Environmental Research 191 (2020) 110112

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Spatial-temporal association of soil Pb and children's blood Pb in the Detroit Tri-County Area of Michigan (USA)

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ARTICLE INFO

Keywords:
Children's blood lead decrease
Lead aerosols
Soil lead decline rates
Topsoil lead
Urban lead survey

ABSTRACT

Lead is a well-known toxicant associated with numerous chronic diseases. Curtailing industrial emissions, leaded paint, lead in food, and banning highway use of leaded gasoline effectively decreased children's exposure. In New Orleans, irrespective of Hurricane Katrina flooding, lead declined concurrently in topsoil and children's blood. We postulate that topsoil lead and blood lead decreases are associated and common in U.S. cities. This study tests that concept. A small 2002 soil lead survey of 8 Detroit Tri-County Area census tracts was repeated in October 2019. Between 2002 and 2019, Detroit median soil lead decreased from 183 to 92 mg/kg (or 5.4 mg/kg/yr.) and declined in Pontiac from 93 to 68 mg/kg (or 1.4 mg/kg/yr.). Median soil lead remained ~10 mg/kg in outlying communities. Median soil lead (in mg/kg) in communities at $<$ 21 km compared to $\geq$ 21 km from central Detroit, respectively, decreased from 183 to 33 (P-value 10^{-12}) in 2002 and from 92 to 35 (P-value 10^{-07}) in 2019. Children's lead exposures were highest in Detroit (population 0.7 million in 2010) and lower by more than half in Pontiac (population 60 thousand in 2010). Between 2002 and 2018, children with blood lead $\geq$4.5 μg/dL in Detroit declined from 44% to 5%, and in Pontiac from 17% to 2%. The most vulnerable children live in the most lead contaminated communities. To meet the goal of primary prevention for children, along with other efforts, this study supports landscaping with low lead soil to reduce exposure in lead contaminated communities.

1. Introduction

The central question of this study is whether there is evidence that soil lead (SPb) and blood lead (BPb) undergo concurrent declines in communities of the Detroit Tri-County Area as previously described for New Orleans communities (Mielke et al., 2019). This study was undertaken in the context of a prior lead (Pb) study that described the concurrent declines of soil lead (SPb) and children's blood Pb (BPb) during an interval of ~15 years in New Orleans (Mielke et al., 2019). The New Orleans study is unique for its large size and the results of the robust associations (P-values 10^{-17} and 10^{-11}) of concurrent SPb and BPb decreases in 2001 and 2017, respectively (see Table 1, p. 22061, Mielke et al., 2019). The decreases occurred in both Hurricane Katrina-flooded and, unexpectedly, unflooded communities of New Orleans. If the outcomes were so remarkably robust, then they suggest that concurrent SPb and BPb declines are probably occurring in less than 2 decades in other cities (Mielke et al., 2019). This study explores SPb and BPb changes in the Detroit Michigan Tri-County Area during an interval of 17 years.

Although the health effects of Pb exposure were known for at least 2000 years, the magnitude of societal adverse health damage was not fully comprehended until after the middle of the 20th century (Needleman and Gee, 2013). Appropriately sensitive analytical tools for measuring Pb evolved slowly and were not widely available until the 1960's (Parsons and McIntosh, 2010). Meanwhile, commercial Pb production increased exponentially, dispersing enormous quantities of Pb into the environment, especially during the 20th century (Patterson, 1980). In concert with advances of analytical tools, the connections between Pb dust particles, Pb contaminated urban soil environments, and adverse health effects of Pb were measured beginning in the 1960's to the present (Patterson, 1980; Mielke and Reagan, 1998).

Reducing Pb aerosol sources diminished Pb dust accumulation on outdoor and indoor surfaces and decreased children's exposure. The

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https://doi.org/10.1016/j.envres.2020.110112
Received 19 May 2020; Received in revised form 13 August 2020; Accepted 14 August 2020
Available online 27 August 2020

Table 1
Soil Pb percentiles for all samples in the 2002 and 2019 surveys of the Detroit Tri-County Area. Samples were analyzed by EDXRF. The results were compared for significant differences by MRPP.

Soil Pb (mg/kg)	2002	2019	
	All samples	All samples	
N Samples	152	152	
min	10	10	
10%	10	10	
25%	24	21	
50%	**92**	**58**	
75%	200	152	
90%	375	257	
max	1147	910	
MRPP P-value			0.013

rapid phasedown of Pb additives in gasoline coincided with a sharp decline of children's BPb in the U.S. and abroad (Annest et al., 1983; Pirkle et al., 1994; Landrigan et al., 2018). After an initially rapid decline in children's BPb the reduction continued at a slower rate (McClure et al., 2009–2015; Tsoi et al., 2016; Panticet al., 2018). The role of SPb in the decline is an important question. The Cochrane Collaboration, an important international organization for evaluating the effectiveness of medical interventions, indicated that soil remediation and/or a combination of actions to reduce children's Pb exposure were not been reviewed because of a lack of data for a comprehensive analysis (Nussbaumer-Streit et al., 2016. The present study contributes to filling the SPb data gap described by the Cochrane Collaboration.

Previous research in Detroit and Flint Michigan indicated that BPb declines appeared to be related to SPb decreases (Zahran et al., 2013; Laidlaw et al., 2016). This study builds on research published in January 2003 from a small SPb survey conducted during October 2002 in Detroit, Pontiac, and small outlying residential communities (Wendland-Bowyer, 2003). Here we update children's Pb exposure in Detroit and Pontiac and introduce newly collected SPb sample data from 8 census tracts after a 17-year interval. The goal is to determine whether the declines in SPb and BPb over 17 years in the Michigan Tri-County Area are consistent with the concurrent reductions of children's SPb and BPb observed in Metropolitan New Orleans.

2. Methods

The location for this study is the Detroit Michigan Tri-County Area. The survey design involved selecting three groups of census tracts based on criteria deemed important as determinants of the quantities of SPb based on previous research (Mielke et al., 1983, 1989, 2005). The three groups of census tracts were from a large city, Detroit (4 census tracts) a smaller city, Pontiac (2 census tracts); and newer less urbanized communities (2 census tracts). Another factor considered was the distance from downtown Detroit, 1401 West Fort Street (U.S. Post Office), to the centroid of each census tract. Four Detroit census tracts were within 21 km and the four 4 census tracts were located equal to or beyond 21 km of downtown Detroit.

2.1. Soil Pb data

The soil sample collection protocol was refined in a 1998–2002 survey in New Orleans (Mielke et al., 2005). The same protocol was applied to Detroit collections in 2002 and repeated in the 2019 surveys (Mielke et al., 2005, 2019). The field collections for both Detroit surveys were conducted by co-authors Eric Powell and Aila Shah (Wendland-Bowyer, 2003). Topsoil samples 2–3 cm deep were collected from 8 census tracts located in the Tri-County Area of Detroit. The U.S. census tract boundaries for 2000 were used for both surveys (Census Bureau. 2019., 2019). The new SPb survey was conducted October 2019. The protocol requires the collection of 19 topsoil samples per census tract. Sample locations were selected from residential sites throughout each census tract. Four different soil sample types were collected in each census tract: 9 samples were from within 1 m of residential streets (residential street-side soils), 4 samples were from within 1 m of busy streets (busy street-side soils), 3 samples from within 1 m of house sides (foundation soils) and matched with street side samples, and 3 samples were collected away from streets and foundations in yards, vacant land, or parks (open space soils). Sample locations were geocoded by street address using Google Maps. All the data was integrated and further analyzed using ESRI ArcGIS Desktop10 software (Environmental Systems Research Institute, 2011).

A handheld Energy Dispersive X-ray Fluorescence (EDXRF) instrument was used for analysis (Thermo-Fisher. https://ww, 2020). The archived samples from the 2002 survey and the fresh samples of the 2019 survey were analyzed. Soil samples were dried, sieved to 2 mm, and stored in low-density polyethylene bags. Analysis was done on soil samples in the bag. Each sample was tested for 30 s to estimate total SPb. All samples measuring below the detection limit (20 mg/kg) were assigned a value of 10 mg/kg. A reference sample and blank were included throughout sample analysis (How to Test Soil for Lead, 2020). The XRF results are equivalent to 1 M HNO_3 leachate results observed in previous studies (Mielke et al., 2005).

2.2. Blood Pb data

Children's BPb data was provided on request from the Michigan Department of Health and Human Services (MDHHS) (MIDHHS Michigan blood lead data request, 1998–2017). The dataset is maintained by the Michigan Childhood Lead Poisoning Prevention Program (MICLPPP). The MICLPPP BPb data for Detroit and Pontiac was transmitted as the percent of children under 6 years old with BPb $\geq$4.5 µg/dL ("elevated blood lead") by year. It was current as of September 17, 2018 and includes data for 1998–2017. Each child is counted only once per year. If a child had multiple tests in the year, the highest BPb obtained from a venous test was counted. If no venous test was performed, the highest BPb obtained from a capillary blood draw was counted. If the type of test was unknown, the highest BPb obtained from an unknown sample type was counted (MIDHHS Michigan blood lead data request, 1998–2017).

2.3. Study limitations

One important difference between the New Orleans and Detroit surveys is the number of census tracts sampled in each city. The New Orleans study consisted of 274 census tracts (N ~ 4800 samples per survey) that were collected in an area of 427 km^2 (Mielke et al., 2019). In the Detroit Tri-County Area, 8 census tracts (N = 152 samples per survey) collected in an area of 5095 km^2. The task of repeating a survey for 8 census tracts after a gap of 17 years is problematic. While the dataset for Detroit Tri-County Area is limited, the permutation statistical results of the SPb environmental signal combined with the BPb response of children from MICLPPP data provides evidence about spatial-temporal changes.

2.4. Permutation statistical methods

Deciphering possible spatial-temporal changes from a relatively small dataset (N = 152 × 2) surveyed in 2002 and 2019 in the relatively large Detroit Tri-County Area is the quest for this study. Statistical analysis often involves removal of outliers as well as transformations of data to meet the assumptions and conform to the normal distribution required by some statistical models. We use Multi-Response Permutation Procedure (MRPP) which is a data-dependent model that uses all available, non-transformed data. MRPP is part of a group of statistical tests developed by P.W. Mielke, Jr. and others (Berry et al., 2014; Cade and Richards, 2005). The tests are particularly valuable for analysis of small datasets such as available in this study. MRPP calculates the exact moments of the underlying distribution of all possible permutation arrangements of the observed data and provides an approximate and accurate probability value without assuming normality or homogeneity of variance. An important feature of MRPP is that unlike most statistical techniques, it is compatible with Euclidean geometry on which cartography is based (Mielke and Berry, 2007).

3. Results and discussion

3.1. Soil Pb

Overview of the decline of SPb in Detroit's Tri-County Area.

This study includes soil samples collected in October 2002 and October 2019, respectively. The samples are collected by census tracts in Detroit and suburbs, Pontiac, and outlying communities of the Detroit Tri-County Area.

A SPb decrease occurred between the two surveys. The median SPb decreased from 92 mg/kg in 2002 to 58 mg/kg in 2019 (P-value = 0.013). Additional evaluation considered the SPb results as a function of distance from the center of Detroit.

Comparisons between census tracts < 21 km vs. ≥ 21 km from downtown Detroit.

Further assessment of environmental Pb was conducted by sorting the SPb data by distance within the Detroit Tri-County Area. Eight census tracts were sorted into two groups of 4 census tracts according to their distances from Detroit's downtown main office of the U.S. Postal Service (USPS), 1401 West Fort St, Detroit, MI. One set of 4 census tracts are located within 21 km of the downtown USPS, and the second set of 4 census tracts are located equal to or greater than 21 km from the downtown USPS. Fig. 1 is a map showing the two groups of census tracts.

As illustrated in Fig. 1, the Detroit Tri-County Area was divided into census tracts centered < 21 km of downtown Detroit and census tracts ≥ 21 km including the smaller city of Pontiac and outlying rural communities. There are important differences between the two areas. The Detroit sector has a larger population and a long history of industrialization. The Pontiac/outlying sector has a smaller population, is less industrialized, and more agricultural.

Table 2. Distance from Detroit Main PO (Fig. 2).

Table 2 shows the SPb data by percentiles according to distance from the downtown Detroit USPS for the 2002 and 2019 surveys of the census tracts in this study. The permutation test (s) P-values are listed below Table 2. The results show that for 2002 the median SPb for the Detroit group was 183 mg/kg compared to 33 mg/kg for the Pontiac and distant census tracts (P-value 9.0×10^{-12}). In 2019, the median SPb for the Detroit group was 92 mg/kg compared with 35 mg/kg for the more distant group of census tracts (P-value 6.9×10^{-7}). In the 2002 and 2019 surveys SPb was much higher in the Detroit Sector than in the outlying Sector. Distance from downtown Detroit plays a significant role in SPb contamination in the Detroit Tri-County Area, a finding observed in the

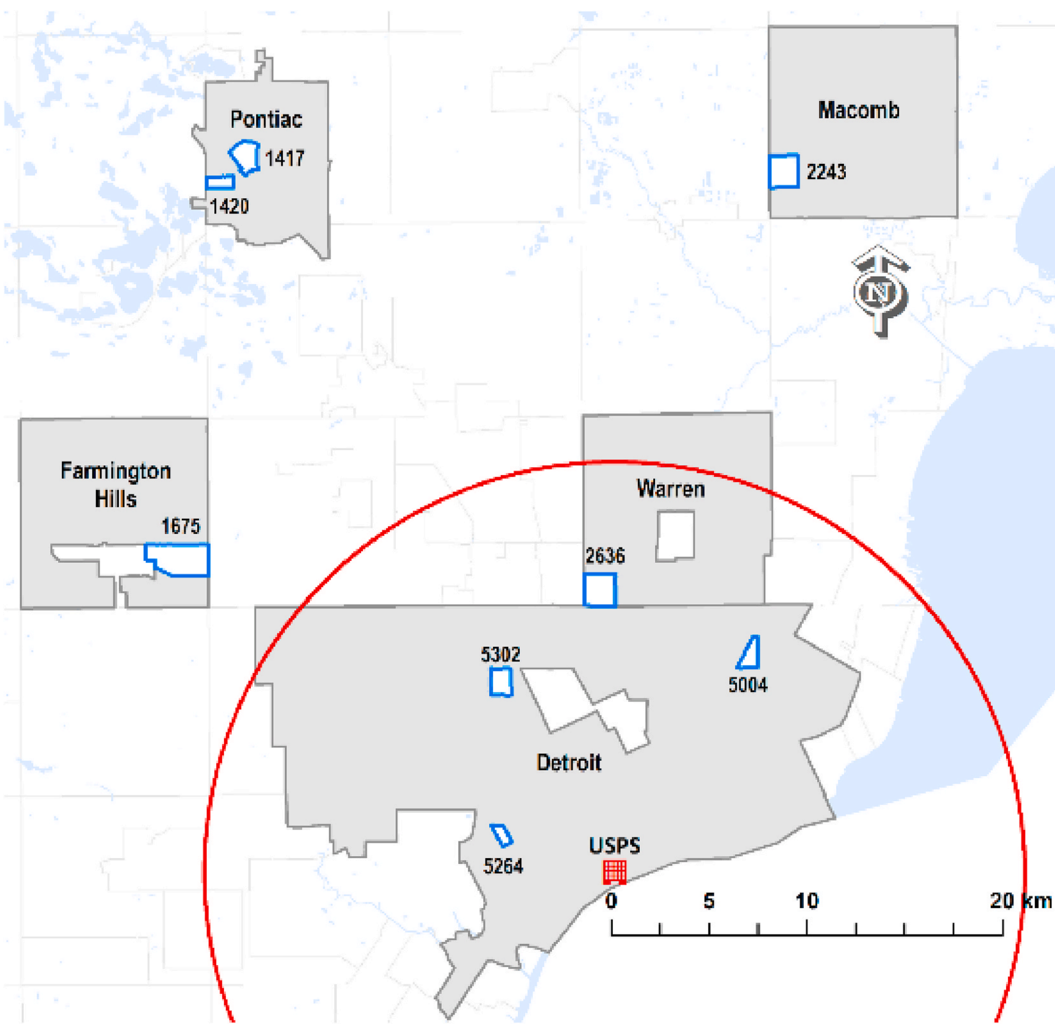

Fig. 1. Soil Pb data according to census tract distance from Detroit's downtown Post Office USPS. There are 4 census tracts <21 km in downtown Detroit USPS, and 4 census tracts, Pontiac, Macomb and Farmington Hills ≥21 km of Detroit USPS.

Table 2
Soil Pb in Detroit Tri-County Area census tracts. The data is presented in percentiles for the two surveys, divided into the NEAR and FAR groups. The census tracts include 4 in Detroit (NEAR) 2 in Pontiac, and 2 census tracts in the less urbanized areas of Farmington Hills and Macomb Township (FAR). The MRPP P-values for various group comparisons are included.

	NEAR	NEAR	FAR	FAR
	2002	2019	2002	2019
N	76	76	76	76
Min	10	10	10	10
10%	37	20	10	10
25%	88	46	10	10
50%	**183**	**92**	**33**	**35**
75%	348	203	104	74
90%	523	335	174	139
Max	1147	910	475	790
Comparisons	**P-value***			
NEAR 02 vs. FAR 02	$\mathbf{9.0 \times 10^{-12}}$			
NEAR 19 vs. FAR 19	$\mathbf{6.9 \times 10^{-07}}$			
NEAR 02 vs. NEAR 19	**0.003**			
FAR 02 vs. FAR 19	**0.499**			

*MRPP
NEAR = < 21.0 km to downtown Detroit (US Post Office)
FAR = ≥ 21.0 km to downtown Detroit (US Post Office)

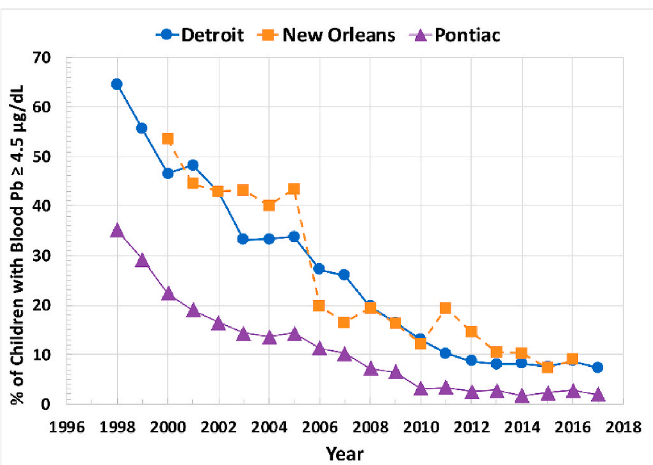

Fig. 2. Illustrates the percent of children under 6 years old with BPb ≥ 4.5 µg/dL by year. Results for Detroit and Pontiac are for children tested from 1998 through 2017 and for New Orleans's children tested from 2000 through 2016. The Michigan data is from the MDHHS.

Baltimore urban garden study (Mielke et al., 1983). The SPb decreases demonstrated by NEAR and FAR communities in both 2002 and 2019 are robust and consistent with the findings observed in New Orleans (Mielke et al., 2019).

Between 2002 and 2019, the median SPb in the Detroit sector (NEAR) saw the largest change from 183 to 92 (P-value 0.003). In the Pontiac and rural community sector (FAR), the SPb was 33–35 mg/kg in 2002 and 2019, respectively, and essentially unchanged (P-value = 0.499). The SPb decreases between 2002 and 2019 mainly occurred within the most intensely urbanized area < 21 km of the center of downtown Detroit compared with ≥ 21 km in the least urbanized Pontiac and rural sector of the Detroit Tri-County Area.

3.2. *Comparisons according to degree of urbanization*

Further analysis was done by dividing the census tracts into 3 groups according to the combination of city size and degree of urbanization. Table 3 lists the SPb results according to city, Detroit (census tracts representing a large city), Pontiac (census tracts representing a small city), and Farmington Hills and Macomb Township (census tracts representing less urbanized outlying communities).

When comparing changes between surveys, the smallest P-values (largest changes) occurred in the most urbanized communities (census tracts) of Detroit, and the largest P = values (slightest or no change) are associated with Pontiac and the least urbanized census tracts, Farmington Heights and Macomb Township. When comparing 2002 vs. 2019 surveys, the P-values are smaller (0.003) for Detroit than Pontiac (0.423) indicating essentially no statistical difference. This finding underscores the limitations of this study.

The challenges for determining temporal changes of urban SPb from a small sample set are demonstrated by the SPb results for Pontiac. Table 3 shows the large P-value (i.e., not a statistically significant change) for Pontiac between 2002 and 2019. This result is due to SPb data in one census tract (1420) that increased in 2019 compared to 2002. As a result, the Pontiac SPb data for 2019 is higher at the 90th (283 vs. 272) and maximum (790 vs. 475) than for the 2002 data. Out of 152 newly collected soil samples, 19 (12.5%) exhibited an increase while 133 (87.5%) soil samples showed either a decrease or no change in SPb collected in 2019 compared with SPb samples collected in 2002. The results from one census tract (or 12.5% of the newly collected samples) have influenced the following: the P-value between 2002 and 2019 for Pontiac, the 2019 Detroit vs. Pontiac P-value, and the 2019 the P-value result between Pontiac vs. FH/MT. An additional limitation is that dust loading was not measured in this study.

Nevertheless, this study shows median SPb in Detroit > Pontiac > Farmington Heights and Macomb Township, and this is consistent for the declining SPb observed between the 2002 and 2019 surveys.

Fig. 2 displays the decline in the percentage BPb ≥4.5 µg/dL for children tested annually in Detroit, New Orleans and Pontiac.

The results in Fig. 2 for children's BPb in Detroit, Pontiac, and New Orleans show declining trends between 1998 and 2017. In addition to temporal decreases of BPb, the children of Pontiac consistently exhibit lower BPbs than children living in Detroit. This observation is consistent with previous studies in Minnesota, The Netherlands, and Beijing regarding the effect of city size on BPb (Mielke et al., 1989; Brunekreef et al., 1983; Mao et al., 2014). Additionally, between 2010 and 2015 studies across Michigan, including of Detroit and Flint, show that BPb declined over five years. Summertime seasonal peaks of BPb indicate that outdoor play activities and soil resuspension are a driving factor for children's Pb exposure responses (Zahran et al., 2013; Laidlaw et al., 2016).

Table 3
Soil Pb percentiles (mg/kg) of samples grouped according to degree of urbanization. The MRPP P-values for group comparisons are listed in order of strength/significance.

	Detroit		Pontiac		FH & MT	
SPb (mg/kg)	2002	2019	2002	2019	2002	2019
N	76	76	38	38	38	38
Min	10	10	10	10	10	10
25%	88	46	43	42	10	10
50%	**183**	**92**	**93**	**68**	**10**	**10**
75%	348	203	152	118	24	29
90%	478	327	272	283	55	66
Max	1147	910	475	790	155	80
P-value*		*0.003*		*0.423*		*1.000*

MRPP results. Detroit including Warren Pontiac
FH & MT: Farmington Hills & Macomb Township

2002	***P-value****
Detroit vs. Pontiac	2.9×10^{-04}
Detroit vs. FH/MT	6.6×10^{-13}
Pontiac vs. FH/MT	3.4×10^{-09}
2019	
Detroit vs. Pontiac	*0.083*
Detroit vs. FH/MT	2.0×10^{-10}
Pontiac vs. FH/MT	6.7×10^{-09}

***MRPP**

Note that overall, there is a decline of children's BPb in Detroit, Pontiac, and New Orleans. Comparing the children living in Detroit with Metropolitan New Orleans indicates larger BPb variations for New Orleans children in 2005 through 2007. These years were before and after Hurricane Katrina, which flooded large areas of the city, forcing citizens to evacuate when city services ceased (McQuaid and Schleifstein, 2006). However, the results from the New Orleans study demonstrated that despite the Hurricane, SPb and BPb decreased concurrently in both flooded and unflooded communities of the city (Mielke et al., 2019). Children living in the smaller city of Pontiac, have reduced BPb responses compared with the larger cities of Detroit and New Orleans. This trend is consistent with results in other studies conducted among cities of differing sizes (Mielke et al., 1989; Brunekreef et al., 1983; Mao et al., 2014).

As shown in Fig. 3, children's Pb exposure is unequally distributed in the Detroit Tri-County Area. Research conducted by Bickel in 2010 observed that BPb of children living in Detroit inner city ZIP Code Tabulation Areas were 2–3 times higher than children living in outlying ZIP Code Areas (Bickel, 2010). Spatial disparities in BPb are described in multiple studies including Indianapolis, Philadelphia, and Syracuse (Filippelli et al., 2015; Philadelphia Child Blood, 2013–2015; Johnson and Bretsch, 2002).

3.3. Airborne Pb inputs and legacy SPb

Along with smelters, various manufacturing facilities, and deteriorating lead-based paint, there is one source that stands out as a contributor to the pattern of settled Pb dust in urban areas. In 1925 the gasoline additive tetraethyl Pb (TEL) was approved for use by the US Public Health Service (Treasury, 1925). Michigan and especially Detroit was the center for automobile development and technological innovation, including the promotion of TEL (Kovarik, 2005). Vehicles fueled with leaded gasoline exhausted various sized particles in proportion to traffic flows, and cities were especially susceptible to Pb contamination. The use of TEL grew exponentially through the 1950s, into the 1970s, and peaked in 1975 (Michael et al., 2004). Air pollution control regulations were introduced to improve urban air quality. The technical feat was achieved by the addition of the catalytic converter to the exhaust system. Removal of TEL as an additive was required to prevent damage to the catalyst (O'Connor, 1975). In the US, inputs of Pb aerosols declined after 1975. Demand for unleaded gasoline increased in proportion to vehicles equipped with catalytic converters.

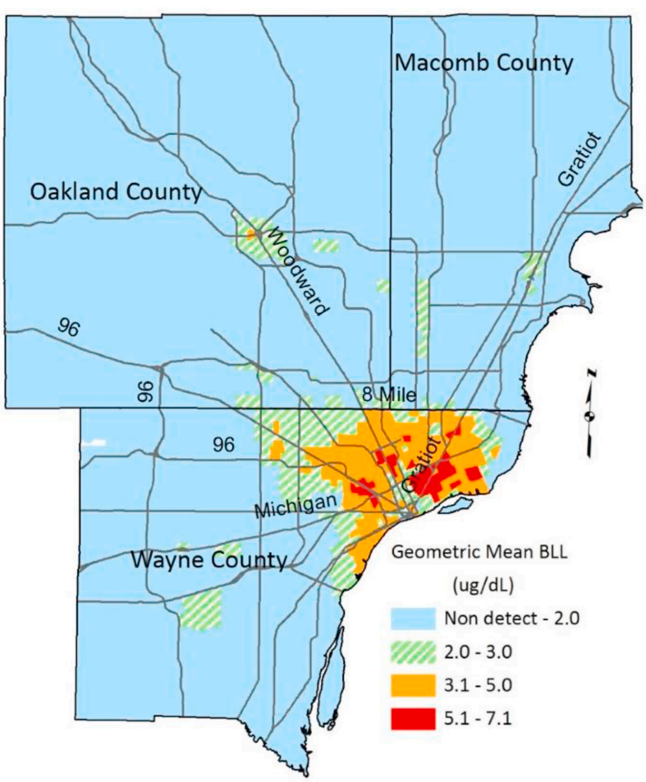

Fig. 3. Spatial distribution of the geometric mean blood lead of children ≤6 years old in the Detroit Tri-County Area 2010 (Mao et al., 2014). Republished with permission, Michael Bickel, P.E., Metro Engineering Solutions, Livonia Michigan.

From 1950 through 1982, Pb emitted from the use of leaded gasoline (0.53 g per liter or 2 g per US gallon) resulting in a total in the US of about 4.6 million tonnes (Mielke et al., 2011). Detroit ranked 4th of 90 US cities during this era and the city was subjected to an estimated >38,100 tonnes of Pb aerosols emitted as exhaust combustion particles (Mielke et al., 2011). For the Detroit Tri-County area (5095 km^2) the amount of Pb emitted is estimated at 7.5 tonnes per km^2. However, the most densely populated and older Detroit urbanized area is approximately 185 km^2. If we assume that during the decades of TEL use, half of the estimated Pb (19,050 tonnes) were atmospherically deposited in the confines of older Detroit, then 103 tonnes per km^2 of Pb dust would have been exhausted in Detroit's oldest urban communities along with the collective Pb exhaust from smelters and other industries.

The estimated >38,100 tonnes of combustion particles were composed of about 20,300 tonnes of Pb ≤ 10 μm-sized particles and 17,800 tonnes of Pb ≤ 2.5 μm-sized particles (Mielke et al., 2011). The extremely small combustion particles readily penetrate the membrane of the lung's alveoli and enters directly into the circulatory system. The absorption of Pb via inhalation accounts for the strong association between leaded gasoline use and BPb (Annestet al., 1983). Along with inhalation, ingestion of Pb, especially by children through common hand-to-mouth behavior, is an exposure route from the legacy sources of Pb dust (Mielke et al., 2007). The ease of exposure from of combustion particles accounts for the chronic neurological outcomes associated with Pb exposure (Wang and Xiong, 2017; Cecil et al., 2008; Marshall et al., 2020).

The quantity of legacy SPb in Michigan cities depends on the location of residential communities with respect to distance from the Detroit city center, and traffic flow patterns in each city. Soil Pb is an environmental signal. Depending on census tract location, children's Pb exposures responses mirror community wide Pb aerosol inputs. Pb dust deposition on topsoil, seasonal Pb dust resuspension, and aerosol transport are important processes that link SPb with children's Pb exposure (Laidlaw et al., 2005; Laidlaw and Filippelli, 2008; Levin et al., 2020). The outdoor environmental Pb contributes to indoor environmental Pb contamination via aerosol resuspension and footwear track-in of Pb into home interiors (Hunt et al., 2006; Hunt and Johnson, 2012). Legacy Pb in topsoil is a persistent multi-route source of exposure via inhalation, direct hand-to-mouth ingestion, and climate driven dust resuspension of Pb aerosols (Mielke et al., 2019, 2020).

3.4. Processes that reduce urban soil Pb

In most cities and towns, processes operate to decrease legacy SPb, especially in surficial layers. Given that SPb concentrations are often depth dependent and highest in surficial soils or A horizons, any process that mixes, buries, or transports contaminated surficial horizons will tend to decrease SPb in surficial layers (Li and Shuman, 1996; Galbraith, 2018). Although not yet widely studied in cities, many soil processes are likely responsible, processes known as urban pedogenesis (Wade, 2020). Cities are landscapes intensively built upon and rebuilt, and repeatedly cut and filled. Soils are dynamic in rural landscapes, but in the cities mulching, landscaping, construction are also ongoing dynamic processes. Considering Pb contamination as a 20th-century input to the city's soils, we can expect that over time SPb concentrations will diminish simply due to the city's physical growth and development.

Several approaches have been developed to address urban SPb contamination (Laidlaw et al., 2017).

In addition, many city soils are subject to high rates of erosion from water and wind. Erosion by water can redistribute Pb-contaminated soil particles, especially over decadal time scales, depositing them in floodplains and transporting them through storm drains. Erosion rates of 10–100 Mg/ha per year equate to the removal of about 0.7–7 mm of surface soil per year, and thus erosion is an important flux for understanding changes in SPb over decades of time (García-Ruiz et al., 2015). Several cm of surface soil can be lost per decade, leaving behind subsoil with lower SPb concentrations. Wind erosion can also redistribute Pb-contaminated soil particles, potentially mixing them with particles with lower Pb concentrations. The spatial redistribution of SPb-contaminated particles by wind and water contrasts greatly, with water tending to collect particles in urban legacy sediments and wind tending to diffuse particles over broad areas (Breshears et al., 2003). Soil movement by earthworms, insects, and mammals, known as bioturbation, mixes surface-with sub-soils on decadal time scales, potentially diluting SPb in surficial layers given lower SPb at depth (Wilkinson et al., 2009). Finally, in humid climates, the vertical leaching of soluble SPb into subsoils may occur. Given the general insolubility of SPb (Li and Shuman, 1996), however, we tend to discount leaching as mobilizing substantial quantities of Pb, although measurements are very few. It is the city pedogenetic process that tend hypothetically to lower concentrations in surface soils. In 1882, Darwin noted in his Earthworm book: "*Although the superficial layer of vegetable mold … is no doubt of the highest antiquity, yet in regards to its permanence … its component particles are in most cases removed at not a very small rate, and are replaced by others due to the disintegration of the underlying materials*" (Darwin, 1882). The processes of particle redistribution are greatly accelerated in cities and we hypothesize that they lower concentrations of Pb in surface soils over decadal time scales (Richter et al., 2020).

In summary, urban pedogenetic processes decrease SPb and alter its geospatial distribution and overall Pb concentrations including bioavailability. This is an important topic for further applied research to better understand, remedy soil Pb contamination, and promote primary prevention in environmental health.

4. Conclusions

The central question is whether robust spatial-temporal declines of community soil Pb (SPb) and blood Pb (BPb) are occurring beyond New Orleans. Testing the concept entails a place where soils are systematically collected 10–20 years apart. This study reports on such a situation in the Detroit Tri-County Area. The initial SPb survey (n = 152 samples in 8 census tracts) was conducted in October 2002 and published in the Detroit Free Press in 2003. The follow-up soil survey was conducted in October 2019 on the same 8 census tracts using the same established collection protocol.

Pertaining to SPb, an overall decrease from medians of 92 to 58 kg/mg between 2002 and 2019 (P-value = 0.013) was observed. Then the sample sets were sorted into two groups (NEAR and FAR) based on the distance from the downtown center of Detroit. In 2002, the SPb medians for NEAR and FAR decreased from 183 mg/kg to 33 mg/kg (P-value = 9.0×10^{-12}), respectively. In 2019, the median SPb NEAR and FAR decreased from 92 mg/kg to 35 mg/kg (P-value = 6.9×10^{-07}), respectively. Also, between 2002 and 2019 the median SPb of the Detroit census tracts had an annual decrease of 5.4 mg/kg. For Pontiac, the median SPb decreased 1.4 mg/kg per year. These results are consistent with the findings in New Orleans.

Pertaining to children's BPb, the Michigan Child Lead Poisoning Prevention Program reports declines for Detroit that match those observed for New Orleans children. Children's BPb in Pontiac also declined. The percent of children with blood lead ≥4.5 μg/dL for Detroit children decreased from 43% in 2002 to 8% in 2017 and for Pontiac children, from 17% in 2002 to 2% in 2017. These results are consistent with the New Orleans findings.

In summary, SPb and BPb both declined in the Detroit Tri-County area. These outcomes are consistent with the New Orleans results. Although SPb and BPb are declining, some interior communities of Detroit and Pontiac remain excessively Pb contaminated compared with outlying communities. If the spatial-temporal association between SPb and BPb is robust, then, in addition to other prevention efforts, lessening community exposure to SPb is proactive for primary lead prevention.

Funding

Generous support by The Ling and Ronald Cheng Fund, Al French, Mary An Godshall, Allen and Laura Carmen, Jack Eichenbaum, and the Department of Pharmacology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

Daniel Albright, MPH Departmental Specialist Childhood Lead Poisoning Prevention Program Michigan Department of Health and Human Services. Michael Bickel P.E., Engineer at Metro Engineering Solutions, Livonia Michigan. In memory of Paul W. Mielke Jr., who audaciously challenged common practices in statistics.

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