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

Sammy Zahran [a,b], Howard W. Mielke [c,*], Shawn P. McElmurry [d], Gabriel M. Filippelli [e], Mark A.S. Laidlaw [f], Mark P. Taylor [f]

[a] Department of Economics, Colorado State University, Fort Collins, CO, 80523-1771, United States
[b] Robert Wood Johnson Health and Society Scholar, Department of Epidemiology, Columbia University, New York, NY, 10032, United States
[c] Department of Pharmacology, Tulane University School of Medicine, 1430 Tulane Ave SL-83, New Orleans, LA 70112, United States
[d] Department of Civil & Environmental Engineering, Wayne State University, Detroit, MI 48202, United States
[e] Department of Earth Sciences and Center for Urban Health, Indiana University-Purdue University Indianapolis (IUPUI), Indianapolis, IN 46202, United States
[f] Environmental Science, Department of Environment and Geography, Faculty of Science, Macquarie University, North Ryde, Sydney NSW 2109, Australia

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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.

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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* Corresponding author at: Department of Pharmacology, Tulane University School of Medicine, 1430 Tulane Avenue-SL83, New Orleans, LA 70112-2632, United States. Tel.: +1 5049883889.
E-mail addresses: szahran@colostate.edu, sz2401@columbia.edu (S. Zahran), hmielke@tulane.edu (H.W. Mielke), s.mcelmurry@wayne.edu (S.P. McElmurry), gfilippe@iupui.edu (G.M. Filippelli), markas1968@gmail.com (M.A.S. Laidlaw), mark.taylor@mq.edu.au (M.P. Taylor).

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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 ×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 μg/mL) at the beginning and then every 20 samples, calibration verification standards (1 and 10 μg/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 μg/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 (μg/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