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Spatiotemporal exposome dynamics of soil lead and children's blood lead pre- and ten years post-Hurricane Katrina: Lead and other metals on public and private properties in the city of New Orleans, Louisiana, U.S.A.

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A R T I C L E I N F O

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A B S T R A C T

Background: Anthropogenic re-distribution of lead (Pb) principally through its use in gasoline additives and lead-based paints have transformed the urban exposome. This unique study tracks urban-scale soil Pb (SPb) and blood Pb (BPb) responses of children living in public and private communities in New Orleans before and ten years after Hurricane Katrina (29 August 2005).

Objectives: To compare and evaluate associations of pre- and ten years post-Katrina SPb and children's BPb on public and private residential census tracts in the *core* and *outer* areas of New Orleans, and to examine correlations between SPb and nine other soil metals.

Methods: The Louisiana Healthy Housing and Childhood Lead Poisoning Prevention Program BPb (µg/dL) data from pre- (2000–2005) and post-Katrina (2010–2015) for ≤6-year-old children. Data from public and adjacent private residential census tracts within *core* and *outer* areas are stratified from a database that includes 916 and 922 SPb and 13,379 and 4830 BPb results, respectively, from pre- and post-Katrina New Orleans. Statistical analyses utilize Multi-Response Permutation Procedure and Spearman's Rho Correlation.

Results: Pre- to Post-Katrina median SPb decreases in public and private *core* census tracts were from 285 to 55 mg/kg and 710–291 mg/kg, respectively. In public and private *outer* census tracts the median SPb decreased from 109 to 56 mg/kg and 88–55 mg/kg. Children's BPb percent ≥5 µg/dL on public and private *core* areas pre-Katrina was 63.2% and 67.5%, and declined post-Katrina to 7.6% and 20.2%, respectively. BPb decreases also occurred in *outer* areas. Soil Pb is strongly correlated with other metals.

Conclusions: Post-Katrina re-building of public housing plus landscaping amends the exposome and reduces children's BPb. Most importantly, Hurricane Katrina revealed that decreasing the toxicants in the soil exposome is an effective intervention for decreasing children's BPb.

1. Introduction

The exposome refers to the totality of environmental exposures from conception and throughout the lifespan (Wild, 2005, 2012). The dynamic inputs, transformations, storages, and outputs of anthropogenic and non-anthropogenic materials are part of an inter-connected "metabolism of cities" that shape the urban exposome (Wolman, 1965). Multiple studies have confirmed health effects of low level lead exposure (US DHHS, 2012). This study focuses on the spatiotemporal exposome dynamics of soil lead (SPb) and children's blood Pb (BPb) in public and private communities of New Orleans.

A defining event for New Orleans occurred on 29 August 2005 when Hurricane Katrina made landfall to the South and East of New Orleans. The storm surge breached the levee system and triggered a powerful flood of sediment laden water that engulfed 80% of the city (McQuaid and Schleifstein, 2006). The depth of the sediment varied depending on elevation and distance from the coast. This study relies on the unique condition of the availability of comparable and matched SPb and BPb databases from before and ten years after the storm event to evaluate the effect that flooding had on the soil Pb exposome and children's exposure in New Orleans (Mielke et al., 2016).

Apprehension about the lack of progress in reducing health disparities indicates that new concepts, research, and interventions are needed to affect real change (Juarez et al., 2014). Public policy

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efforts to intervene in children's Pb exposure include education and cleanout of household dust (Yeoh et al., 2014). These actions focus on Pb-based paint for reducing children's BPb. A critical medical issue about these actions is their ineffectiveness (Kennedy et al., 2016; Yeoh et al., 2014). Along with following changes in the SPb exposome and BPb responses before and after Hurricane Katrina, this study seeks evidence-based understanding about the metabolism of cities that drive urban exposome dynamics and improve intervention methods for reducing children's Pb exposure.

2. Methods

2.1. New Orleans public and private properties in the context of pre- and post-Hurricane Katrina

Soil trace metal dusts including Pb are invisible. To visualize the metal dust content in soil requires field sampling, Analytical Chemistry methods, sample preparation, extracting, quantifying metals, and Geographic Information Science (GIS) methods to map the data. This study focuses on SPb in a portion of the New Orleans database (Mielke et al., 2016). Orleans Parish, Louisiana (parish=county) is coterminous with the City of New Orleans. The 1990 U.S. census tracts were used to define properties (U.S. Census 1993). Public properties refer to census tracts where the Housing Authority of New Orleans residential units exist. These are exclusively public properties; however after Katrina they were subject to public/private management agreements. Private properties refer to census tracts adjacent to public properties. The census tracts with private properties also include public schools, parks, and playgrounds. Fig. 1 shows the areas of public and private residential properties (census tracts) in the context of the soil Pb maps of pre- and ten years post-Katrina New Orleans. As explained in further detail in the discussion, hotspots are the result of multiple sources of lead contamination including traffic congestion, lead-based painted housing, as well as, former incinerators, and lead smelters.

After Hurricane Katrina almost all public properties were razed and rebuilt with “lead-free” housing. It is important to note that the federal paint standard includes an allowable amount of lead for paint applied on or after August 14, 2009 of 90 ppm Pb by weight in paint (US HUD, 2012). The rebuilt public housing properties were renamed (see: Housing Authority of New Orleans). For consistency with previous studies the original public housing names are used in this study (Mielke et al., 2011b).

As shown in Fig. 2, there are four groups of properties that make up this study dataset, Public Core, Public Outer, Private Core, and Private Outer. In the case of the Public groups there are 6 properties located within the inner city *core* and 4 properties located in the *outer* areas of New Orleans. The 6 Public Core properties were Lafitte (LAF), BW Cooper (BWC), Guste (GUS), CJ Peete (CJP) and St. Thomas (two census tracts STHn and STHs), and the 4 Public Outer properties were St. Bernard (two census tracts, STBw and STBe), Desire (DES) and Fischer (FIS). Two of the old Housing Authority of New Orleans public properties, Iberville (IBE) and Florida (FLO), are either under reconstruction or unoccupied vacant land. The *core* and *outer* public properties were constructed at the same time with the same construction materials (Mielke et al., 2011b). Fig. 2 also shows 26 Private Core and 13 Private Outer properties adjacent to the Public properties. In the case of private properties, the *core* is where the older, more densely traffic-congested communities exist, and the *outer* private properties generally have newer housing, and are located in less traffic-congested communities (Mielke et al., 2011b).

2.2. Soil Pb and other metals at public and private properties in New Orleans

The data for this study is stratified by the four groups described above. The pre-Hurricane Katrina SPb data is from soil samples collected between January 1998 and January 2001 (Mielke et al., 2005). The post-Katrina SPb data is from a survey of the same census tracts between June 2013 and June 2015. The samples from both surveys were collected, prepared, and analyzed using the same

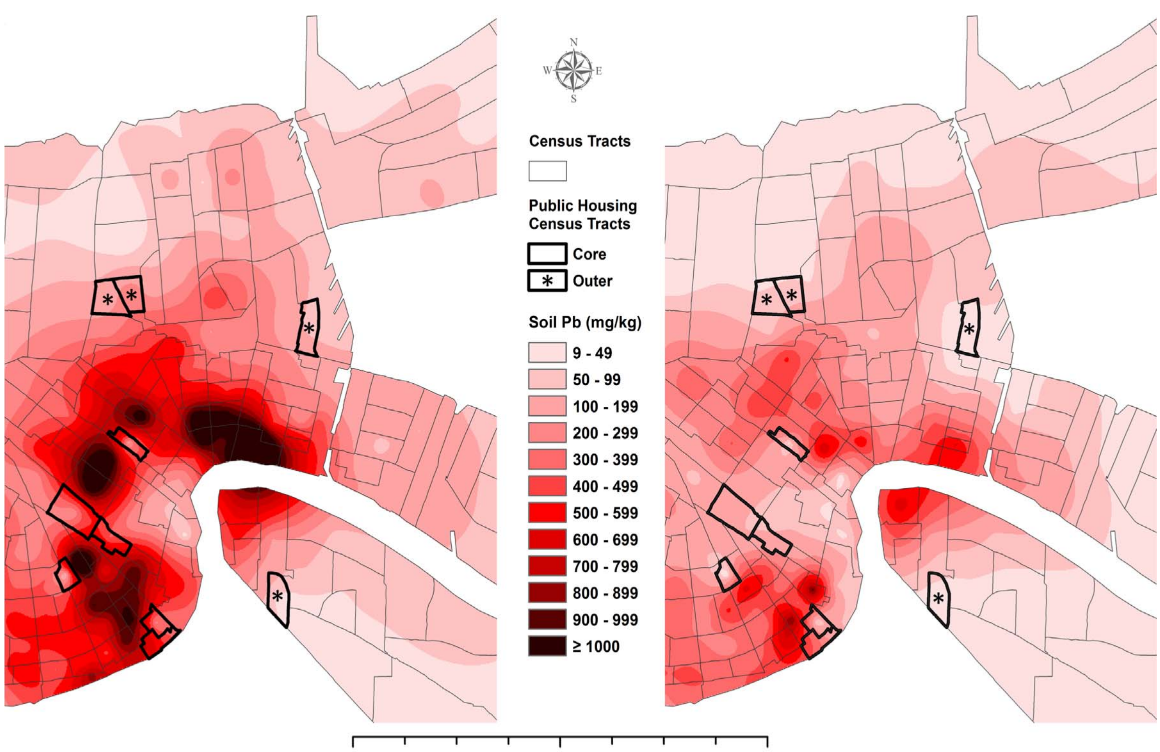

Fig. 1. Maps showing public housing census tracts in the context of the City of New Orleans surficial soil lead (SPb) spatial distribution in pre-Hurricane Katrina (left) compared with ten years post-Hurricane Katrina (right). The private properties are in census tracts adjacent to the public census tracts as shown in Fig. 2.

Fig. 2. Map showing census tracts of public and private properties in *core* and *outer* areas of the City of New Orleans.

techniques by the same personnel (Mielke et al., 2005, 2016). The SPb and BPb database has been described (Mielke et al., 2016). The SPb database includes 3314 samples pre-Katrina and 3320, post-Katrina. The soil samples in both pre- and 10 years post-Katrina surveys were collected at a median density of 38/km^2 (ranging from 7 to 83/km^2). The area of census tracts is optimally based on a population of 4000, but in reality the range is 2500–8000 inhabitants (U.S. Census Bureau, 1994). The higher the population density, the smaller the area of the census tract and vice versa, hence, the soil sample density is closely linked with population density. The SPb data subset on public and adjacent properties for this study are 916 and 922 soil sample results from pre- and post-Katrina periods and represent 27.6% and 27.7%, respectively, of the original database (Mielke et al., 2016).

The pre-Katrina samples were analyzed with a ™SPECTROFLAME-ICP Model P Inductively Coupled Plasma-Optical Emissions Spectrometer (ICP-OES) with background correction for Pb. The post-Katrina analysis of metals was conducted utilizing a ™SPECTRO CIROS CCD ICP-OES instrument applying background correction to Pb and nine other metals: zinc (Zn), cadmium (Cd), copper (Cu), chromium (Cr), nickel (Ni), cobalt (Co), vanadium (V), manganese (Mn), and titanium (T). As part of the analysis protocol, instrument calibration used National Institute of Standards and Technology (NIST) traceable standards. In addition, 5% of the soil samples in each census tract were extracted and analyzed in duplicate. For both pre-and post-Katrina surveys the same in-house reference soil was included during analysis. The Pb results for the in-house reference samples were consistent for the pre- and post-Katrina surveys.

2.3. Children's blood Pb data at public and private properties in New Orleans

The source for the ≤6 years old children's BPb data was the Louisiana Healthy Housing and Childhood Lead Poisoning Prevention Program from pre-Katrina (2000–2005) and post-Katrina (2010–2015). The Louisiana State Department of Health follows the protocol established by the Centers for Disease Control and Prevention (CDC) for collection, preparation, and analysis of blood Pb for ≤6 years old children (Louisiana childhood blood lead surveillance system, 2015; Louisiana Lead Poisoning Prevention Program Rules, 2013–2015). The BPb results are given in μg/dL. An elevated BPb (EBPb) is defined as being equal or above the reference value of 5 μg/dL established in 2012 (CDC 2012, U.S. CDC 2016). The BPb database for Orleans Parish consists of 39,620 and 17,739, pre- vs. post-Katrina periods (Mielke et al., 2016). The data subset for this study includes 13,379 and 4,830 BPb results from pre- and post-Katrina surveys, respectively, stratified by public and private properties within *core* and *outer* areas (Public Core, Public Outer, Private Core, Private Outer) as mapped in Fig. 2. The data subset for this study consists of 33.8% and 27.2% of the BPb data available for public properties and private properties, respectively, of the original pre- and post-Katrina database for Orleans Parish (Mielke et al., 2016).

2.4. Statistical methods

In this study a Multi-Response Permutation Procedure (MRPP) for univariate group data is utilized for analysis (Blossom, 2005; Mielke and Berry, 2007). The method is analogous to one-way analysis of variance, or *t*-test for univariate data. Permutation methods are a robust, data dependent statistical approach based on congruent data and analysis spaces (Mielke and Berry, 2007; Mielke et al., 2011).

Associations between Pb and nine other soil metals were evaluated using Spearman's Rank-order Correlation, a nonparametric test (Spearman's Rho, 2010). The correlation coefficient measures the strength and direction of the association between two ranked variables and includes an associated P-value. A small P-value indicates that the probability for the results being due to chance alone is small.

Table 1
Summary statistics for soil lead (SPb) on public and private properties from the *core* and *outer* areas of the City of New Orleans during pre-and ten years post-Katrina. The MRPP P-values for sample group comparisons are included. Soil lead (SPb) values are in mg/kg.

Period	Location	N	Min	25%	50%	75%	Max	P-Value*	Period	Location	P-Value
Pre-K (2001)	**Public Core**	113	3	113	**285**	492	6382		**Pre-K**	**Public Core vs. Public Outer**	6.5E−07
	Private Core	482	3	278	**710**	1591	48,894	1.8E−09		**Private Core vs. Private Outer**	3.6E−30
	Public Outer	76	5	42	**88**	189	1536				
	Private Outer	245	3	40	**109**	271	9236	0.073			
Post-K (2015)	**Public Core**	114	3	22	**55**	201	3560		**Post-K**	**Public Core vs. Public Outer**	2.5E−04
	Private Core	494	5	106	**291**	762	21,565	4.2E−07		**Private Core vs. Private Outer**	9.4E−16
	Public Outer	76	3	17	**32**	74	630				
	Private Outer	238	4	28	**56**	156	4415	0.002			

Pre-K: Pre-Katrina
Post-K: Post Katrina
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http://www.fort.usgs.gov/products/software/blossom/blossom.asp
* P-Value for MRPP Test with default settings.

3. Results

3.1. The SPb on public and private properties pre- and ten years post-Katrina

Table 1 provides an overview of the pre- and ten years post-Katrina SPb on Public and Private, Core and Outer areas of New Orleans. (Refer to Fig. 1.) When comparing the pre- and ten years post-Katrina results for public and private properties in the *core* and *outer* areas of the city, note the decreases in post-Katrina SPb. Evaluating group comparisons, the differences between the pre-Katrina SPb of the public and private *outer* properties are minor (P-value=0.073). This statistical finding is likely a result of large differences in variance of pre-Katrina SPb on the public *outer* properties along with an unequal sample size (N=245 vs. 76). In contrast, there were larger differences (P-value=0.002) for the post-Katrina SPb on *outer* public and private properties. This statistical finding for post-Katrina SPb of public vs. private *outer* properties is likely due to the consistently lower SPb across the spectrum on the public properties, and the P-value is smaller despite the unequal sample size.

3.2. Children's BPb at public and private properties pre-and ten years post-Katrina

Table 2 summarizes the BPb data of children ≤6 years old in the eight groupings for this study, and includes MRPP comparisons. Evaluating the BPb in pre- and post-Katrina groupings reveals a substantial decrease between the two time periods. The pre-Katrina public *core* children's BPb is lower than the private *core* BPb. This is not the case in pre-Katrina results where higher children's BPb values are observed in public *outer* (median=5 μg/dL) than values in private *outer* properties (median=4 μg/dL, P-value=1.2×20^{-50}).

3.3. Summary statistics of SPb and BPb including percent of elevated BPb (EBPb)

Table 3 shows the descriptive statistics including percent of EBPb for the eight groupings. The table also shows data for the public *core* and public *outer* individual census tracts. It's readily apparent that the EBPb percent was high in the pre-Katrina period. Post-Katrina, there were large reductions in EBPb, especially for the children living in public *core* (from 63.1% to 7.6%) and private *outer* (from 52.6% to 3.4%) areas. In post-Katrina the most striking differential exposure is seen in public *core* (7.6%) vs. private *core* (20.2%) census tracts of New Orleans.

3.4. Associations of SPb and nine other soil metals

Table 4 shows Spearman's Correlation matrices with P-values for pairs of soil metals in the four groups: Public Core, Private Core, Public Outer, and Private Outer. Pre-Katrina had background correction for Pb but not for all the elements. The post-Katrina results included background corrections for all of the elements measured and these results are given in Table 4 a-d. For post-Katrina results, there is a strong positive correlation and extremely small P-values for all four groups between Pb and Zn, Cd, Cu, Cr, Co, and V. Table 4 also shows a strong positive correlation of Pb with Mn and Ti in the *core* of the city and less so in the *outer* areas of the city.

Table 2
Summary statistics for Blood lead (BPb) of children living on public and private properties in *core* and *outer* areas of the City of New Orleans. The MRPP P-values for group comparisons are included. BPb values are in μg/dL.

Period	Location	N	Min	25%	50%	75%	Max	P-Value*	Period	Location	P-Value*
Pre-K (00–05)	**Public Core**	2406	< 1	3.9	**6.0**	9.6	45.6		**Pre-K**	**Public Core vs. Public Outer**	1.37E−28
	Private Core	4920	< 1	4.0	**7.0**	11.1	92.0	9.9E−11		**Private Core vs. Private Outer**	3.8E−292
	Public Outer	2090	< 1	3.1	**5.0**	7.5	50.4				
	Private Outer	3963	< 1	3.0	**4.0**	6.0	98.0	1.2E−50			
Post-K (11–15)	**Public Core**	605	< 1	0.5	**1.4**	2.5	17.3		**Post-K**	**Public Core vs. Public Outer**	2.3E−04
	Private Core	2532	< 1	1.2	**2.4**	4.4	40.5	3.0E−34		**Private Core vs. Private Outer**	6.7E−70
	Public Outer	387	< 1	0.5	**1.0**	2.1	12.6				
	Private Outer	1306	< 1	0.5	**1.2**	2.4	24.0	0.008			

Pre-K: Pre-Katrina
Post-K: Post Katrina
Blossom Version W2008.04.02, Science Center, U.S. Geological Survey2150 Center AV BLDG C, Fort Collins, CO 80526-8118, USA
http://www.fort.usgs.gov/products/software/blossom/blossom.asp
* P-Value for MRPP Test with default settings.

Table 3
Median pre- and ten years post Katrina group data for the *core* and *outer* 39 census tracts of the private properties and the individual data for *core* and *outer* for public census tracts. Units: N=sample numbers, med=median, value range, elevated blood lead percent ≥5 µg/dL.

Location	Pre-K Soil Pb			Pre-K Blood Pb			Post-K Soil Pb			Post-K Blood Pb		
	N	med	range	N	med	% ≥5 µg/dL	N	med	range	N	med	% ≥5 µg/dL
Private Core (26 CTs)	482	**710**	48,892	4920	**7.0**	67.5	494	**291**	21,560	2532	**2.4**	20.2
Private Outer (13 CTs)	245	**109**	9234	3963	**4.0**	36.3	238	**56**	4411	1306	**1.2**	7.0
Public Core (6 CTs)		**285**				63.1[a]		**55**				7.6[a]
LAF	19	**180**	1000	594	**5.7**	59.1	19	**35**	474	59	**1.7**	10.2
GUS	18	**401**	6367	287	**4.8**	49.1	19	**115**	1366	55	**1.0**	1.8
BWC	19	**224**	2036	872	**6.0**	62.7	19	**116**	3555	82	**1.3**	7.3
STHn	19	**285**	555	238	**7.5**	73.5	19	**53**	259	257	**1.4**	6.2
STHs	19	**573**	2974	167	**8.6**	78.4	19	**336**	2233	32	**1.5**	6.3
CJP	19	**124**	398	248	**7.5**	69.4	19	**11**	51	120	**1.2**	1.7
Public Outer (4 CTs)		**88**				52.6[a]		**32**				3.4[a]
FIS	19	**37**	269	368	**4.2**	45.4	19	**25**	619	109	**0.5**	4.6
DES	19	**83**	140	15	**5.8**	53.3	19	**14**	52	145	**1.2**	2.8
STBw	19	**139**	512	354	**5.4**	53.7	19	**60**	618	40	**1.1**	0.0
STBe	19	**281**	1531	1353	**5.2**	54.3	19	**73**	249	93	**1.1**	4.3

[a] overall percentage of children living on public properties with blood lead equal to or above five µg/dL, i.e., % elevated BPb (EBPb).

4. Discussion

4.1. Strengths and limitations

The New Orleans studies include a city-scale perspective, a systematic collection of thousands of soil samples analyzed for metals and stratified by community, tens of thousands children's BPb stratified by community, and enduring for over two and a half decades. A unique feature of this study is that it took advantage a natural experimental occurrence, the flooding event of 80% of New Orleans on August 29, 2005, that could never be deliberately planned or justified on scientific or ethical grounds (Mielke et al., 2016; Zahran et al., 2010). The New Orleans SPb surveys began in 1991, were redone in 1999–2001, and this study updates the public and private subset of the database (Mielke, 1991; Mielke et al., 2005, 2016).

After Katrina there was an influx of young white families into some communities, however the African-American population of New Orleans remained relatively stable at 67.3% in 2000, 60.2% in 2010, and 59.6% in 2014 (U.S. Census Bureau, 2000; American Community Survey, 2010, 2014, 2015). Because of advancing ages, the ≤6-years-old children tested underwent a total change between pre- and ten years post-Hurricane Katrina. For each survey year, children ≤6-years-old are viewed independently, a practice which is the accepted for each cycle of the National Health and Nutrition Examination Survey (NHANES).

Lead dust is assumed to play a key role in the exposome. Gauging SPb and BPb differences between *core* and *outer* locations of public and private properties, pre- and post-Katrina provides evidence about the exposome but not necessarily about specific Pb sources in either the soil or blood. Levin et al. (2008) outlined multiple sources of Pb that may contribute to children's risks of exposure and stated (twice!) that blood lead "…can rise 1–5 µg/dL for every 1000 ppm increase in soil lead." This study provides empirical evidence to examine this statement.

4.2. Blood lead before and ten years after Katrina: New Orleans and NHANES data

The human response to the urban exposome is discovered by measuring children's BPb. Fig. 3 shows the changes in the BPb of ≤6 years old children in New Orleans before and ten years after Hurricane Katrina compared with the NHANES BPb data matched for ≤6 years old children. Note in 1999–2002 and 2003–2006 the large differences between the BPb of children in New Orleans compared with the NHANES BPb results of children for the same time period.

On 7 September 2001 (just prior to the September 11 World Trade attacks), to reduce children's Pb exposure, the New Orleans City Council passed a lead-based paint ordinance (New Orleans 12–2012; Rabito et al., 2004). Enforcement of the ordinance was underfunded and haphazard. As shown in Fig. 3, despite the lead-based paint ordinance, the BPb of children decreased at about the same rate as the NHANES results from 1999-2002 and 2003-2006 (0.5 µ/dL vs. 0.3 µg/dL). A similar outcome was also reported in a study comparing recurring lead poisoning in children living in states with lead-based paint laws compared with states without them (Kennedy et al., 2016). The recurrence of lead poisoning was the same in both groups of states and the conclusion drawn was that lead laws were questionable as an effective tool for preventing the reoccurrence of children's lead poisoning (Kennedy et al., 2016).

After 2003–2006, or post-Katrina, as shown in Fig. 3, New Orleans children's BPb underwent a far steeper rate of decline than the rate of decline of the national NHANES BPb results. By 2011–2014 the BPb of New Orleans children was only slightly larger (0.83 µg/dL) than the NHANES results for the same years. The general national decline of BPb compared with the steeper New Orleans downward BPb trend raises critical questions concerning processes behind the national as well as the local exposome as they relate to children's exposure. This same issue was encountered in another study that observed the national exposure decline and attempted to control for its confounding influence on decreases in BPb at historical mining sites (Schoof et al., 2015).

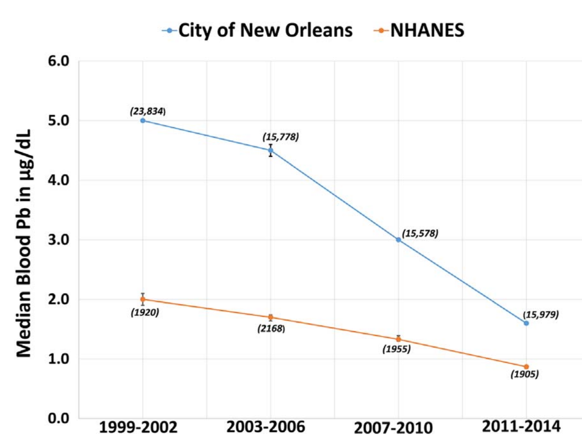

Fig. 3. The notable decrease of New Orleans post-Katrina ≤6 years old children's blood lead (BPb) results from 2003 to 2006 through 2011–2014 compared with the ≤6 years old BPb results of the NHANES. National Health and Nutrition Examination Survey, 2016 during the same years. Error bars represent the 95% confidence interval. Hurricane Katrina flooded 80% of New Orleans on 29 August 2005. Number of BPb results in parenthesis.

4.3. Pre-Katrina exposome of public and private properties and lead ordinances

Prior to Hurricane Katrina studies were conducted on public and adjacent private properties. On public properties, federal Pb regulations were in place and children were expected to benefit by having lower BPb levels (Rabito et al., 2003). However, children living in public housing in New Orleans reported BPb levels higher than children living in private properties where lead regulations were not enforced (Rabito et al., 2003). The pre-Katrina differences in BPb between public and private properties are shown in Table 2. The children living at outer public properties had a substantially higher EBPb percent (52.6%) than children living on outer private properties (36.3%, P-value=1.2×10^{-50}). This outcome raises further questions about the effectiveness of lead-based paint regulations as a primary preventive measure for reducing children's Pb exposure.

The public housing of New Orleans was constructed during the 1930's through the 1940's with the same materials and brick facades (Mielke Howard et al., 2008). Comparing SPb on public and private properties in the *core* and *outer* areas of New Orleans provides insight into the Pb flows as part of the city's metabolism. Table 1 shows the findings of the pre-Katrina SPb survey. The median SPb on public properties was 285 mg/kg and 88 mg/kg, respectively, for the *core* and *outer* areas of the city. Although constructed with the same building materials and within the same time period there were major differences in SPb. This indicates that there is another source of Pb that differentially contaminates soil in the *core* and *outer* areas of the city (Mielke et al., 2008).

A similar differential pattern, but with larger differences is found on private properties in the *core* and *outer* properties of New Orleans. Table 1 shows that pre-Katrina private properties display a SPb disparity between the *core* (median 710 mg/kg) and *outer* (median 109 mg/kg) areas of the city. While the explanation for SPb on private properties could be attributed to the presence of lead-based paint and age-of-housing differences, the SPb differences on public properties constructed at the same time with the same materials in the *core* and *outer* areas cannot be explained by lead-based paint or age-of-housing differences (Mielke et al., 2008).

4.4. Metabolism of the city and SPb exposome disparities in core and outer communities

A follow-up study to Mielke et al. (2008) considered the SPb disparity issue. Anthropogenic quantities of Pb in lead-based paint and the vehicle fuel additive tetraethyl lead (TEL) were estimated for the city. The quantities of Pb for these two major commercial products along with their effects on the SPb disparity in the *core* and *outer* city (Mielke et al., 2011b).

Paint coatings are visible and attract attention. The potential amount of Pb in paint dust accumulated in the city was estimated by weighing the paint chips during an exterior paint removal project on a large home and combining the results with the Pb content results of a collection of paint samples from communities throughout New Orleans (Mielke et al., 2001b). The accounting assumed that all 86,000 homes in New Orleans were the same large size, power-sanded (i.e., the lead-based paint pulverized into invisible dust), and the dust residue remained thereby contaminating soil. A liberal estimate of 1000 metric tons of Pb dust can be accounted for from exterior lead-based paint (Mielke et al., 2011b).

The accounting for invisible Pb deposited into the city from the use of TEL was based on annual amounts of Pb in fuel, the vehicle travel distances recorded for major highways, the average fuel efficiency per gallon over the years, and EPA estimates of the fate of automobile exhaust particles (Mielke et al., 2011b, 2011c). At least 10,000 metric tons of Pb dust are accounted for in New Orleans from TEL in fuel exhausted by vehicle traffic between 1950 and 1984 (Mielke et al., 2011c). Thus, at least 10 times more Pb dust can be accounted for by the use of TEL than by the use of Pb-based paint on homes (Mielke et al., 2011b). The quantity of invisible Pb-dust in air that was deposited from vehicle exhaust provides an explanation for the observed SPb disparity found between a city's *core* areas where decades of high traffic volumes occur compared with *outer* areas where lower traffic volumes exist (Mielke et al., 2011b). These results corroborate the differences in Pb dust observed in houses and on children's hands as a factor in childhood Pb exposure between the inner city and suburbs by researchers during the 1970 s (Sayre et al., 1974; Vostal et al., 1974). The SPb disparity between the *core* and *outer* city, large and small cities, is a common characteristic that accounts for Pb dust and Pb exposure can be best understood from the use of TEL as a vehicle fuel additive (Datko-Williams et al., 2014; Mielke and Reagan, 1998; Mielke et al., 2011b).

The effect of TEL aerosols on children's BPb was also observed by researchers during the 1980's and 1990's. Removal of TEL from highway fuel was done to protect the catalytic converter from being damaged by Pb. During the decade of declining TEL use, children's BPb underwent a simultaneous reduction (Annest et al., 1983). The rapid phasedown of TEL began on 1 January 1986, and the response by U.S. children to the Pb reduction was a 72% and 77% decrease of EBPB for non-Hispanic black and non-Hispanic white children, respectively, in the NHANES data from prior to the 1986 rapid phasedown and ten years afterward (Pirkle et al., 1994).

Although TEL was removed from fuels for highway use it continues to be legal for non-highway use (off road vehicles, farm tractors, snowmobiles, boats etc.). Mogas is unleaded fuel used for highway vehicles and low lead aviation gasoline (LL avgas) has 1.1 g/gallon TEL additives for fueling reciprocating piston engines of small aircraft. The EPA estimates that avgas accounts for about 60% of the Pb aerosol exposome in the U.S. (Kessler, 2013, U.S. EPA, 2008). Children's exposure response to Pb from avgas was demonstrated by a study showing that BPb is higher for children living within 0.5–1 km general aviation airports (the facilities where avgas is used as a fuel for small piston aircraft) compared with children living at a distances further than 1 km from these airport facilities (Miranda et al., 2011). Learning deficits are one of the costs to children's health associated with the continued use of avgas (Wolfe et al., 2016). Another lingering problem with maintaining TEL in avgas is that it results in crossover to other non-highway applications such as fuel to power gas turbine engines at electrical peaking facilities (Rising, 2004). The exposure outcomes from the dust released by the use of TEL additives in fuel highlights its reputation for producing an international public health disaster (Kovarik, 2005; Thomas et al., 1999).

Besides linkage between the input of massive quantities of Pb aerosols with BPb, the particles also deposit and accumulate on the Earth's surface. When Pb dust from any source is deposited on uncontaminated soil it transforms the soil into a Pb source. Dry weather and droughty soil generally occur toward the end of summer, and when winds lift up Pb contaminated soil the outcome is Pb aerosol in the soil-to-air-to-inhalation pathway of exposure (Laidlaw and Filippelli, 2008). As recognized when TEL was used in vehicle fuel, children are especially susceptible to Pb via the inhalation route of exposure. Soils as a source of air Pb have been studied in several cities (Filippelli and Laidlaw, 2010; Laidlaw et al., 2005, 2012, 2016). Seasonal differentials of BPb exposure is one of the outcomes of the Pb contaminated soil exposome. For example, in the seasonal climate of Michigan, USA, children's BPb is lowest during the winter when children spend much of their time indoors (where presumably, the largest hazard risk to lead-based paint and lead dust exists) and highest during late summer months when air Pb increases, windows are open, and children play outdoors (Laidlaw et al., 2016; Zahran et al., 2013). The metabolism of the city includes complex interactions between Pb inputs, storage, transformations and outputs in the exposome. When SPb is curtailed, children's BPb response also subsides (Mielke et al., 1997, 1999, 2007; Zahran et al., 2013).

4.5. Post-Katrina observations on public and private properties

After Hurricane Katrina two major studies were published that contemplated children's lead exposure response to flooding 80% of New Orleans. Assuming that lead-based paint was the principal cause of exposure one study predicted that unregulated and haphazard renovation of lead-based painted homes would increase both SPb and BPb after Katrina, and predicted dire consequences for the future health of the children of New Orleans (Rabito et al., 2012).

Another post-Hurricane Katrina study arrived at a different conclusion. Based on a post-Katrina SPb survey and fresh BPb results in 46 census tracts, the study identified a trend toward reduction in both SPb and BPb and proposed that the results support policy actions to address SPb as a way to improve conditions for children (Zahran et al., 2010). The study challenged the idea that lead-based paint alone was the main source of BPb, and it was the harbinger for this SPb and BPb project.

The outcomes of the pre- vs. post-Katrina changes in the SPb exposome and children's BPb exposure responses on public and adjacent private properties in the *core* and *outer* census tracts of New Orleans are summarized in Table 3. The far right column lists the pre- and post-Katrina percent of children with BPb≥5 μg/dL. First, comparing pre- and post-Katrina periods, all public and private properties experienced a sharp decrease in SPb and BPb. Furthermore, as noted in Fig. 3, children's BPb in New Orleans decreased at a faster rate than observed in NHANES children's BPb over the same time periods. In pre- Katrina New Orleans it was common to find an EBPb percent of over 50% for children living on public and private properties. Ten years post-Katrina the percent of EBPb became of 7.6% and 3.4%, respectively, for children living on public properties in the *core* and *outer* areas of the city.

Following Katrina, the 1930's and 1940's brick public housing of New Orleans were demolished and replaced with “lead-free” housing. As discussed previously, there is still an allowable amount of lead, now 90 mg/kg. Landscaping with low Pb (< 20 mg/kg) alluvial sediments transported from outside the city to most of the construction sites was done to raise the elevation of the ground (Mielke et al., 2010, 2011b). Several collections of alluvial sediments have been tested for Pb and other trace metals show the same results and the fact that the reduction of SPb is stable after the inundation from Katrina (Mielke et al., 2000, 2006b, 2011a). Private properties did not undergo rebuilding or landscaping and the exposure disparity increased, as predicted by Mielke et al. (2011b). Before Katrina the private to public EBPb disparity ratio was 67.5–63.1% or 1.07 and about the same. Ten years after Katrina the private to public EBPb disparity ratio became 20.2–7.6%, a factor of 2.66 indicating an increased exposome disparity between children living on *core* private and public properties. Experience in New Orleans demonstrated the possibility of intervention of Pb contaminated soil with water permeable geotextiles, emplacing 15 cm or more of low Pb soil (< 40 mg/kg), and toping with plant/grass to create low SPb areas safe for children; periodic testing of SPb integrated into the project assures upkeep of lead-safe areas for children (Mielke et al., 2011a).

Even with the new no-lead housing on public properties the children living there still present with EBPb of 7.6% and 3.4%, respectively, in the *core* and *outer* areas of the city. Confounding issues arise from the assumption in this study that SPb is the source of children's BPb, and that exposure occurred within the assigned public or private properties. The dynamic processes of Pb exposure for an individual child are not easy to sort out. Confounding variables include lack of knowledge about where every child lives and plays each day. A given child may be assigned to one census tract but as part of their daily activities actually spend their day at another location, such as a childcare center or alternative caretaker's home and outdoor play area

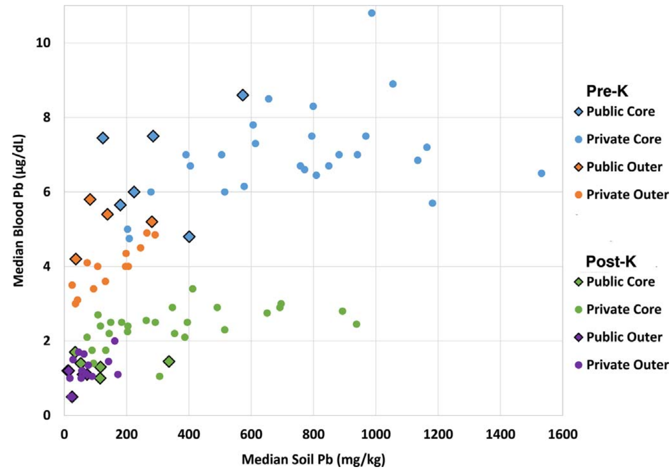

Fig. 4. Median soil lead (SPb) vs. median blood lead (BPb) of public (10 census tracts) and private properties (39 census tracts) in the City of New Orleans before and ten years after Hurricane Katrina. The data for the 10 public census tracts is from Table 3 and all data for the 39 private property census tracts are given in Supplement 1.

that may be more or less contaminated with lead-based paint and Pb dust. The effect of these confounding variables on Pb exposure of individual children are not known. Nevertheless, the collective BPb results of children living within various communities provides a strong indication that SPb plays a large role in the urban exposome (Mielke et al., 2013).

Despite the observed improvements, ten years after Katrina many New Orleans children are still excessively exposed to Pb. There is a disparity in percent EBPb between private *core* (20.2%) and *outer* (7.0%) communities of the city. There is also an even larger EBPb disparity between the children living in new public *core* housing (7.6%) compared with the EBPb of children (20.2%) living in *core* private housing of the city.

4.6. Pre- and post-Katrina SPb and BPb at public and private properties in New Orleans

Fig. 4 summarizes the median SPb and BPb data for the 10 public and 39 private properties of the pre- and post-Katrina results in the *core* and *outer* areas of New Orleans (see Table 3 and data in Supplement 1). Examination of Fig. 4 reveals the overall magnitude of the pre- vs. post-Katrina differences between BPb and SPb on public and private properties within the *core* and *outer* groups from this study. Note that for all groups of properties there is a sharp reduction

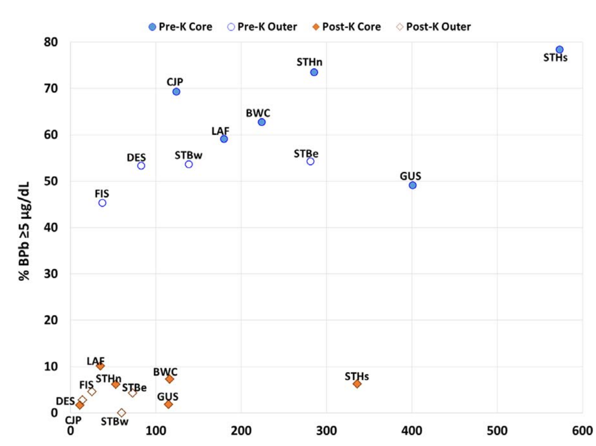

Fig. 5. Census tract medians for SPb vs. percent BPb ≥5 μg/dL of public housing census tracts in pre- and post- Katrina City of New Orleans. The SPb and BPb data for this figure are from Table 3. See Fig. 2 for locations of each census tract.

Tables 4

a-d. Spearman's Rank-order Correlation matrices, with P-values (in italics) for SPb and nine other metals in post-Katrina samples. Samples were analyzed with background correction on a simultaneous Spectro™ CIROS CCD ICP-OES.

Spearman's Rho

a. Public Core

	Zn	Cd	Cu	Cr	Ni	Co	V	Mn	Ti
Pb	0.873	0.831	0.877	0.790	0.819	0.614	0.703	0.574	0.777
	1.1E−36	**3.1E−30**	**1.8E−37**	**1.7E−25**	**8.5E−29**	**3.9E−13**	**3.0E−18**	**2.4E−11**	**2.7E−24**
Zn		0.734	0.888	0.846	0.828	0.596	0.678	0.572	0.835
		1.4E−20	**1.3E−39**	**2.6E−32**	**6.0E−30**	**2.6E−12**	**1.2E−16**	**2.9E−11**	**8.1E−31**
Cd			0.809	0.727	0.762	0.563	0.671	0.540	0.685
			1.3E−27	**5.2E−20**	**7.8E−23**	**6.9E−11**	**3.1E−16**	**5.8E−10**	**4.5E−17**
Cu				0.857	0.883	0.599	0.749	0.597	0.849
				5.4E−34	**1.6E−38**	**2.0E−12**	**9.7E−22**	**2.5E−12**	**7.3E−33**
Cr					0.814	0.552	0.770	0.633	0.886
					3.0E−28	**1.9E−10**	**1.3E−23**	**4.3E−14**	**3.3E−39**
Ni						0.689	0.759	0.624	0.829
						2.5E−17	**1.3E−22**	**1.2E−13**	**5.3E−30**
Co							0.669	0.688	0.573
							4.4E−16	**2.9E−17**	**2.7E−11**
V								0.744	0.685
								2.5E−21	**4.1E−17**
Mn									0.567
	N=114								**4.9E−11**

b. Private Core

	Zn	Cd	Cu	Cr	Ni	Co	V	Mn	Ti
Pb	0.850	0.829	0.732	0.747	0.707	0.650	0.752	0.696	0.509
	6.0E−139	**2.5E−126**	**6.7E−84**	**3.1E−89**	**5.0E−76**	**1.5E−60**	**4.1E−91**	**6.8E−73**	**7.2E−34**
Zn		0.884	0.793	0.808	0.752	0.666	0.649	0.635	0.547
		1.6E−164	**5.2E−108**	**2.4E−115**	**2.8E−91**	**1.5E−64**	**1.7E−60**	**4.5E−57**	**6.5E−40**
Cd			0.750	0.766	0.803	0.690	0.723	0.678	0.550
			2.8E−90	**1.3E−96**	**9.7E−113**	**5.3E−71**	**4.8E−81**	**8.8E−68**	**2.1E−40**
Cu				0.766	0.726	0.573	0.680	0.626	0.604
				2.4E−96	**4.3E−82**	**1.6E−44**	**2.8E−68**	**3.4E−55**	**1.6E−50**
Cr					0.718	0.628	0.705	0.627	0.696
					2.3E−79	**1.2E−55**	**2.6E−75**	**2.6E−55**	**7.2E−73**
Ni						0.718	0.756	0.708	0.589
						1.8E−79	**1.6E−92**	**1.7E−76**	**2.3E−47**
Co							0.715	0.726	0.564
							1.4E−78	**4.5E−82**	**7.6E−43**
V								0.808	0.691
								2.5E−115	**1.8E−71**
Mn									0.578
	N = 494								**2.1E−45**

c. Public Outer

	Zn	Cd	Cu	Cr	Ni	Co	V	Mn	Ti
Pb	0.783	0.543	0.798	0.622	0.641	0.435	0.628	0.189	0.451
	6.6E−17	**4.1E−07**	**6.4E−18**	**2.0E−09**	**4.6E−10**	**8.6E−05**	**1.3E−09**	**0.101**	**4.4E−05**
Zn		0.577	0.848	0.583	0.721	0.468	0.343	0.229	0.504
		5.0E−08	**4.0E−22**	**3.4E−08**	**2.0E−13**	**2.0E−05**	**0.002**	**0.047**	**3.5E−06**
Cd			0.625	0.593	0.689	0.446	0.259	0.279	0.521
			1.5E−09	**1.7E−08**	**6.0E−12**	**5.4E−05**	**0.024**	**0.015**	**1.4E−06**
Cu				0.693	0.750	0.547	0.525	0.367	0.506
				4.0E−12	**6.0E−15**	**3.2E−07**	**1.1E−06**	**0.001**	**3.1E−06**
Cr					0.655	0.393	0.500	0.421	0.704
					1.4E−10	**4.5E−04**	**4.3E−06**	**1.5E−04**	**1.3E−12**
Ni						0.677	0.509	0.389	0.471
						1.9E−11	**2.7E−06**	**0.001**	**1.7E−05**
Co							0.550	0.499	0.367
							2.6E−07	**4.4E−06**	**0.001**
V								0.422	0.409
								1.4E−04	**2.4E−04**
Mn									0.295
	N=76								**0.010**

d. Private Outer

	Zn	Cd	Cu	Cr	Ni	Co	V	Mn	Ti
Pb	0.784	0.778	0.741	0.656	0.627	0.340	0.592	0.593	0.394
	9.9E−51	**1.8E−49**	**1.1E−42**	**1.3E−30**	**2.1E−27**	**7.3E−08**	**6.4E−24**	**5.2E−24**	**2.9E−10**
Zn		0.808	0.818	0.653	0.621	0.331	0.584	0.606	0.451
		4.1E−56	**1.4E−58**	**2.3E−30**	**9.2E−27**	**1.7E−07**	**3.6E−23**	**2.7E−25**	**2.6E−13**
Cd			0.731	0.543	0.802	0.541	0.802	0.762	0.442
			4.7E−41	**1.3E−19**	**8.5E−55**	**1.7E−19**	**9.3E−55**	**2.3E−46**	**8.6E−13**
Cu				0.688	0.591	0.307	0.578	0.561	0.533
				1.2E−34	**7.9E−24**	**1.4E−06**	**1.3E−22**	**3.7E−21**	**7.8E−19**
Cr					0.410	0.223	0.466	0.436	0.706
					4.7E−11	**5.2E−04**	**3.3E−14**	**1.8E−12**	**2.9E−37**
Ni						0.634	0.807	0.742	0.329
						3.8E−28	**6.6E−56**	**6.6E−43**	**2.0E−07**
Co							0.611	0.658	0.320
							8.7E−26	**6.4E−31**	**4.6E−07**
V								0.786	0.479
								4.2E−51	**4.6E−15**
Mn									0.430
	N = 238								**4.0E−12**

of BPb and SPb between pre- and post-Katrina exposomes. Comparing BPb of children living on public properties with children living on adjacent private properties reveals that post-Katrina public properties are places were BPb tends to be substantially lower than private properties.

The focus this study is public properties. The results in Table 3 lists the SPb and BPb medians, ranges, and percent of EBPb ≥5 μg/dL for each of the *core* and *outer* public census tracts, pre- and post-Katrina. Fig. 5 illustrates the details for SPb and EBPb on public properties pre- and post-Katrina.

Levin et al. (2008) emphatically state (twice!) that blood lead "... can rise 1–5 μg/dL for every 1000 ppm [ppm=mg/kg] increase in soil lead." The 1–5 μg/dL for every 1000 mg/kg statement does not match the observed BPb response of New Orleans children to the SPb on public and private properties of New Orleans. In this study 1–5 μg/dL changes in BPb are associated with SPb increments of 10–100 mg/kg. Children are extremely sensitive to the air-to-inhalation as well as the soil-to-hand-to-mouth ingestion exposure routes. In order to meet the extraordinary vulnerability needs of children to Pb dust and SPb an effective health standard requires a margin-of-safety. In studies which involve ingestion of toxic substances, U.S. federal regulations require a margin-of-safety factor of at least 10 (US DHHS, 2005). The inclusion of a margin-of-safety requires a major downward adjustment in SPb standards which is currently 400 mg/kg (U.S. EPA 2015). As shown in Fig. 4 for New Orleans, communities where the median SPb is < 40 mg/kg are places where children's median BPb is below 2 μg/dL (Mielke et al., 2016). Fortunately, because the median Pb of non-urban U.S. soil is 16.5 mg/kg, all U.S. cities have the natural low Pb soil resources available nearby to reduce the SPb exposome to the 20–40 mg/kg range (Gustavsson et al., 2001). In its overview of community and preventive health, The Louisiana Department of Health and Hospitals (2015) touches on the link between Pb content of Mardi Gras beads and their possible contamination from street dust and SPb after they are thrown during the parades.

Finally, as shown in Table 4 a-d, it is important to highlight the idea that the urban exposome consists of multiple elements. Blood Pb is commonly measured in children but other elements are not normally included in clinical testing. As demonstrated in Table 4a-d exposure to SPb is accompanied by the potential exposure to 9 other elements. However, note that for each of the four data subsets, Core Public, Core Private, Outer Public, and Outer Private paired with Pb the elements Pb Zn, Cd, Mn and Cr have large correlation coefficients and small P-values. This poses an additional issue about the metabolism of cities. For example, the phytotoxic effects on wheat (related to grasses) is, in order of toxicity, Zn > Cd > Mn > Cr (Shaikh et al. (2013)). One of the manifestations of the association of Pb with phytotoxic elements in soil may be a reduction in vigorous growth of ground cover where SPb is elevated. In the urban exposome the combination of elements may exaggerate the exposure hazard risk and exacerbate the availability and potency of SPb. In addition to metals, organic compounds such as polycyclic aromatic hydrocarbon compounds (PAHs) are a component of the combustion of fossil fuels. A similarly strong correlation and small P-value have been observed between metals and PAHs in community soils of New Orleans (Mielke et al., 2001a, 2004).

5. Conclusion

5.1. Blood Pb intervention by treating the SPb exposome

Discovery of elevated Pb exposure is accomplished by measuring children's BPb. If BPb is elevated, then the reaction is to intervene to reduce exposure. The prescribed intervention is based on the assumption that Pb-based paint is the principal source of exposure and remedial actions include education of parents and cleanup of household Pb dust. Several lines of evidence indicate that focusing education, lead-based paint, and household dust cleanup is not effective in reducing Pb exposure.

After Hurricane Katrina, a significant spatiotemporal decrease of Pb in the soil portion of the urban exposome took place. Furthermore, a steeper decline of children's BPb occurred in New Orleans than for U.S. children observed by NHANES BPb results. The reduction of SPb and decrease of children's BPb provides insight into the metabolism of the city and the dynamic relationship between the SPb part of the exposome and children's Pb exposure. The pre- and post-Katrina observations in New Orleans offer lessons about effective proactive Pb intervention methods. First, children are extremely vulnerable to Pb contamination of the exposome, and for that reason a margin-of-safety factor must be included to prevent exposure. Second, measuring children's BPb cannot be justified as the principal method for discovery. Direct measurement and survey of Pb in the exposome (air, soil, water, toys, hair coloring agents, dietary supplements, etc.) must be routinely implemented. A useful tool for Pb discovery in the soil exposome is the handheld X-Ray Fluorescence spectrometer. Third, as demonstrated by Hurricane Katrina the storm surge of sediment laden flood water into the city reduced the Pb exposome and decreased the BPb of children living in public and private properties of the *core* and *outer* areas of the city. In New Orleans covering Pb contaminated soil containing 20–40 mg/kg Pb establishes an exposome that decreases the BPb in children. New Orleans and all cities have sources of low Pb soils nearby that can be used to cover Pb contaminated urban soil and reduce children's BPb.

Most importantly, the natural experiment of Hurricane Katrina demonstrates the value of decreasing Anthropogenic Pb dust in housing and the soil portion of the exposome as a method for children's BPb intervention. The experience supports the idea that decreasing interior and exterior Pb dust sources including the soil Pb portion of the urban exposome benefits the health of children and, over time, the welfare of the entire community. If proactive intervention were used to decrease Pb dust in houses and soils in high Pb communities, then the expected outcome is a reduction in BPb disparities between public and private properties in *core* communities as well as decreasing BPb inequalities between *core* and *outer* communities of the city.

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Conflict of interest

None of the authors report a conflict of interest connected with this study.

Human subject data

Unidentifiable human subject's blood Pb data were obtained by official request from the Louisiana Department of Health.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envres.2017.01.036.

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