

Spatial relationships between lead sources and children's blood lead levels in the urban center of Indianapolis (USA)

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Abstract Urban children remain disproportionately at risk of having higher blood lead levels than their suburban counterparts. The Westside Cooperative Organization (WESCO), located in Marion County, Indianapolis, Indiana, has a history of children with high blood lead levels as well as high soil lead (Pb) values. This study aims at determining the spatial relationship between soil Pb sources and children's blood lead levels. Soils have been identified as a source of chronic Pb exposure to children, but the spatial scale of the source–recipient relationship is not well characterized. Neighborhood-wide analysis of soil Pb distribution along with a furnace filter technique for

sampling interior Pb accumulation for selected homes ($n = 7$) in the WESCO community was performed. Blood lead levels for children aged 0–5 years during the period 1999–2008 were collected. The study population's mean blood lead levels were higher than national averages across all ages, race, and gender. Non-Hispanic blacks and those individuals in the Wishard advantage program had the highest proportion of elevated blood lead levels. The results show that while there is not a direct relationship between soil Pb and children's blood lead levels at a spatial scale of ~ 100 m, resuspension of locally sourced soil is occurring based on the interior Pb accumulation. County-wide, the largest predictor of elevated blood lead levels is the location within the urban core. Variation in soil Pb and blood lead levels on the community level is high and not predicted by housing stock age or income. Race is a strong predictor for blood lead levels in the WESCO community.

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Abbreviations

WESCO Westside Cooperative Organization
Census Block Geographic unit used by United
States Census Bureau for tabulation
of 100 % data. This can correspond
to a city block in an urban setting
Block Group Made up of several Census Blocks.
Smallest geographic unit for which

	the United States Census Bureau publishes sample data
Census Tract	Designed by the United States Census Bureau to be relatively homogeneous units with respect to population characteristics, economic status, and living conditions. Census tracts average about 4,000 inhabitants
Pb	Lead
BLL	Blood lead level
µg/dL	Microgram per deciliter
ppm	Parts per million

Introduction

The legacy of Pb deposition in urban soils from Pb-based paint, Pb additives in gasoline, and industrial sources is not uniform (Chaney et al. 1989; Filippelli et al. 2005; Laidlaw et al. 2005; Mielke et al. 2003), with urban soil Pb loading being particularly high due to the concentration of traffic volume, housing, and industrial facilities (Filippelli and Laidlaw 2010; Filippelli et al. 2005; Mielke and Reagan 1998; Mielke et al. 2003). Urban concentrations of soil Pb are typically several orders of magnitude higher than background values, and values tend to be greatest near legacy sources like roadways, Pb-painted structures, and Pb smelting facilities due to deposition of sediments over existing soils (Filippelli et al. 2005). These legacy sites become prime factors in Pb exposure to humans and Pb poisoning in children (Filippelli et al. 2005; Mielke et al. 2003).

While the reduction in Pb poisoning cases is considered one of the most stunning examples of public health success (Silbergeld 1997), the unfortunate truth is that there is still an unequal distribution of Pb poisoning cases in the United States (Gould 2009). Based on the recently published NHANES data, the overall prevalence of blood lead levels ≥ 10 µg/dL in all children regardless of race has decreased from 8.6 % during the years 1988–1991 to 1.4 % for the years 1999–2004, representing an 84 % reduction (Jones et al. 2009). While there is little difference in blood lead levels between non-Hispanic whites and Hispanic populations, there still exists a relatively larger gap between these two groups and that of non-Hispanic blacks with non-Hispanic blacks having an

average of 2.8 µg/dL compared to 1.9 µg/dL (Hispanic) and 1.7 µg/dL (non-Hispanic white) (Jones et al. 2009).

Prior research has shown a direct relationship between diffuse soil Pb in Marion County, Indianapolis, Indiana, and elevated levels of lead in children's blood (Filippelli et al. 2005). In 2008, Marion County had a population just over 876,000 with 32.5 % being minority and average per capita income \$25,546 (US Census Bureau 2008). Given the financial and logistical burden to remediate soil with elevated Pb on a city level, it has been proposed that if the same direct relationship between blood lead levels and soil Pb holds true for smaller communities, then remediation could be targeted in areas with greatest needs. The Westside Cooperative Organization (WESCO) located in the 46222 zip code of Marion County was chosen to determine whether a spatial relationship exists between low dose chronic exposure to elevated soil Pb and elevated blood lead levels on a smaller, neighborhood scale as opposed to a larger, county-wide scale. This area was chosen for study as the majority of residents are Hispanic or non-Hispanic blacks, low income, and living in older homes (many pre-1920s). Additionally, WESCO has a history of elevated blood lead levels as a direct result of previous Pb industry located in the southern portion of the neighborhood. WESCO also has an interest in environmental and urban renewal. Using blood lead levels in the WESCO area from existing medical records and a year-long filter pilot study, we assessed whether there is a relationship between interior dust, immediate vicinity soil Pb and children's blood lead levels.

The ultimate aim of this study is to compare the sections of the WESCO community to determine whether there is a difference in diffuse Pb soil concentrations—in other words, whether any “hot-spots” of Pb contamination exist. Additional aims were to examine the patterns of Pb concentration in WESCO and determine whether a correlation exists between age of the homes in the area, location of previous Pb industry and diffuse Pb in soil and to determine whether a relationship exists between the amount of the Pb in the soil and children's blood lead levels in the area using mined data from Regenstrief medical record system. Finally, this research hopes to gain a broader understanding of how Pb is spread through the environment on a small geographic scale using high-resolution sampling.

Materials and methods

Soil samples

A total of 266 soil samples were collected (December 2007–August 2009) from within the WESCO study area. Soil collection techniques involved a pooled sample of the upper 5 cm of soil from a one-square foot area of each site with each sample geo-located. It is important to note that the WESCO neighborhood contains a former Super Fund site known as “Avanti.” Many of the homes surrounding the Avanti site were subject to remediation in the 1990s. Soil samples were taken both in the remediated area and in the surrounding areas. Samples were dried overnight at 110 °C and sieved to <63 micron fraction and then weighed and ashed at 550 °C for 2 h and reweighed, to determine the organic matter content by loss-on-ignition (LOI). After ashing, the residue was digested at room temperature in 50-mL HDPE disposable centrifuge tubes for 24 h in 2 M trace metal grade hydrochloric acid on a shaker table. This sample preparation method is similar to EPA-SW846 Method 3050b, but with the substitution of ashing followed by HCl instead of nitric acid + peroxide. We have found that the technique yields results that are within tolerance for Pb in NIST-certified standards and is faster and less prone to user error (Morrison-Ibrahim 2010). Following digestion, samples were then centrifuged at 9,000 rpm for 10 min. Samples, blanks, and certified consistency standards were analyzed in triplicate using Leeman Labs PS 950 inductively coupled plasma-atomic emission spectrometry (ICP-AES) coupled with a CETAC AT5000+ ultrasonic nebulizer.

Furnace filter samples

Seven households agreed to take part in the year-long filter analysis study (Morrison-Ibrahim 2010). One of these homes was located directly across the street from the previously mentioned Avanti Super Fund site and was subject to top-soil remediation as a result of high soil Pb levels. At each home, new 3 M Filtrete MPR (microparticle performance rating) filters were installed. Starting in December of 2007 and every 2 months thereafter for 1 year, the new filters were placed in the homes and the old ones removed for analysis. All filters were processed using an investiga-

tional digestion technique that involved disassembling the cardboard frame and wire supports from filters. For each filter set, a clean, unused blank filter was processed and analyzed. Filters were then cut into two-inch-wide strips, weighed, dried overnight at 110 °C and reweighed and secured in plastic jars. Digestion of the filters involved initial removal of grease and oil residue with ethanol and overnight shaking. The ethanol was evaporated, and then 100 mL of 2 M trace metal grade hydrochloric acid and 2 mL of hydrofluoric acid were added, and the digestion vessels were shaken for 72 h. The extractant was then filtered using Whatman 2.5 µm particle retention filter paper, and 0.5 g of boric acid was added to stabilize the extractant; this mixture was then shaken overnight. The filters were processed and analyzed in triplicate along with NIST standards using Leeman Labs PS 950 ICP-AES coupled with a CETAC AT5000+ ultrasonic nebulizer. A number of metals, including Pb, were determined using this technique; percent error on replicate samples ranged from 5 to 30 %, with the replicate error for Pb averaging 8 %.

Study population

In order to study the effects of neighborhood Pb levels in soil and its relationship to children’s blood lead levels, data were mined using the Regenstrief medical record system, known internationally as one of the largest electronic medical records databases, has been in operation since 1973 and has over 660 million distinct observations from several of the major hospital systems and affiliated clinics in the Indianapolis area. The research protocol was approved by the IUPUI/Clarian Institutional Review Board. Children between the ages of 0 and 5 during the years 1999–2008 with a recorded address in Marion County and at least one serum Pb level (measured in µg/dL) were included. Other data collected included serum hematocrits, race/ethnicity, insurance status (as a proxy for income), date of serum Pb test, and the child’s age at the time of testing. Testing months were broken down into seasons as follows: winter (December, January, February), spring (March, April, May), summer (June, July, August), and fall (September, October, November). The geometric means, averages, and percentages were generated using SAS software, Version 9.1 (SAS Institute Inc. 2002–2003).

US census data/tax assessor data

To understand the demographic profile for Marion County, specifically race and percentage of children under the age of 5 years, block and block group were mapped by zip code using the available 2000 US Census data. Additionally, the age and addresses of residential homes in the WESCO area were accessed from the Marion County tax assessor's office. Area-level data on housing age was calculated by averaging these data by US Census block and block group and mapped.

Spatial analysis

In order to map the average blood lead levels for the children in the dataset, patient records from Regenstrief medical record system were geocoded using ARCMAP[®]9.2 (ESRI 2009). Street names, locations, and address numbers were mapped using topologically integrated geographic encoding and referencing (TIGER) census street data. Exclusion criteria were missing address data, addresses outside Marion County, P.O. Boxes, or lack of blood lead levels results. Addresses were mapped to their corresponding US Census block and block group. Unfortunately, for the time period January 1999–January 2002, blood lead levels lower than 10 µg/dL in the available dataset were recorded categorically as “<10” and therefore had to be excluded from means and analyses requiring continuous variables. The continuous variables for both soil and blood Pb were required for a number of the statistical analyses here, and thus, the categorical data had to be excluded. However, continuous blood lead levels data were available for the time period February 2002–December 2008 and were used for the geospatial analysis. Inverse distance weighting (IDW) was used for soil Pb spatial interpolation.

The benefit of using interpolation techniques is that it allows trends to be mapped without acquiring samples from every point in an area and can reveal potentially high levels that have yet to be physically sampled. Default kriging maps were translated into averages for each zip code, US Census block, and/or US Census block group in Marion County. A prediction error map was created and used to compare against the sample standard deviation. If the standard error is larger than the original sample standard

deviation, this will result in unreliable kriging maps. Also mapped were the proportions of children with ≥ 10 µg/dL for each US Census block group.

Results

Soil samples

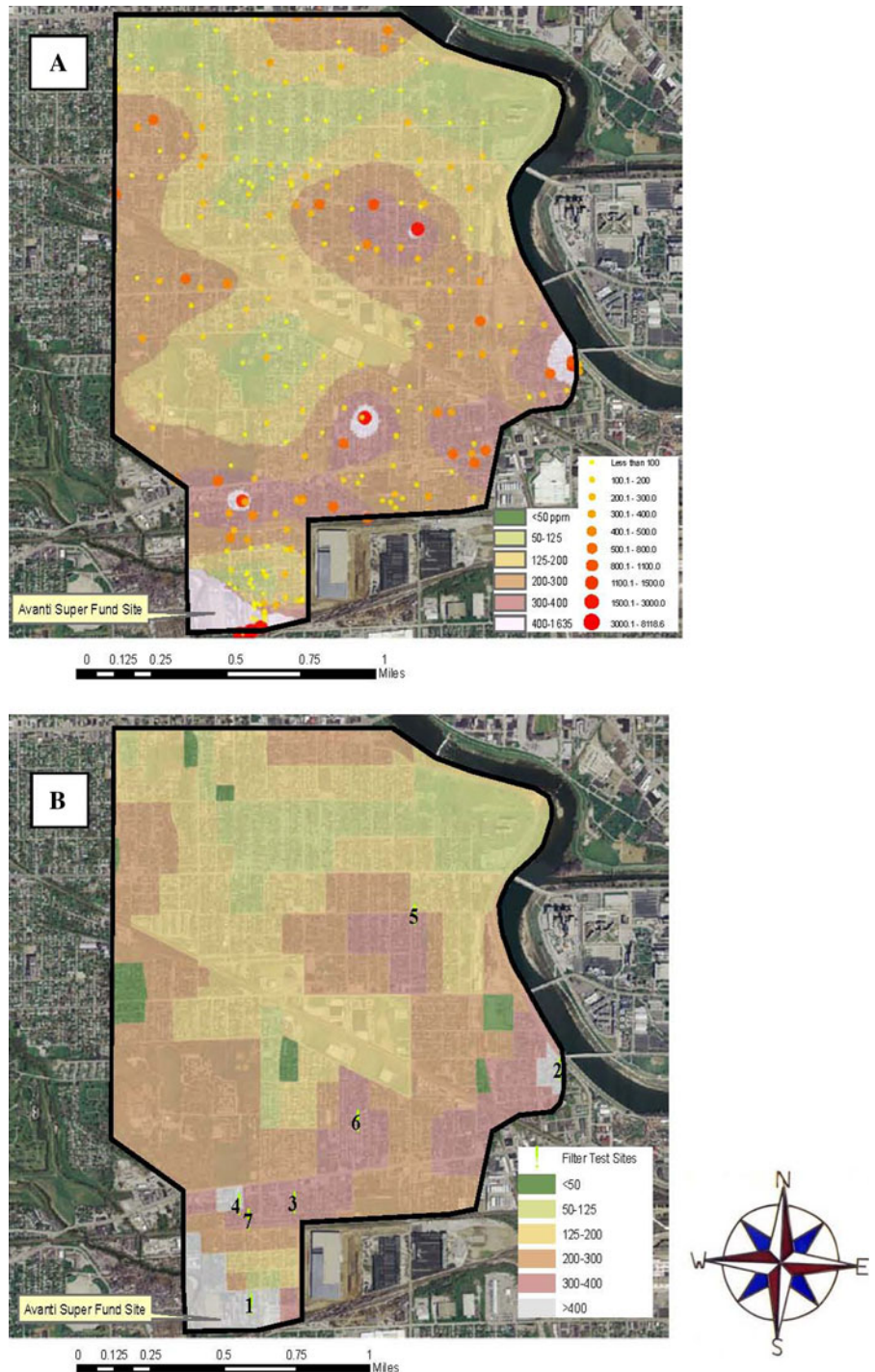
The overall average concentration of soil Pb for all 266 samples taken was 259 ppm (SD = 597). This average is driven by three extremely high samples that were located just outside the non-remediated Avanti Super Fund site (8,119, 3,759, 2,310 ppm). The overall average after removing these three samples is 207 ppm ($n = 263$; SD = 242) (Fig. 1a). The average Pb soil value inside the remediated Super Fund site was 115 ppm (SD = 108), with minimum values of 5 ppm and maximum value of 436 ppm ($n = 47$). Hotspots of higher concentrations were found in areas just north of the remediated Super Fund site as well as along the Michigan Street corridor (Fig. 1a).

Study population

A total of 16,232 records for the years January 1999–December 2008 were used for categorical analyses. Approximately 14 % of all children in Marion County live within the 46222 zip code ($n = 2,260$) and 50 % of children in the 46222 zip code live in WESCO ($n = 1,143$). The percentage of all children tested with ≥ 10 µg/dL was approximately 4.3 % with the study area of WESCO exhibiting a higher rate of 7.7 % (Table 1). Tables 1 and 2 show the increase in percentages of children with elevated blood lead levels and averages and geometric means as you move from the large geographic scale of the Marion County to the smaller zip code of 46222 and finally to the neighborhood of interest (WESCO). The average age of subjects at testing was 22 months with the youngest patient being 1 month old. Mean serum hematocrit level was 36 and appears not to be significantly associated with blood lead levels ($p > 0.05$).

The total number of patients available for continuous data analysis was 12,431 (for period of February 2002–December 2008). Averages and geometric means as well as comparisons to the US population are shown in Table 3 (US EPA 2010). The WESCO

Fig. 1 Inverse distance weighted map (IDW) of WESCO showing actual sampling points (1a). This map was then contoured and smoothed every 25 feet and averaged into US Census Blocks with sites of long-term filter testing shown (1b)



neighborhood has a higher geometric mean, averages and percentage of children with blood lead levels ≥ 10 $\mu\text{g}/\text{dL}$ as compared to Marion County children and zip code 46222 (Fig. 2). In WESCO, 33.4 % of

those tested were classified as non-Hispanic black, 16 % non-Hispanic white, and 47 % Hispanic (compared to overall Marion County which is 88 % white, 9 % black, and 4 % Hispanic).

Table 1 Demographic composition of children less than the age of five who had a recorded blood lead levels in the Regenstrief medical record system database for the period January 1999–February 2008 by % ≥ 10 $\mu\text{g}/\text{dL}$, ≥ 5 $\mu\text{g}/\text{dL}$, and ≥ 2 $\mu\text{g}/\text{dL}$

		Jan 99–Dec 08 children tested % ≥ 10 ($\mu\text{g}/\text{dL}$)			Jan 99–Dec 08 children tested % ≥ 5 ($\mu\text{g}/\text{dL}$)			Jan 99–Dec 08 Children tested % ≥ 2 ($\mu\text{g}/\text{dL}$)		
		Marion County	Zip code 46222	WESCO	Marion County	Zip code 46222	WESCO	Marion County	Zip Code 46222	WESCO
Age	All children	4.32	4.90	7.65	13.79	19.71	27.27	63.85	75.06	82.52
	0–5 months	0	0	0	11.11	100.00	0	62.68	100	66.67
	6–30 months	3.57	4.12	6.41	12.75	18.8	26.00	66.67	74.60	81.98
	31–60 months	6.68	7.74	11.88	16.94	23.26	32.04	67.38	76.74	84.53
Gender	Male	4.74	4.45	8.13	14.48	19.79	27.75	64.65	76.04	84.21
	Female	3.88	5.35	7.19	13.06	19.64	26.82	63.00	74.06	80.91
Race	Black	5.22	6.35	9.92	16.3	20.78	26.53	73.57	81.28	86.12
	Hispanic	2.98	4.53	7.69	10.59	18.70	27.78	56.54	69.78	78.85
	White	3.30	3.93	4.42	18.34	16.67	23.68	65.74	86.34	89.47
Insurance	Commercial	2.66	2.04	4.26	11.91	17.39	23.53	52.80	67.39	82.35
	Medicaid	4.39	4.54	6.88	13.8	19.20	26.38	64.35	75.21	82.38
	Wishard advantage	7.33	25.00	34.21	20.26	42.86	56.67	72.03	80.95	83.33
	Self-Pay	4.71	0	–	10.00	22.22	33.33	55.00	66.67	83.33

Table 2 Demographic composition of children less than the age of five who had a recorded blood lead levels (BLLs) in the Regenstrief medical record system database for the period February 2002–December 2008

		Feb 02–Dec 08			Feb 02–Dec 08		
		Average BLLs ^a ($\mu\text{g}/\text{dL}$)			Geometric mean BLLs ^a ($\mu\text{g}/\text{dL}$)		
		Marion County	Zip code 46222	WESCO	Marion County	Zip code 46222	WESCO
Age	All children	2.76 (12,431)	3.45 (1,664)	4.28 (883)	1.81	2.32	2.90
	0–5 months	2.11 (9)	2.00 (1)	–	1.37	2.00	–
	6–30 months	3.14 (9,347)	3.32 (1,319)	4.03 (693)	1.78	2.27	2.79
	31–60 months	2.63 (3,075)	3.96 (344)	5.17 (190)	2.00	2.55	3.30
Gender	Male	2.82 (6,404)	3.35 (839)	4.26 (432)	1.85	2.33	2.99
	Female	2.70 (6,025)	3.55 (825)	4.29 (451)	1.78	2.31	2.81
Race	Black	3.09 (4,056)	3.8 (486)	4.69 (253)	2.12	2.62	3.12
	Hispanic	2.41 (5,573)	3.33 (920)	4.26 (478)	1.56	2.11	2.76
	White	3.05 (1,856)	3.34 (183)	3.63 (117)	1.98	2.72	3.05
Insurance	Commercial	2.23 (697)	2.51 (46)	2.90 (17)	1.86	1.82	2.37
	Medicaid	2.76 (11,259)	3.33 (1,557)	4.04 (824)	1.43	2.30	2.84
	Wishard advantage	3.87 (311)	9.33 (42)	11.7 (31)	2.30	4.46	5.68
	Self-pay	3.00 (80)	2.93 (9)	3.72 (6)	1.51	2.06	2.63

Values in parenthesis are sample size

^a Blood lead levels

Table 3 Comparison of survey data for the total number of patients available for continuous data analysis was 12,431 with the geometric mean blood lead levels for those patients in the database during the period February 2002–December 2008 and compared to the blood lead concentrations for the US population (US EPA 2010)

	Years	Geometric mean in µg/dL			WESCO
		US population	Marion County	46222	
Total	99–00	1.7	NA	NA	NA
	01–02 ^a	1.5	2.02	2.19	2.27
	03–04	1.4	2.34	2.65	3.07
	05–06	1.3	2.00	2.56	3.27
	07–08	1.3	1.36	1.95	2.68
0–1 Years	99–00	NA	NA	NA	NA
	01–02 ^a	NA	1.50	2.61	2.88
	03–04	NA	1.72	2.54	3.06
	05–06	NA	1.43	2.10	3.27
	07–08	NA	1.10	1.23	1.59
1–5 Years	99–00	2.2	NA	NA	NA
	01–02 ^a	1.7	2.09	2.17	2.25
	03–04	1.8	2.40	2.66	3.07
	05–06	1.5	2.11	2.61	3.27
	07–08	1.5	1.40	2.06	2.80
Males	99–00	2.0	NA	NA	NA
	01–02 ^a	1.8	2.14	2.29	2.18
	03–04	1.7	2.41	2.57	3.13
	05–06	1.5	2.07	2.58	3.38
	07–08	1.5	1.35	1.99	2.91
Females	99–00	1.4	NA	NA	NA
	01–02 ^a	1.2	1.93	2.06	2.39
	03–04	1.2	2.27	2.73	3.01
	05–06	1.1	1.93	2.53	3.19
	07–08	1.1	1.37	1.91	2.45
Hispanic/Mexican	99–00	1.8	NA	NA	NA
	01–02 ^a	1.5	1.76	1.89	1.76
	03–04	1.6	2.05	2.60	2.87
	05–06	1.3	1.78	2.39	3.30
	07–08	1.3	1.15	1.70	2.62
Non-Hispanic blacks	99–00	1.9	NA	NA	NA
	01–02 ^a	1.7	2.30	2.23	2.56
	03–04	1.7	2.63	2.96	3.35
	05–06	1.4	2.37	2.98	3.56
	07–08	1.4	1.67	2.28	2.73
Non-Hispanic whites	99–00	1.6	NA	NA	NA
	01–02 ^a	1.4	1.99	2.94	2.77
	03–04	1.4	2.58	2.58	3.30
	05–06	1.3	2.23	2.68	3.08
	07–08	1.2	1.45	2.80	2.81

^a Data recorded for the time frame “01–02” for Marion County, 46222 and WESCO are for February 2002–December 2008 and therefore maybe be lower than expected

US census data/tax assessor data

According to the Marion County tax assessor's data, the oldest home in the WESCO area was built in 1849. Of the 5065 homes in WESCO, 89 % of these homes were built before 1960 with the median home build year being 1920. The age of home appears to not be a contributor to blood lead levels due to the lack of variation in year built. Using US Census data, approximately 7.4 % of the total population in Marion County is under the age of 5 years and US Census block groups contain on average 6.9 % children under the age of five. Only 8.4 % of the 658 US Census block groups in Marion County have >10 % children under the age of five with the highest being 44 %. All WESCO US Census block groups have 5–10 % of the total population being children <5 years of age.

Furnace filter testing

Of the seven homes that were included in the long-term pilot dust sampling (Fig. 1b), one home was in the area that was remediated as part of the Avanti Super Fund site in the 1990s. Although filter testing was carried out every 2 months over the course of year, it was determined that the months of November, December, and January were the only months where the home owners ran their furnace consistently and therefore the only data points entered into the linear regression analysis. After removing the study home that was located in the remediated Super Fund area, simple linear regression (with average soil Pb being the independent variable and average Pb dust in the home as the dependent variable) results show that 57 % of the variation of Pb dust ($\mu\text{g/g}$) in the home could be explained by the amount Pb in the surrounding soil (Fig. 3). This is an important finding highlighting that this technique appears to be a useful alternative to ascertain the interior dust accumulation in homes and that local soils play a big role in the amount of Pb dust migrating into the home.

Spatial analysis

Of the 16,232 (January 1999–December 2008) records used, 86 % were matched during geocoding with a score of 80–100 %, 5 % were matched with a score of 60–80 %, and approximately 9 % of the addresses could not be matched and subsequently mapped. The

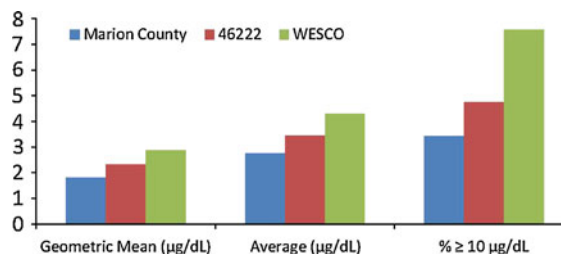


Fig. 2 Overall geometric mean and averages for all children in the study for the period February 2002–December 2008 and percentage $\geq 10 \mu\text{g/dL}$ for the period January 1999–December 2008

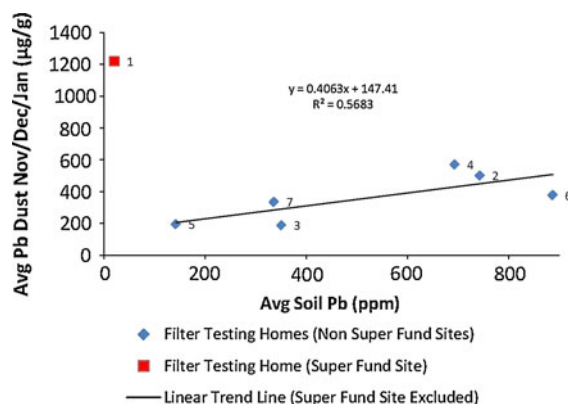


Fig. 3 Interior filter dust versus Pb dust surrounding the seven homes that took place in the year-long filter study. Home 1 was excluded from the linear regression due to the fact it is located in the area that was remediated as an EPA Super Fund site

mean blood lead levels of all children tested in Marion County by US Census block from February 2002–January 2008 were mapped (Fig. 4a). The area at the center of the map shows lower blood lead levels due to the fact that very few children live in the downtown business district. Averaged blood lead levels in the north central section of WESCO ($>5 \mu\text{g/dL}$) exhibit higher blood lead levels than other areas in the same neighborhood (Fig. 4b). The pattern of elevated blood lead levels for this area also reflects the neighborhoods racial breakdown with the same area being $>75 \%$ non-Hispanic black (Fig. 4c). When mapping blood lead levels in Marion County by zip code for the period January 1999–December 2008, the greatest percentage of children with blood lead levels $\geq 10 \mu\text{g/dL}$ is located in the urban core and decreases outward (Fig. 5). Analysis comparing soil Pb and averaged blood lead levels for each US Census block, the data available appear to show no significant correlation

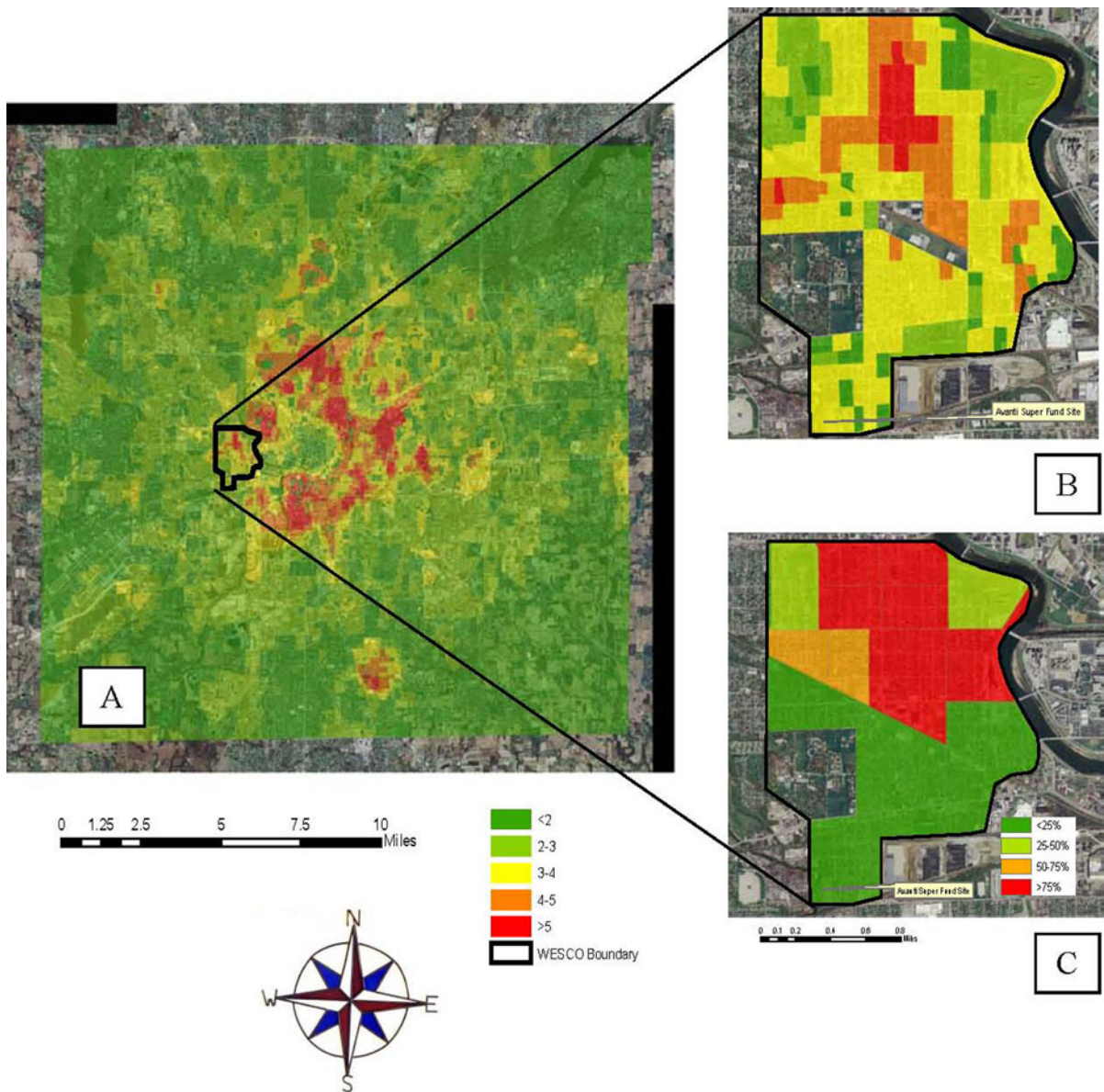


Fig. 4 Average blood lead levels for Marion County using ordinary kriging and smoothed then averaged by US Census Block for the period February 2002–December 2008 ($n = 1,2431$) (a) with the WESCO study area as a subset (b). Note the urban core of higher blood lead levels with decreasing values as you move toward suburban areas. Area at the center of

the map shows lower blood lead levels due to the fact that very few children live in the downtown business district. WESCO map shows higher blood lead levels in the north central area, which is also related to the fact this area being higher overall percentage of the total population of blacks (c)

between blood lead levels and soil Pb at the US Census block/neighborhood level. It should be noted that soil samples were collected in residential areas, and not all yards were accessible. In these cases, roadside/

curbside convenience samples were taken, which might have biased against a correlation at the US Census block/neighborhood level if these data were not representative of yard sample data.

Temporal trends

Despite an increase in the number of children tested, there is a continual decrease over time of the geometric mean of blood lead levels due to the reduction in anthropogenic sources of Pb in the environment including Pb paint usage and Pb in gasoline as well as the closure of former Pb smelting industry (Fig. 6). Given the homogeneity of the age of residential structures in WESCO, this variable was not considered substantial for inclusion in the analysis. The blood lead levels data confirm the past research showing that the urban core has higher geometric means as well as higher percentages of elevated blood lead levels. While the geometric mean for all US children is $<2 \mu\text{g/dL}$ (US EPA 2010), many Marion County children and subsequently WESCO children are still at levels much higher (Fig. 7).

Discussion

In this study, children aged 6–30 months have higher average blood lead levels than the 0–5-month-old children; males have higher average blood lead levels than females, at both the county and zip code level (Table 2). Few studies have compared blood lead levels in an age stratification model for chronic exposure, but based on population studies, blood lead levels are higher in the 2-year-old (toddler) age group than the 1-year-old (infant) age group (Yiin et al. 2000; Haley and Talbot 2004). This increase with age is due to increased mobility and hand-to-mouth behaviors of older children. Thus, the findings of this study are consistent with a behavioral driver of elevated blood lead levels in the toddler group. Interestingly, the older 31–60-month population exhibited a decrease in blood lead levels at the county level, but increased blood lead levels at the zip code and neighborhood level compared to the 6–30-month population. The primary differences between the County demographic and the zip code and neighborhood demographics are socioeconomic and racial; for example, the average household income for Marion County as a whole is \$40,278, and for zip code 46222 is \$27,297. This difference in socioeconomic status likely then leads to differences in frequency of blood lead testing, in nutrition, in access to health care, and other related factors between the greater county-wide

population and the smaller subset population. One or more of these factors are likely driving the trend toward increased blood lead levels beyond the 2-year age group in the zip code and neighborhood.

Average population blood lead levels have been related to gender, with males exhibiting blood lead levels that are $\sim 0.5 \mu\text{g/dL}$ higher than females (US EPA 2010). In this study, males tend to have slightly higher blood lead levels than females at the county scale (Table 2), but not at the zip code or neighborhood scales, where females have only slightly higher blood lead levels than males. This indicates that the population-scale gender difference generalization does not continue down to the level, where the influence of differential exposure burden is a more important driver across genders.

One of the most significant differences in average blood lead levels is related to race. Within the WESCO neighborhood, non-Hispanic blacks have average blood lead levels of $4.69 \mu\text{g/dL}$, whereas Hispanics average $4.26 \mu\text{g/dL}$ and non-Hispanic whites average $3.63 \mu\text{g/dL}$. These are all well above the average blood lead levels for each race in Marion County as a whole (Table 2). These racially related differences are consistent with those observed in national surveys (Table 3; CDC 2011).

One of the purposes of this study is to understand the small-scale spatial variations in both blood lead levels and in soil Pb values, with the aim of understanding the spatial link between potential exposure source (i.e., soils) and the exposed population. The WESCO community comprises three major racial groups, but these groups have relatively comparable socioeconomic status. Furthermore, housing stock age is relatively old (89 % before 1960 and median house age of 1920) and constant. Thus, Pb-based paint application is expected to be relatively consistent throughout the neighborhood. We found that soil Pb values exhibit a significant range in values across WESCO (Fig. 1). When soil Pb sample values are averaged at the census block level, regions emerge with relatively low soil Pb, including portions of the central and northern part of WESCO. Furthermore, areas of the south and west part of the neighborhood exhibit relatively high soil Pb values (Fig. 1). This variation is not likely due to Pb-based paint because of housing age consistency across the neighborhood, but rather to traffic volume and industrial sources. When viewed in relation to average blood lead levels

Fig. 5 County breakdown of percentage of children with elevated blood lead levels by zip code for the period January 1999–December 2008

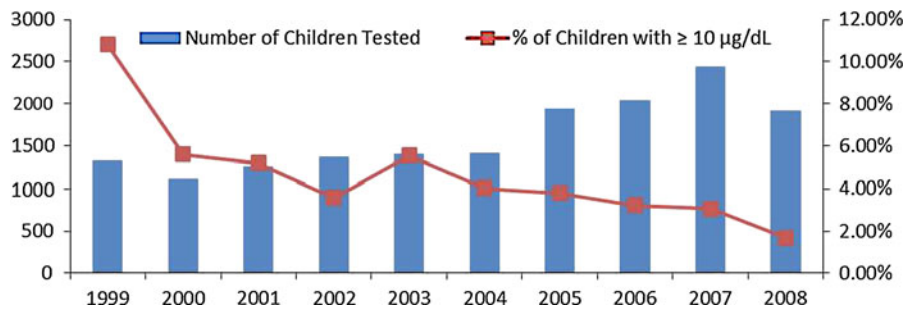
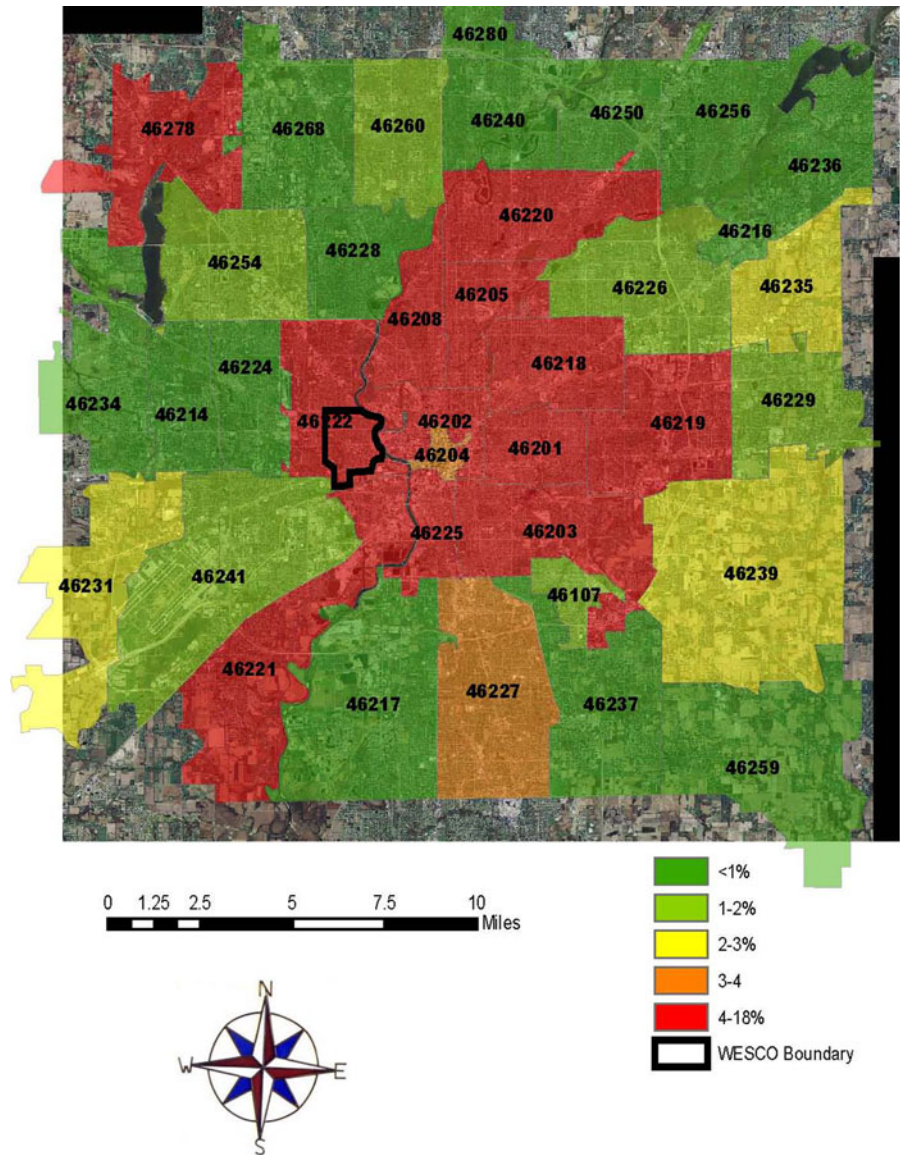
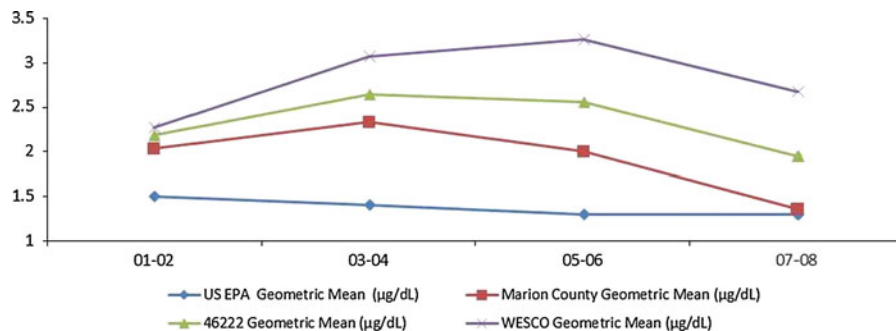


Fig. 6 Number of children tested during the study period of January 1999–December 2008 with the percentage of children with elevated blood lead levels. Note the number of children

being tested is increasing but the overall percentage of children being Pb poisoned decreasing

Fig. 7 Geometric means for the US population children (US EPA 2010), Marion County, zip code 46220, and WESCO. Note that geometric means are higher in Marion County, zip code 46222, and the WESCO neighborhood than national means



(Fig. 4b), no consistent spatial relationship emerges between soil Pb and blood lead levels at the neighborhood scale. As noted before, average soil Pb values are higher in WESCO than in Marion County as a whole, as are average blood lead levels. The lack of a clear spatially driven relationship between soil Pb and blood lead levels within WESCO may be due to spatial differences racial composition of WESCO. The sub-neighborhood where the average blood lead levels are highest (Fig. 4b), and soil Pb is only slightly elevated (Fig. 1), is dominated by non-Hispanic blacks (Fig. 4c). Thus, it appears that race trumps soil Pb values in driving small spatial-scale differences in blood lead levels.

The pilot home filter testing study results show that proximal soil Pb concentrations around the homes account for almost 60 % of the variation in the Pb dust inside on the filter. An interesting finding, and one that needs further exploration and research, is that the one home with the highest interior Pb was in the area of the Avanti Super Fund soil remediation site. As the average of samples in this area was 115 ppm, significantly less than the overall average of 259 ppm, proximal soil resuspension cannot be driving the signal here. But extremely high values of soil Pb are found just adjacent to the Avanti plant site (i.e., ~8,000 ppm). We suggest that the high interior Pb values of the home within the Avanti Super Fund remediation zone is due to (1) fugitive dust still being emitted from the Pb-contaminated soils in and around the Avanti site itself and/or (2) residual dust remains in the house and is being actively redistributed. Recent testing at the Avanti site itself, conducted while demolition of buildings was occurring in January 2012, revealed average surface soil values of 23,070 ppm ($n = 4$; min. = 998 ppm; max. = 49,350 ppm; Filippelli et al. unpublished data), thus favoring the

fugitive dust hypothesis. This is further supported by the fact that soil Pb values of the fill used to remediate yards were likely close to the natural soil background level (~30–50 ppm), and now, 15 years later, average 2.3–3.8 higher than this. Regardless of which is the critical cause for elevated interior dust Pb levels, either of these scenarios lends caution to the assumption that the current model for soil remediation is adequate for protecting human health.

Conclusion

Data from the study confirm the hotspots of elevated blood lead levels as represented by county-wide mapping with the urban core posing the greatest general risk for children living in cities. The novel technique for examining interior house Pb accumulation proved successful both analytically and for identifying one site with remediated Pb but with obviously significant Pb accumulation from fugitive dust from the smelter's non-remediated areas. Additionally, soil Pb is correlated with interior Pb accumulation at least as identified within the constraints of the filter sampling. This investigation reveals that soil Pb and blood lead levels share high degree of variability at the neighborhood level (WESCO) with neither being predicted by the age of housing. While income was not a predictor of BL blood lead levels L variation, race indeed did emerge as an indicator for potential elevated BLLs.

Since 1999, the percentage of children who exhibit elevated blood lead levels has slowly decreased due to the removal of anthropogenic sources of Pb in the environment; however, the current push to reduce the “action level” to <5 µg/dL or even <2 µg/dL (Zahran et al. 2009) means that many children will continue to

be subject to the adverse effects of Pb in the environment with 64 % Marion County children and 83 % of WESCO children under the age of five with blood lead levels ≥ 2 $\mu\text{g/dL}$. Ultimately given that it has been reported that each dollar spent on lead prevention efforts produces \$17–\$221 in benefits including higher IQ, more tax revenue, lower spending on special education needs and less criminal activity (Gould 2009) targeting smaller areas such as neighborhoods for remediation would provide the most cost efficient way of reducing the adverse health effects of Pb in children.

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