also known as enumeration districts) are a sensible geo-statistical unit for describing neighborhood conditions.

Critical to this study is that within each census tract 19 soil samples were systematically collected from *four location types*: within 1 m of home foundations, within 1 m of busy streets, within 1 m of residential streets, and open spaces (i.e., away from roadways and buildings such as parks or large residential lots). Home foundation samples reasonably approximate lead-based paint risk, particularly exterior paint, *as well as aerosolized Pb deposited in soil next to home foundations*. Pb contamination at other soil sample *locations*: busy streets, residential side streets, and open spaces are more likely sourced by leaded vehicle fuel, but also integrate Pb from other media, including lead-based paint. Exposure to lead-paint within homes, in the form of large chips or house dust, as well as outside of homes during demolitions are also well documented sources of exposure (Jacobs and Nevin, 2006; Levin et al., 2008; Rabito et al., 2007).

Extraction procedures for soil sample analysis involved room temperature leachate methods using 1 M nitric acid (HNO_3), a method that correlates well with total methods (Elias et al., 1996; Mielke et al., 1983). This method is safer, faster and lower cost per sample compared with those methods using boiling, concentrated HNO_3 . The extraction protocol requires mixing 0.4 g of dried and sieved (#10 USGS <2 mm) soil with 20 ml of 1 M HNO_3 followed by slow agitation on an Eberbach shaker for 2 h at room temperature (~22 °C). The extract is then centrifuged (10 min at 1600 $\times g$) and filtered using Fisherbrand® P4 paper. The extract is stored in 20 ml polypropylene vials until analyzed. A Spectro Analytical Instruments CIROS® CCD Inductively Coupled Plasma Atomic Emission Spectrometer (ICP-AES) is used to analyze the Pb in each sample. Quality assurance and quality control (QA/QC) is accomplished by calibrating the ICP-AES with certified U.S. National Institute of Standards and Technology (NIST) traceable standards. For each run verification includes the following QA/QC actions at the rate of 1 per 20 samples: The NIST standard (0 and 5 $\mu\text{g}/\text{mL}$) at the beginning and then

every 20 samples, calibration verification standards (1 and 10 $\mu\text{g}/\text{mL}$ NIST traceable standards), an in-house reference inserted for analysis, a duplicate sample, and a sample blank were also included. The in-house reference (Pb content ~170 mg/kg) is from New Orleans City Park. If verification results differ by >10% the sample run is repeated. The final soil Pb database is the result of the analytical results minus the sample blanks for each soil sample collected in each census tract of metropolitan New Orleans (Mielke et al., 2005).

Overall, the soil survey resulted in 5467 surface samples collected at the rate of ~19 samples from each of the 286 census tracts (Mielke et al., 2005). The neighborhood soil Pb data are summarized as the median value by sample location from home foundations, busy streets, residential streets and open spaces per census tract expressed in mg/kg units. In addition to taking the median of soil Pb samples within each census tract, we operationalized the risk of soil Pb exposure by: (1) taking the mean of soil samples within census tracts, (2) calculating a distance weighted mean soil Pb risk for each child, leveraging the residential location of each child and soil sample location, and (3) interpolating the average soil Pb content within a census tract by ordinary Kriging. All three methods generated highly correlated results ($r = 0.89$ to 0.96) with the median of soil Pb samples within the census tract performing best in children's blood Pb prediction models.

In the analyses outlined below we aim to discover which neighborhood *soil sample location* best predicts variation in child blood Pb. Descriptive statistics on Pb by soil sample location type are summarized in Table 1.

2.2. Blood lead (Pb) age, and sex data

Blood Pb data for New Orleans were collected and organized by the Louisiana Healthy Homes and Lead Poisoning Prevention Program, 2011 (LAHHLPPP). Details of the childhood blood Pb surveillance system are provided in the LAHHLPPP report that documents the details of the combined datasets of both public health and private lab data used to monitor exposures. Medical personal are strongly encouraged to report all children's blood Pb samples to the LAHHLPPP. The datasets were obtained through a formal application by the authors to the LAHHLPPP and individual children are not identifiable in the data set.

Each blood Pb sample was geocoded and matched to the boundaries of the corresponding 1990 census tract. Blood Pb values are expressed in $\mu\text{g}/\text{dL}$ units. Blood Pb for 55,551 children from the years 2000-late August, 2005 were included in this analysis. In addition to blood Pb results, the LAHHLPPP data contain information on the age and the sex of the child, as well as the year the blood sample was taken. These variables are included as control variables in statistical models. Residential tenure data from the 2000 Population and Housing Census (item PCT49) show that 85.42% of the population in Orleans Parish had the same address or resided in the same parish from 1995 to 2000, so that age of the child may be conceived as an adequate (though imperfect) surrogate for length of exposure (Zahran et al., 2011).

2.3. Statistical procedures

To analyze blood Pb in children ($\mu\text{g}/\text{dL}$) as a function of location types of soil lead exposure, we used a *generalized least squares random effects regression* where j denotes a census tract neighborhood, i denotes

Table 1
Descriptive statistics on Pb levels in soil (mg/kg) by location type.

Variable	P _{.01}	P _{.05}	P _{.10}	P _{.25}	P _{.50}	P _{.75}	P _{.90}	P _{.95}
Busy Street	5.1	11.0	20.8	57.7	156.1	413.9	765.0	1156.1
Foundation	3.2	6.2	8.9	28.5	136.6	1289.0	4637.7	9236.0
Open Space	4.0	6.9	9.6	23.4	71.1	300.0	870.2	1490.0
Residential Street	5.0	9.6	14.9	38.2	104.7	325.4	804.0	1365.0

a sampled child, and y_{ij} denotes the blood Pb level of child i in census tract j . Our regression model is:

$$y_{ij} = \beta_0 + \beta_1 B_j + \beta_2 F_j + \beta_3 O_j + \beta_4 S_j + \Gamma_1 D_i + \Gamma_2 T_i + u_j + e_{ij} \quad (1)$$

where, β_0 is the average blood Pb of children across neighborhoods, and B_j is the busy street soil Pb level in a neighborhood, F_j is the home foundation soil Pb level in a neighborhood, O_j is the open space soil Pb content in a neighborhood, S_j is the residential street soil Pb quantity in a neighborhood, D_i is vector of child demographic characteristics, and T_i is the year the blood sample was taken from child i . The random effects model divides the residual term in two parts: (i) a census tract-specific error component, given by u_j ; and (ii) a child-specific error component, which varies between children and census tract, given by e_{ij} . The neighborhood level residual u_j is the difference between census tract j 's child blood Pb mean and the overall mean, with the mean child blood Pb for census tract j being $\beta_0 + u_j$. The census tract-specific error component is meant to capture the combined effects of omitted census tract characteristics or unobserved heterogeneity like age of housing stock or socioeconomic conditions (Rabe-Hesketh and Skrondal, 2008). The child-specific residual e_{ij} is the difference between observed blood Pb level of child i and the average blood Pb of children sharing census tract j , where $e_{ij} = y_{ij} - (\beta_0 + u_j)$. Both residual terms are assumed to be Gaussian with zero means: $u_j \sim N(0, \sigma_u^2)$ and $e_j \sim N(0, \sigma_e^2)$.

To estimate the likelihood of a child's blood Pb exceeding 5, 10, 15, or 20 $\mu\text{g}/\text{dL}$ as a function of soil Pb location types, we use a random intercept logistic regression. The random intercept model relaxes the assumption of conditional independence in the standard logistic regression by adding a census tract-specific random intercept (ζ_j) to the binary prediction equation. Unobserved characteristics at the neighborhood level are integrated in ζ_j , provided $\zeta_j | x_{ij} \sim N(0, \sigma_\zeta)$ and i are independent across tracts j , and assuming that, given $\pi_{ij} = \Pr(y_{ij} | x_{ijj})$, y_{ij} are independently distributed as $y_{ij} | \pi_{ij} \sim \text{binomial}(1, \pi_{ij})$. The model is defined as:

$$\text{logit} \left\{ \Pr(y_{ij} = 1 | x_{ij}, \zeta_j) \right\} = \beta_0 + \beta_1 B_j + \beta_2 F_j + \beta_3 O_j + \beta_4 S_j + \Gamma_1 D_i + \Gamma_2 T_i + \zeta_j \quad (2)$$

with, all other terms defined as in Eq. (1).

To statistically assess the relative importance of each soil Pb location type in predicting variation in child blood Pb, we use a variance decomposition analysis. The relative importance soil Pb location types is determined by averaging semi-partial coefficients obtained for each predictor across all $p!$ orderings (Zahran et al., 2011). This procedure is specifically designed for statistical problems with co-linear predictors. We detail the logic of our variance decomposition procedure. For the squared multiple correlation coefficient for p predictors, $R_{0.123\dots p}^2$, the p th squared semi-partial correlation coefficient is given by

$$r_{p.123\dots p-1}^2 = R_{0.123\dots p}^2 - R_{0.123\dots p-1}^2 \quad (3)$$

Additionally, $R_{0.123\dots p}^2$ can be defined in terms of squared semi-partial correlation coefficients as

$$R_{0.123\dots p}^2 = \frac{1}{p} \sum_{i=1}^p \sum_{j=1}^p V_{ij} \quad (4)$$

where

$$V_{ij} = \frac{1}{\binom{p-1}{j-1}} \sum_{\mathcal{A} \setminus \{i\}} \binom{p-1}{j-1} r_{0(i.\mathcal{A})}^2 \quad (5)$$

and $\mathcal{A} \{1, \dots, p\}$ is a subset of 1, ..., p containing a combination of $j - 1$ predictor indices. Thus, $R_{0.123\dots p}^2$ is decomposable into $p(2^p - 1)$ squared

semi-partial correlation coefficients. The relative importance or contribution to explained variance of soil Pb location predictor i , $i = 1, \dots, p$, is given by

$$C_i = \frac{1}{p} \sum_{j=1}^p V_{ij} \times \quad (6)$$

And, since

$$R_{0.123\dots p}^2 = \sum_{i=1}^p C_i \quad (7)$$

the C_i values constitute exhaustive partitions of $R_{0.123\dots p}^2$. The derived C_i values corresponding to each soil Pb location type constitute the average of semi-partial coefficients obtained for each soil Pb location type across all $p!$ orderings of predictors. By dividing individual C_i values by the sum of C_i 's, one can determine the proportion of explained variance in a fully specified model attributable to each soil Pb location type (busy streets, home foundations, open spaces, and residential streets), allowing one to order soil Pb location types by their predictive utility.

3. Results

Table 2 shows the descriptive statistics on the average blood Pb of children residing in neighborhoods of either high ($>P_{0.50}$) or low ($<P_{0.50}$) measured soil Pb in busy street, home foundation, open space, and residential street soil sample location types, as well as different combinations of all types. Moving down the principal diagonal, we show the unconditioned average blood Pb levels of children residing in high traffic busy street soil Pb quantity ($\mu = 7.175 \mu\text{g}/\text{dL}$, $\sigma = 6.153 \mu\text{g}/\text{dL}$) to low traffic residential street Pb quantity ($\mu = 3.995 \mu\text{g}/\text{dL}$, $\sigma = 3.038 \mu\text{g}/\text{dL}$). The importance of soil location Pb risk, a more telling feature of Table 2, involves joint conditions where one type of neighborhood soil Pb is high and another is low (see also Mielke et al., 2013).

For instance, among the 27,758 children residing in census tracts with high residential foundation soil Pb, reflecting the high risk of exterior paint Pb exposure, we observed an average child blood Pb level of 7.172 $\mu\text{g}/\text{dL}$. By contrast, for the 27,787 children living in neighborhoods with low home foundation soil Pb risk, average blood Pb was 41.7% lower at 4.18 $\mu\text{g}/\text{dL}$. By combining the neighborhood condition of high foundation Pb with low residential street Pb risk, we observe an average blood Pb of 4.671 $\mu\text{g}/\text{dL}$ in 3624 children, inducing a near 35% decline over the unconditioned high soil foundation risk scenario. Similarly, by combining low foundation soil risk with high residential street Pb risk, we find that average blood Pb in 3583 children living in such neighborhoods is 6.109 $\mu\text{g}/\text{dL}$, constituting a 46.2% increase over the unconditioned low foundation risk scenario. Of the four soil location types, residential street Pb seems to exercise the greatest influence over average children's blood Pb.

To extend the suggestive results in Table 2, we have reported findings from our random effects regression analyses. In Table 3, we report a series of models. To account for skew in soil Pb predictors, and to approximate the known diminishing return dose–response curve reported elsewhere (Mielke et al., 2007; Zahran et al., 2011), we regress child blood Pb on the square root of Pb in each soil location type. For ease of interpretation, coefficients are expressed in standard deviation terms. In Model 1, child blood Pb is regressed on the time trend variable, showing that child blood Pb in New Orleans has declined over time ($b = -0.094$, $p < 0.001$). In Model 2, the demographic variables of sex and age were added. As observed in prior studies (Zahran et al., 2011), male children have higher blood Pb than females ($b = 0.285$, $p < 0.001$), and blood Pb rises with age ($b = 0.624$, $p < 0.001$). In Model 3, child blood Pb is regressed on soil Pb location types. Soil Pb location type coefficients express the expected change in children's

Table 2
Average child blood Pb ($\mu\text{g}/\text{dL}$) by levels soil Pb (High vs. Low) and by soil location type.

	High busy street	Low busy street	High foundation	Low foundation	High open space	Low open space	High residential street	Low residential street
High busy street	7.175 (6.153) 26,914		7.558 (6.367)	5.178 (4.375)	7.509 (6.290)	5.529 (5.120)	7.568 (6.339)	4.483 (3.692)
Low busy street		4.169 (3.294) 27,144	5.232 (4.288)	3.997 (3.069)	5.212 (4.205)	3.983 (3.066)	6.210 (5.046)	3.906 (2.891)
High foundation			7.172 (6.132) 27,758		7.449 (6.253)	5.513 (5.041)	7.548 (6.353)	4.671 (3.473)
Low foundation				4.180 (3.335) 27,787	5.039 (4.009)	4.043 (3.194)	6.109 (4.801)	3.894 (2.954)
High open space					7.116 (6.050) 27,609		7.481 (6.263)	4.563 (3.301)
Low open space						4.252 (3.553) 27,936	24,134 (5.635)	3624 (2.990)
High residential							3563 7,362 (6.193) 27,717	24,373
Low residential								3,995 (3.038) 27,828

Note: Statistics reported include mean blood Pb level, then standard deviation in parentheses, and then count of children observed.

blood Pb by a standard deviation increase in the square root of soil Pb (mg/kg). As suggested in Table 2, results from Model 3 indicate that residential street soils more strongly predict child blood Pb than foundation soils, busy street soils, and open space soils. Model 4 is our fully saturated model of soil Pb location sources and control variables. Other things held equal, we find that a standard deviation increase in busy street soil Pb, increases the expected child blood Pb by 0.291 $\mu\text{g}/\text{dL}$. By contrast, a standard deviation increase in residential street soil Pb increases the expected level of child blood Pb by over 1 $\mu\text{g}/\text{dL}$ unit (where $p < 0.001$). According to Table 3, residential street soil Pb is manifestly more important than other types of soil Pb in predicting variation in child blood Pb, although all soil Pb sources appear to increase child blood Pb greater than chance expectation. Overall, our suite of predictors accounts for about 76% of the between census-tract variation in child blood Pb.

Table 3
Random Effects Generalized Least Squares Regression Coefficients Predicting Blood Lead Levels in Children ($\mu\text{g}/\text{dL}$).

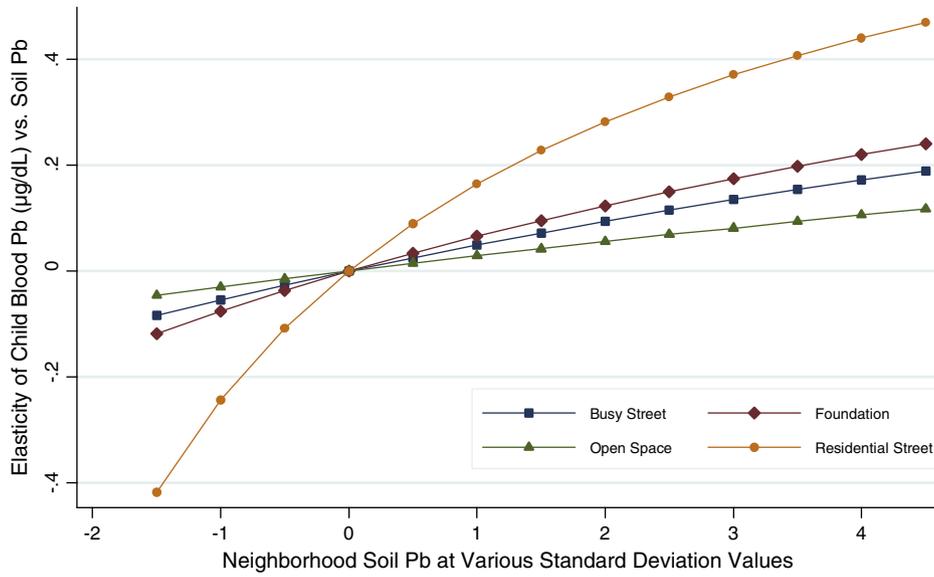
	Model 1 $\mu\text{g}/\text{dL}$	Model 2 $\mu\text{g}/\text{dL}$	Model 3 $\mu\text{g}/\text{dL}$	Model 4 $\mu\text{g}/\text{dL}$
Busy Street			0.279*** (0.102)	0.291*** (0.096)
Foundation			0.401*** (0.088)	0.394*** (0.083)
Open Space			0.185** (0.093)	0.165* (0.087)
Residential Street			1.140*** (0.111)	1.098*** (0.105)
Age		0.624*** (0.021)		0.623*** (0.021)
Male		0.285*** (0.041)		0.302*** (0.041)
Year	-0.094*** (0.014)	-0.116*** (0.014)		-0.111*** (0.014)
Constant	5.739*** (0.115)	5.708*** (0.109)	5.521*** (0.062)	5.665*** (0.069)
Wald X^2	46.05	1016.02	951.65	2082
R^2 between	0.256	0.336	0.754	0.769
N	55,551	53,348	54,052	51,905
Census tracts	280	280	272	272

Standard errors in parentheses *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

In Fig. 1, we show the marginal effects of soil Pb sources on child blood Pb through selected points in the sample space, while fixing control variables at their estimation sample means. On the x-axis, we plotted soil Pb quantities at various standard deviation values. On the y-axis, we plotted the marginal effect of children's blood Pb with respect to soil Pb source values. Our graphic shows the *percentage change* in child blood Pb for a percent increase from a set dosage of Pb content in neighborhood soils, corresponding to all four soil sample locations. Every *dose-response curve* corresponding to each soil Pb type is upward sloping, with the effect on child blood Pb increasing with soil Pb content. With regard to our main research question concerning which soil sample location exercises the greatest impact on child blood Pb, it is evident that residential street soil Pb sample locations are more important in predicting the upstream risk of child blood Pb.

Table 4 reports results from our decomposition of explained variance in Model 3 of Table 3, detailing the relative importance of each soil Pb type in explaining variations in child blood Pb levels. As a check on the calculation, note that the sum of derived *Soil Location Type Contribution* (C_i) values equals the observed R^2 (0.754) in Model 3 of Table 3. Results show that a remarkable 39.07% of *Soil Location Type Contribution* in child blood Pb is attributable to residential street soil Pb, a value almost twice as high as observed for other soil Pb locations. The order of relative predictive importance of soil Pb location type is completed as: residential street 39.07%, busy street soil Pb (21.97%), open space soil Pb (20.25%) and home foundation soil Pb (18.71%).

Next, we derived the likelihoods of child blood Pb exceeding 5, 10, 15, and 20 $\mu\text{g}/\text{dL}$ thresholds as a function of neighborhood soil Pb location types and relevant control variables. Table 5 and Fig. 2 report results for various random intercept logistic regression models. Once again, we found that residential street soil Pb location seems most important in determining whether a child eclipses a blood Pb threshold compared to other soil Pb location types. Other things held equal, a standard deviation increase in residential street soil Pb increases the odds of a child's blood Pb exceeding 5, 10, 15 and 20 $\mu\text{g}/\text{dL}$ thresholds by multiplicative factors of 1.48, 1.71, 1.72, and 1.71, respectively. Whereas other soil Pb locations meaningfully impact the odds of child blood Pb exceeding measured thresholds, estimated effects are manifestly lower than observed for residential street soil Pb. Fig. 2 plots odds ratios corresponding to each soil Pb type reported in Table 5. Plotted point estimates are capped by 95% confidence intervals. It is noteworthy how the lower



Note: *Marginal effects calculated on the basis of fully saturated Model 4 in Table 3, with control variables fixed at sample means.

Fig. 1. Conditional elasticities* of child blood Pb (µg/dL) vs. community soil Pb by soil location. Note: *Marginal effects calculated on the basis of fully saturated Model 4 in Table 3, with control variables fixed at sample means.

estimate of risk from residential street soil locations exceeds or borders the upper estimate of all other soil Pb sample locations analyzed (Fig. 2).

Finally, to establish the robustness of our statistical observations, we completed our analysis with a series of quantile regressions to test whether our results on the predictive power of soil location sources of Pb behave similarly across parametric and non-parametric procedures. We modeled quantile points (τ) of 0.2, 0.4, 0.5, 0.6, and 0.8 in the conditional distribution of child blood Pb as a function of neighborhood soil Pb locations (Koenker and Hallock, 2001). Table 6 shows the non-parametric quantile regression results in which coefficients are expressed in standard deviation terms. As with our parametric models, results show that residential street soil Pb is the strongest predictor of child blood Pb across all quantile points. In fact, in Model 5, where $\tau = 0.8$, we find that the residential street soil Pb is an order of magnitude stronger ($b = 1.86, p < 0.001$) in predictive power than the next most powerful soil location source, busy streets ($b = 0.65, p < 0.001$). Overall, quantile regression results strongly corroborate results from parametric models reported in Tables 3 and 5.

4. Discussion

4.1. Blood Pb and environmental Pb discovery

With respect to the association between soil Pb and blood Pb, studies in Syracuse, New York; Minneapolis and St. Paul, Minnesota; Detroit, Michigan; and New Orleans, Louisiana have arrived at similar conclusions: One can predict spatial variation in children's blood Pb

outcomes from the accumulation of Pb in neighborhood soils (Johnson and Bretsch, 2002; Laidlaw et al., 2005; Mielke et al., 1989, 1997, 1999, 2007; Zahran et al., 2011, 2013). Our study indicates that soils adjacent to residential and busy streets account for the bulk of between-neighborhood variation in child blood Pb levels. Whether the accumulation of Pb near roadways reflects the legacy Pb contamination from gasoline (Laidlaw et al., 2012; Zahran et al., 2013) or the routine demolition of buildings resulting in the release of lead-based paint (Farfel et al., 2003; Rabito et al., 2007), the high-energy environment present on roadways induces atmospheric re-suspension of Pb particles and increases inhalation and accidental ingestion risk facing children (Sabin et al., 2006; Sternbeck et al., 2002; Zahran et al., 2013).

As compared to Model 3 in Table 3 (where all soil location types are included as regressors), a sparse model including only residential and busy street soil samples results in very modest loss of predictive efficacy ($R^2_{0.sbf0} = 0.754$ versus $R^2_{0.sb} = 0.733$), indicating that one can adequately describe neighborhood soil Pb risk with significant reduction in the quantity of soil samples and by concentrating sampling efforts near roadways. In support of this statistical conclusion, Fig. 3 shows the geography of soil Pb in metropolitan New Orleans based only on residential street samples. As compared to the lead map of New Orleans based on all soil sample locations (see Mielke et al., 2011b), Fig. 3 closely approximates the known spatial variation of child risk of exposure to soil Pb.

As noted in the introduction, the medical model of environmental Pb discovery is a downstream methodology, wherein the search for environmental Pb follows from the detection of elevated Pb in a child's blood. By combining two sets of data, the statistical results of our study can meaningfully inform a preventive model of environmental Pb discovery at the neighborhood scale. Just as the age of housing stock in an urban area is used as a statistical shortcut for child risk of exposure to lead-based paint, our results indicate that one can shortcut the characterization of child risk of exposure to soil Pb by concentrating sampling efforts on soil adjacent to residential and busy streets, thereby significantly reducing the total costs (in time, money, and effort) of collection and laboratory work. If a neighborhood soil Pb risk is found to exist, then planning for intervention and additional sampling to characterize the source of exposure is warranted (Bugdalski et al., 2013). Indeed, the approach recommended here may be expedited by improvements in accuracy

Table 4
Calculation of soil source contribution (C_i) to $R^2_{0.1234}$.

	Order of squared semi-partial				C_i	% C_i
	Zero V_{ij}	First V_{ij}	Second V_{ij}	Third V_{ij}		
Busy Street	0.532	0.093	0.030	0.008	0.166	21.97%
Foundation	0.470	0.062	0.020	0.012	0.141	18.71%
Open Space	0.510	0.077	0.019	0.004	0.153	20.25%
Residential Street	0.719	0.231	0.134	0.094	0.295	39.07%

Table 5
Random effects logistic regression odds ratios[†] (and 95% CI) predicting threshold exceedance of blood lead levels in children.

	Model 1 $\mu\text{g/dL} > 5$	Model 2 $\mu\text{g/dL} > 10$	Model 3 $\mu\text{g/dL} > 15$	Model 4 $\mu\text{g/dL} > 20$
Busy street	1.139 (1.037 to 1.250)	1.203 (1.048 to 1.381)	1.266 (1.089 to 1.473)	1.285 (1.078 to 1.532)
Foundation	1.194 (1.102 to 1.295)	1.313 (1.171 to 1.472)	1.270 (1.123 to 1.435)	1.323 (1.151 to 1.522)
Open space	1.140 (1.047 to 1.241)	1.169 (1.035 to 1.320)	1.188 (1.044 to 1.352)	1.138 (0.982 to 1.318)
Residential street	1.484 (1.340 to 1.644)	1.708 (1.478 to 1.975)	1.715 (1.468 to 2.003)	1.714 (1.434 to 2.049)
Age	1.379 (1.353 to 1.406)	1.372 (1.334 to 1.411)	1.323 (1.271 to 1.377)	1.257 (1.189 to 1.330)
Male	1.149 (1.106 to 1.194)	1.167 (1.104 to 1.234)	1.206 (1.114 to 1.307)	1.234 (1.102 to 1.381)
Year	0.975 (0.962 to 0.988)	0.907 (0.890 to 0.925)	0.923 (0.898 to 0.948)	0.948 (0.913 to 0.984)
Wald χ^2	1807.10	1190.45	730.31	425.48
Log likelihood	−30,883.58	−16,634.33	−9367.41	−5386.77
N	51,905	51,905	51,905	51,905
census tracts	272	272	272	272

Note: [†]Confidence intervals in parentheses.

and reliability of hand-held x-ray fluorescence techniques (XRF), which permit soil metals to be measured directly in the field in a few minutes per site.

4.2. Limitations

While our results provide guidance on the relative importance of soil sample locations in predicting the upstream risk of child lead poisoning, our paper does not technically satisfy an economic definition of efficiency. With valid data on the marginal costs of soil sampling and analysis, and greater precision with respect to the declining marginal benefit (in terms of predictive accuracy) in the quantity of soil samples taken, one can determine the equilibrium quantity of soil samples necessary to optimize total benefits over total costs, and the optimal cost-effective sampling strategy across soil location types. Still, across parametric and non-parametric regression procedures, as well as results from our decomposition of between-neighborhood explained variance, we believe that a technically optimal sampling protocol for characterizing neighborhood-level risk of exposure to Pb contaminated soils is to likely involve a significantly lower number of samples than previously assumed and drawn primarily from residential and busy streets soils.

Additionally, while our study provides useful guidance on where to sample in an urban environment to maximize predictive efficiency, this study does not attempt to apportion sources and cannot be used to infer the source of Pb based on sample location. While it may be reasonable to assume that home foundation soils are more likely sourced by the deterioration and haphazard removal of exterior and interior lead-based paints, or that soils proximate to roadsides are more likely sourced by the legacy of leaded gasoline emissions, home and building demolition practices and local weather regimes complicate these simple distinctions. Efforts to identify the multi-media origins of environmental Pb can theoretically tune our statistically-derived guidance to more efficiently characterize neighborhood-level risk of soil Pb exposure but such exercises are beyond the scope of this work.

4.3. Soil guideline values and intervention

With respect to the risk of soil Pb exposure, the US EPA guideline values for soil Pb intervention are 400 ppm for bare soil where children play and 1200 ppm for surrounding soils (U.S. EPA, 2000). These guideline values for soil Pb exceed most international guideline values (Jennings, 2013). Moreover, remediating a single patch of private property abutting a residential street is unlikely to fully insulate

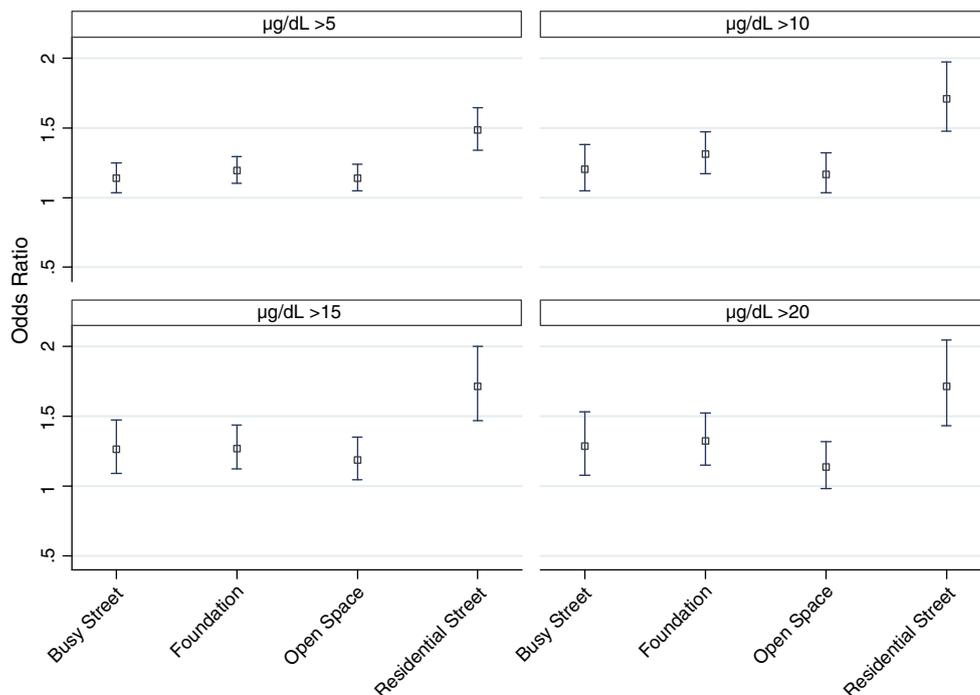


Fig. 2. Random effects logistic regression odds ratios (and 95% CI) predicting blood lead levels in children.

Table 6
Quantile regressions estimates predicting blood Pb LEVELS IN CHILDREN (µg/dL).

	Model 1 τ = 0.2	Model 2 τ = 0.4	Model 3 τ = 0.5	Model 4 τ = 0.6	Model 4 τ = 0.8
Busy street	0.082*** (0.017)	0.202*** (0.015)	0.301*** (0.016)	0.382*** (0.024)	0.650*** (0.047)
Foundation	0.097*** (0.0143)	0.178*** (0.013)	0.233*** (0.014)	0.259*** (0.021)	0.475*** (0.041)
Open space	0.060*** (0.015)	0.083*** (0.014)	0.155*** (0.015)	0.172*** (0.022)	0.124*** (0.045)
Residential street	0.313*** (0.018)	0.634*** (0.017)	0.765*** (0.018)	1.051*** (0.027)	1.864*** (0.054)
Age	0.325*** (0.010)	0.248*** (0.009)	0.381*** (0.009)	0.513*** (0.013)	0.787*** (0.025)
Male	0.068*** (0.019)	0.100*** (0.017)	0.149*** (0.018)	0.194*** (0.027)	0.290*** (0.054)
Year	-0.048*** (0.006)	-0.047*** (0.006)	-0.064*** (0.006)	-0.075*** (0.009)	-0.138*** (0.019)
Constant	2.882*** (0.019)	3.960*** (0.017)	4.593*** (0.018)	5.354*** (0.028)	7.979*** (0.055)
Raw sum deviations	81,443.12	137,700.4	157,539.7	170,359	160,898.7
Min. sum deviations	79,244.56	127,793.4	143,209.5	151,574.7	136,845.2
N	51,905	51,905	51,905	51,905	51,905

Standard errors in parentheses.
*** p < 0.01.

a child from soil Pb exposure (Laidlaw et al., 2012), because Pb risk permeates residential neighborhoods. Results from extensive studies in three major US cities demonstrate the importance of mitigating multiple routes of exposures (Elias et al., 1996). For example, remediation of outdoor soil lead has very little benefit to children that lived in high-rise apartments with interior dust containing high levels of lead (Aschengrau et al., 1994).

International precedence for implementing a national clean soil program (including both inorganic and organic toxins) has been established by the Norwegian government (Ottesen et al., 2008).

Given the widespread availability of low Pb (<20 mg/kg) soil concentrations in the U.S., intervention is possible anywhere (Gustavsson et al., 2001). New Orleans is positioned at the Mississippi River Delta which is composed of sediments containing only trace amounts of Pb transported by the River from the abundant and fertile soils of North American (Mielke et al., 2000). Inner city children, regardless of whether they live in public or private housing, have an incidence of Pb exposure of nearly 30% ≥ 5 µg/dL (Mielke et al., 2011b, 2013). As New Orleans rebuilds residential neighborhoods damaged by Hurricanes Katrina and Rita, there exists an opportunity to protect children into the future by applying a proactive, upstream public health policy to intervene on Pb and other toxins that have accumulated in the soils and play areas of the city. During the past century the growth of automobile oriented urban sprawl or peri-urbanization share similar processes of Pb dust emission and deposition as observed in New Orleans, and thus the results are probably applicable to all major cities.

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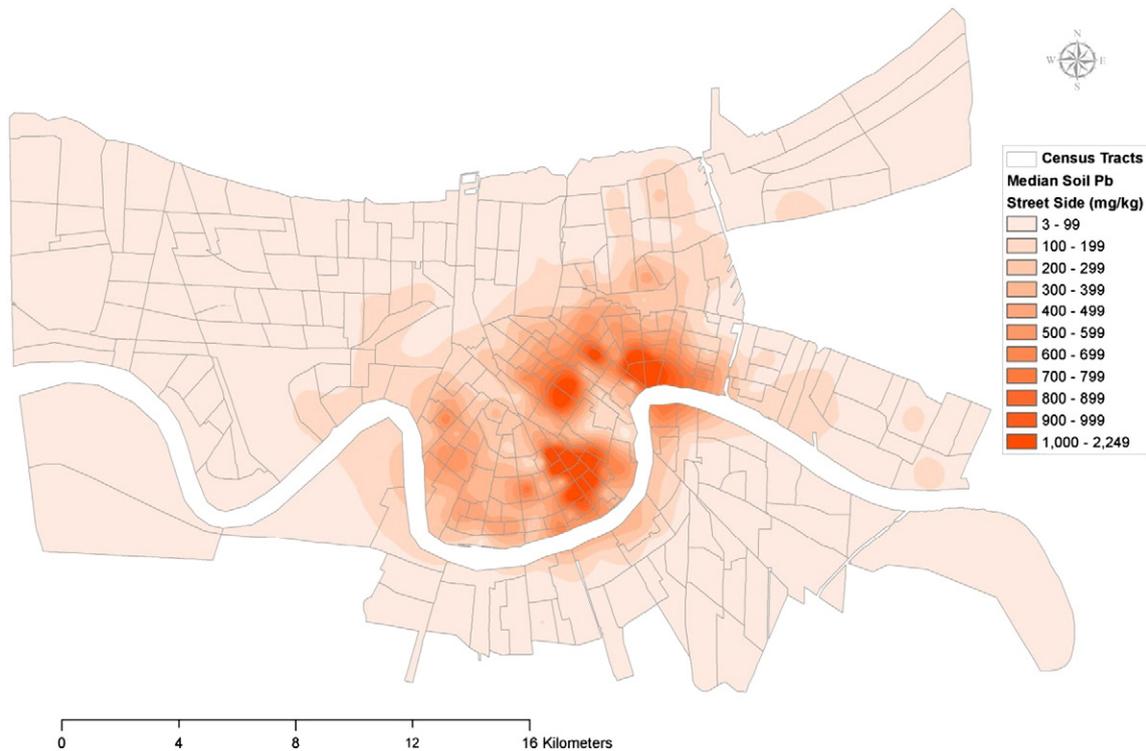


Fig. 3. Lead map of New Orleans based on residential street side samples.

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