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## Review

## Lead (Pb) legacy from vehicle traffic in eight California urbanized areas: Continuing influence of lead dust on children's health

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## ABSTRACT

This article describes the magnitude of U.S. lead (Pb) additives in gasoline from 1927 to 1994 and estimated quantities of Pb dispersed by vehicle traffic in eight urbanized areas (UAs) of California from 1950 to 1982. The findings are the basis for predicting the health impact of Pb on children living in UA of California. Quantitative U.S. national data for 1927–1994 were from the U.S. Senate hearing of the 1984 Airborne Lead Reduction Act. Vehicle traffic data, fuel efficiency, percentage leaded gasoline, and quantities of Pb in gasoline were obtained for 1982 from public and corporate records to estimate vehicle Pb emissions for small to very large UAs of California. California fuel consumption records and yearly quantities of Pb additives per gallon were the basis for estimating the 1950–1982 dispersion of Pb in each UA. Lead additives were calculated by multiplying annual vehicle fuel used by average Pb per gallon. The proportion of Pb additive for each UA was calculated from vehicle miles traveled (VMT) driven in 1982 divided by miles per gallon fuel consumption times the ratio of leaded to unleaded fuel times Pb additive per gallon. U.S. Environmental Protection Agency calculations of the fates of Pb were used to estimate Pb aerosol dispersal in each UA. About 108 billion miles of travel in 1982 within 8 UAs accounts for 3200 metric tons of Pb additives or ~60% total Pb additives in California. Between the 1950–1982 peak of Pb additives, about 258,000 metric tons are accounted for out of the state 412,000 metric tons total during the same time period. The estimates of the quantities of Pb dust that accumulated within various UAs in California assists with predicting the continuing influences of Pb on children's exposure. Mapping the soil Pb reservoir assists with establishing the priority for enhancing environments of children.

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*Abbreviations:* ALRA, Airborne Lead Reduction Act; DVMT, Daily vehicle miles of travel; Miles per gallon, mpg. Fuel economy is defined as miles per gallon up gasoline; NHANES, National Health and Nutrition Examination Survey; UA, Urbanized area; U.S. gallon, 3.79 l; U.S. miles, 1.61 km.

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## 1. Introduction

The quantities of lead (Pb) additives and their dispersion within urbanized areas (UAs) are the topic of this article. The study site is California. Whether it is from deterioration or mismanagement of the large tonnages of intact Pb-based paint in residences, or the equally large tonnages of Pb dust from additives to gasoline, the ultimate results are the continuing exposure of children to Pb dust (Mielke and Reagan, 1998). Exterior soils represent an enormous reservoir of Pb, and indications of the size of the reservoir are noted by studies of children's hands before and after outdoor play and also by direct measurement of Pb loading on the soil surface (Viverette et al., 1996; Mielke et al., 2007b; Nielsen and Kristiansen, 2005). Exterior soils via track-in and resuspended Pb aerosols contribute substantially to the mass transfer of Pb dust into residential interiors (Clark et al. 2004; Caravanos et al., 2005; Hunt et al., 2006; Layton and Beamer, 2009).

At the urban scale, the extent of the impact of Pb additives in gasoline was indicated by findings in garden soils of Baltimore, Maryland (Mielke et al., 1983). Based on vehicle miles of travel, Pb additives in gasoline were calculated at 5000 to 10,000 metric tons for Baltimore City during the era of leaded gasoline (Mielke et al., 1983). The study concluded that the use of leaded gasoline produced a highly polluted inner city compared with a less polluted outlying community and may be an important factor in the childhood Pb exposure problem (Mielke et al., 1983). In the South Coast Air Basin of California the quantities of Pb additives used in gasoline from 1970 to its ban were estimated at 20,000 metric tons (Harris and Davidson, 2005). Because highways were commonly planned and constructed to move traffic into and through cities, UAs of California probably have the same soil Pb and Pb exposure characteristics as described for other UAs (Post, 2007).

The objectives of this article are: 1) to provide an overview of the quantities of Pb additives used in vehicle fuel in the U.S. from 1927 through 1994; 2) to evaluate Pb additives dispersed in 1982 by vehicle traffic in 8 UAs of California; 3) to estimate the total Pb dispersed in each of the 8 UAs from 1950 through 1982, the period bracketing the peak use of Pb additives, and 4), to provide a review of soil Pb and predict the impact of the accumulated Pb on children's Pb exposure for each UA. Fulfilling these objectives should provide characteristics about Pb additives as a function of UAs and residential community location and result in better understanding of the remediation needs to protect children from exposure to Pb dust.

## 2. Methods

Three datasets were developed. First, the U.S. nationwide quantities of Pb additives in gasoline were obtained from corporate and government reports. Data were available from 1927 through 1994, when gasoline contained Pb additives. Second, the 1982 quantities of Pb additives used in eight UAs were calculated from data available from a corporate report and publicly available records for eight cities of California (Ethyl, 1982; U.S. DOTa, 1987). Third, the 1982 proportions of Pb were applied to California data on fuel

consumption from 1950 to 1982 to calculate the approximate quantities of Pb used in each of the same 8 California UAs.

### 2.1. Annual quantities of lead additives in gasoline, 1927–1994

Data of the annual amounts of Pb from 1927 to 1984 were obtained from a figure included in testimony by Ethyl Corporation as part of the Air Lead Reduction Act of 1984 (ALRA, 1984, p. 148). Additional data were from the U.S. Geological Survey (USGS, 2005) Lead End-Use table under gasoline additives from 1985 to 1994 to complete the tabulation. These two data sources describe the Pb quantities used in the U.S. during the 1927–1994 era of Pb additive use in gasoline.

### 2.2. Vehicle traffic and 1982 lead emissions for eight urbanized areas

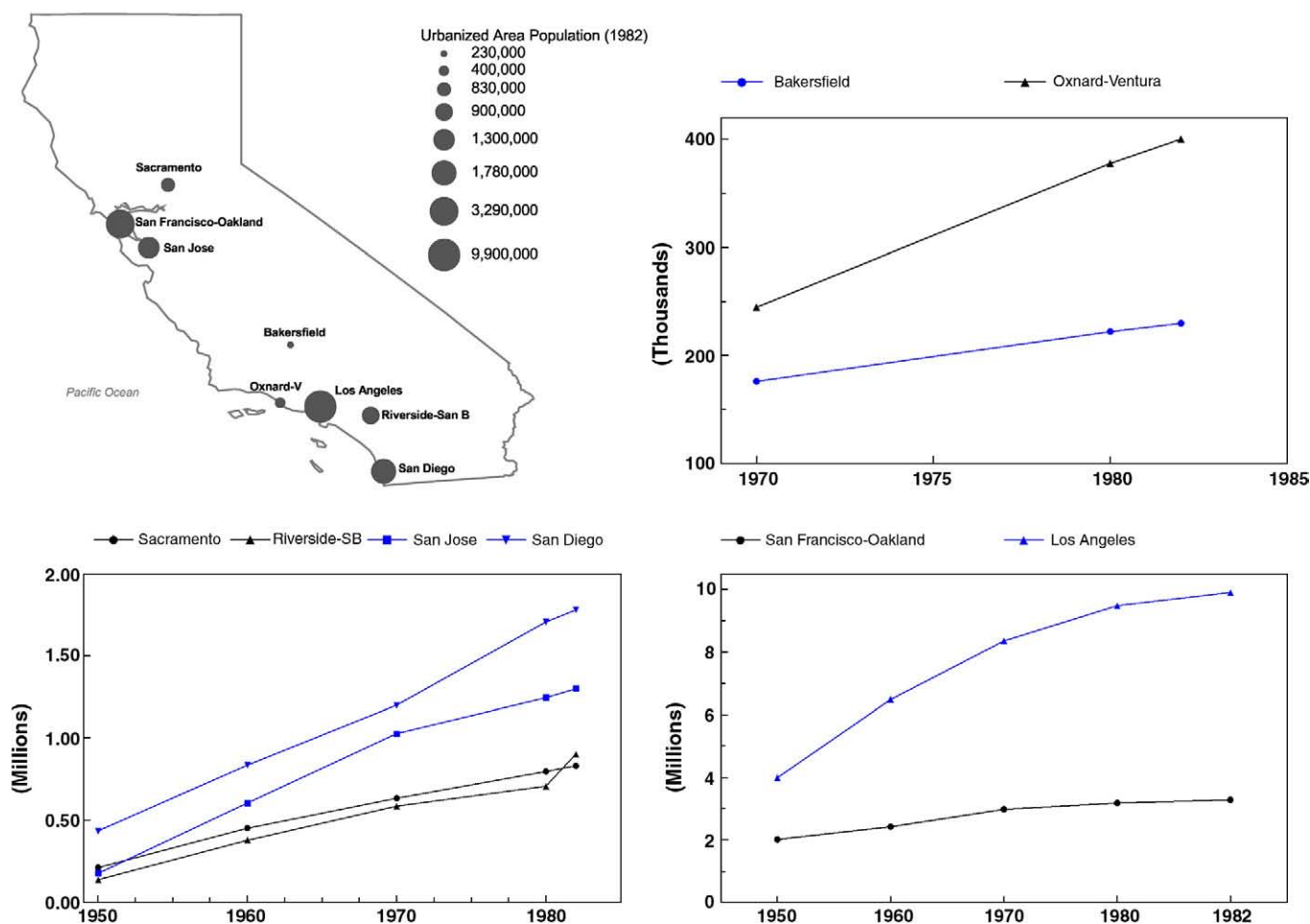
Vehicle traffic data originating with the Federal Highway Administration were compiled by the Texas Transportation Institute (TTI, 2009). The vehicle traffic data were sorted and tabulated for the following 8 UAs of California: Bakersfield, Oxnard–Ventura, Sacramento, Riverside–San Bernardino, San Jose, San Diego, San Francisco–Oakland, and Metro Los Angeles (see Fig. 1). Fig. 1 indicates the population and location of each UA. It also includes graphs of 1950–1982 population changes (U.S. Census Bureau, 1970, 1990). Population data for the smallest UAs were not available for 1950 and 1960. In general, the UA populations grew at a relatively consistent rate. The main exception is Metropolitan Los Angeles, which between 1950 and 1980 grew more rapidly than the other 8 UAs.

To estimate the quantity of Pb attributable to each of the UAs requires three additional variables, the average fuel economy (mpg), the percent leaded gasoline, and the grams of Pb per gallon.

- average fuel economy for 1982 is from the Federal Highway Administration (U.S. DOTa);
- the quantities of various grades of leaded and unleaded gasoline used in California are from the Ethyl Corporation Yearly Report (Ethyl, 1982); and,
- the annual quantities of Pb per gallon of gasoline are from a published report on the long-term historical trends of Pb in gasoline (Shelton et al., 1982).

Data for each urban area were compiled and tabulated. Daily vehicle miles traveled (DVMT) were summed for freeway and arterial street travel and then multiplied by 365 to obtain the reported vehicle miles traveled (VMT) for 1982. From 1982 VMT the gallons of gasoline were estimated by dividing VMT by the 1982 average of 14.1 miles per gallon (U.S. DOTa). The estimated gallons were multiplied by 0.372, assuming the same proportion of leaded gasoline compared with unleaded gasoline for each UA as reported by Ethyl Corporation (1982) for the state of California. Then quantities of Pb were estimated by multiplying the number of gallons of leaded gasoline times 1.14 g per gallon. The estimated Pb quantities were given in metric tons for each urban area in 1982.

According to the U.S. EPA (1986) 75% of the Pb additives were emitted from tailpipes directly into the atmosphere. Particle sizes of



**Fig. 1.** 1982 Population statistics for eight California urbanized areas where the estimated Pb emissions were developed in this study (U.S. Census Bureau, 1970, 1990). Also, the small graphs show that the population of Los Angeles and Oxnard–Ventura urbanized areas in Southern California grew more rapidly than the other urbanized areas. Because the estimates are based on proportions for 1982, the differences in growth rates tend to inflate the estimates of Pb additives emitted in Los Angeles and Oxnard–Ventura UAs and understate the Pb additives in the other UAs during 1950–1982.

the Pb aerosols were allocated into two categories, >10 μm (40%) and <0.25 μm (35%), and these were also calculated for each urban area (U.S. EPA 1986). Twenty-five percent of the Pb in gasoline remains in the engine as Pb adhering to engine-exhaust surfaces (15%), and Pb

remaining in the lubricating oil (10%), and these results are given in Table 1 (U.S. EPA, 1986). The proportion of Pb accounted for by these 8 UAs was 0.63 of the total amount of the 1982 state total of 5180 metric tons for California.

**Table 1**  
Estimated 1982 lead emissions from traffic in eight urbanized areas of California.

Urban area information	Bakersfield	Oxnrd–Vntur	Scrmnto	Rvrstd–Sn Brnrdrn	San Jose	San Diego	Sn Frn–OkInd	Metro LA	1982 Sum
	Sml	Med	Lrg	Lrg	Lrg	Lrg	Vlg	Vlg	
Population (1000s)	230	400	830	900	1300	1780	3290	9900	18,630
U.S. rank	76	64	36	33	23	15	8	2	
Urban area (square miles)	70	170	280	450	325	610	800	1830	4535
Popn density (persons/sq mile)	3286	2353	2964	2000	4000	2918	4113	5410	27,044
Peak travelers (1000s)	95	171	344	374	540	739	1296	3990	7549
Freeway DVMT (1000s)	880	3005	5725	6290	11,040	15,070	29,790	72,475	144,275
Arterial streets DVMT (1000s)	1900	2905	8130	7880	9235	11,905	18,895	90,390	151,240
Total DVMT (1000s)	2780	5910	13,855	14,170	20,275	26,975	48,685	162,865	295,515
Total vehicle miles/year (1000s)	1,014,700	2,157,150	5,057,075	5,172,050	7,400,375	9,845,875	17,770,025	59,445,725	107,862,975
Gal/year (1000s) (mpg = 14.1)	71,965	152,989	358,658	366,812	524,849	698,289	1,260,285	4,216,009	7,649,856
Gal/year leaded 0.372 (1000s)	26,771	56,912	133,421	136,454	195,244	259,764	468,826	1,568,355	2,845,747
Grams of Pb at 1.14 g/gal (1000s)	30,519	64,880	152,100	155,558	222,578	296,130	534,462	1,787,925	3,244,151
Metric tons Pb in gasoline in 1982	31	65	152	156	223	296	534	1788	3244
Pb emissions (75%)	23	49	114	117	167	222	401	1341	2433
Med > 10 μm local (metric tons)	12	26	61	62	89	118	214	715	1298
Med <0.25 μm lng rnge trnsprt	11	23	53	54	78	104	187	626	1135
Lead remaining in engine (25%)	8	16	38	39	56	74	134	447	811
Engine and exhaust system (15%)	5	10	23	23	33	44	80	268	487
Lead in the lubricating oil (10%)	3	6	15	16	22	30	53	179	324

The California proportion of U.S. leaded gasoline was 0.372.

### 2.3. Estimated lead additives in eight California urbanized areas during 1950–1982

Fuel sales for all grades of gasoline in California for 1950–1975 were obtained from Highway Statistics Summary (U.S. DOTb, 1987). The fuel volume by gasoline grade (regular leaded, regular unleaded, premium leaded, and premium unleaded) sold in California during 1975–1982 are listed in the Ethyl Corporation 1982 yearly report (Ethyl, 1982). These gasoline quantities were converted into the amounts of Pb in gasoline by using the data on the historical trends of Pb per gallon of gasoline (Shelton et al., 1982). Further estimates were made by assuming approximately the same proportion of Pb for each California UA between 1950 and 1982 as for 1982. The total amount of Pb additive calculated for California was 412,000 metric tons between 1950 and 1982. The sum of Pb additives estimated for the 8 UAs was 285,000 metric tons. Estimates of the Pb aerosols and Pb remaining in engines and oil are also provided for each UA.

### 3. Results

Fig. 2 illustrates the trend for the entire six decade period of Pb additives in gasoline as reported by Ethyl Corporation and USGS (ALRA, 1984, p. 148; USGS). The sum of Pb additives in gasoline in the United States from 1927 to 1994 was about 5,368,000 metric tons.

Table 1 lists the 1982 estimated Pb additives used in gasoline by vehicle traffic in 8 UAs of California. The 1982 sum of Pb additives for all 8 UAs is estimated at 3244 metric tons. In addition, the particle sizes of the Pb aerosol are estimated along with the quantity of Pb remaining in the engine system and the lubricating oil (U.S. EPA, 1986).

Fig. 3 is a graph of the annual amount of Pb calculated from fuel sales in California between 1950 and 1982. The U.S. amount of Pb additive calculated for the period from 1950 through 1982 is about 4,639,000 metric tons, or about 86% of the total amount of Pb additive (5,368,000 metric tons) used during the years from 1927 through 1994. The 1950–1982 period brackets the years of most intensive use of Pb additives in gasoline.

Table 2 lists the estimated Pb additives for 8 UAs of California during the 1950 and 1982 period. The tabulation applied the proportions for each UA in 1982 to the eight UAs during 1950–1982. The California total quantity of calculated Pb additive between 1950 and 1982 was about 412,300 metric tons. The amount of Pb additive calculated for the eight UAs is 258,400 metric tons, or 63% of the total Pb additive calculated for California during the same time period. An estimation of the various particle sizes of Pb aerosols and

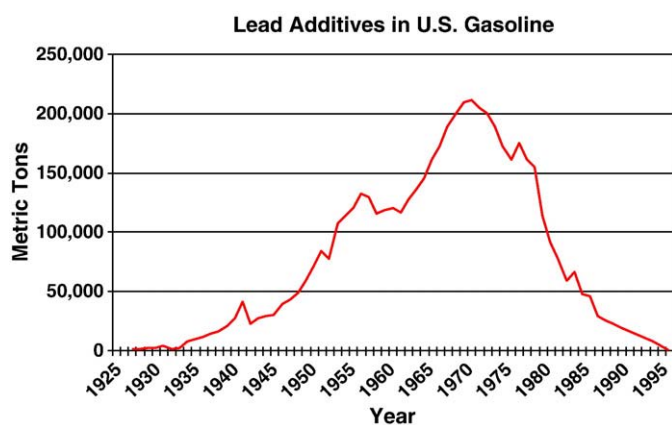


Fig. 2. Total U.S. lead additives in gasoline, 1927–1995, were derived from the proceedings of the U.S. Senate hearings on the Airborne Lead Reduction Act of 1984, S. 2609 (ALRA, 1984) and the U.S. Geological Survey Lead End-Use statistics (USGS, 2005).

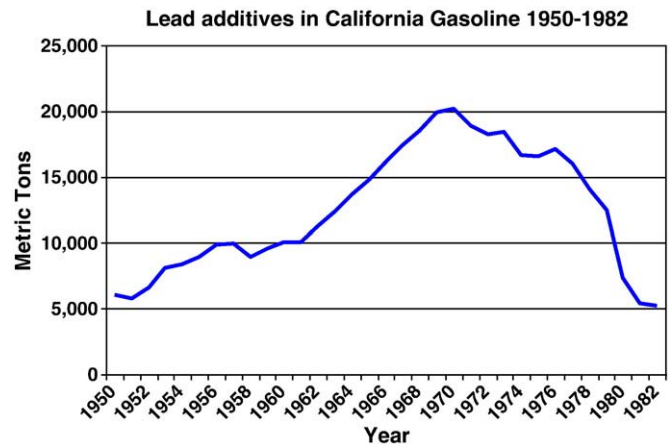


Fig. 3. Lead additives in California gasoline, 1950–1982, were calculated from fuel consumption data from the U.S. Department of Transportation (U.S. DOTb) and the yearly report from the Ethyl Corporation (Ethyl, 1982) using long-term historical trend data on lead additives to gasoline (Shelton et al., 1982). Note that this 32 year span includes the U.S. peak in the use of lead additives.

Pb residues remaining in the engine or crankcase lubricant is also calculated for each of the 8 UAs from the U.S. EPA (1986) data.

### 4. Discussion

#### 4.1. Quantities of lead in gasoline during 1927–1994

Fig. 2 illustrates the historical U.S. use of Pb additives from Ethyl Corporation plus the USGS data. About 5.4 million metric tons of Pb additives were used in U.S. gasoline beginning in 1927 through 1994. Tetraethyl Pb was touted as safe, with low toxicity as a fuel additive and considered a “Gift of God” by the manufacturers, but in reality Pb additives were an international public health disaster (Kovarik, 2005; Needleman, 1998; Rosner and Markowitz, 1985; Thomas et al., 1999). A rapid increase in Pb additives beginning in 1950 occurred as a result of the combination of a decline of public rail transit systems, a rapid growth in vehicle sales, the rapid expansion of the highway system and restrictions on the use of benzene as an anti-knock additive to fuel (Post, 2007). Before 1950, benzene made up several percent of the fuel. Ironically, because of concerns about the toxicity of benzene, Pb additives replaced benzene to meet anti-knock requirements of the increasing market share of high compression engines. A gradual phase down of Pb additives began in 1975 when EPA introduced health-based language into the regulations (Bridbord and Hanson, 2009). Health considerations required cleanup of engine exhaust and this was achieved by the addition of catalytic converters in the production of new cars. Because the catalysts were rendered useless by Pb, Pb additives in gasoline were removed. When the EPA reduction of Pb additives began to falter in the early 1980s, the U.S. Congress stepped in to ban Pb additives with the passage of the Air Lead Reduction Act of 1984 (ALRA, 1984) which resulted in a rapid phase down on January 1, 1986 and a total ban of Pb additives to gasoline sold for highway use on January 1, 1995. The above facts have direct bearing on the characteristics of Pb in UAs of California.

#### 4.2. 1982 Calculations for eight urbanized areas

Table 1 provides data about the calculated quantity of Pb dust emitted by vehicle traffic within eight California UAs during 1982. The quantities of Pb may be conservative because traffic flow data includes only major freeways and arterial roads and not local traffic between the driveway and arterial roads. Because the estimates are based on 1982 proportions by each UA, the Los Angeles total may be too large and this also means that the totals for the other seven UAs may be too

**Table 2**

1950–1982 Estimates of the metric tons of lead which were derived from fuel consumed in eight California urbanized areas. The fate of Pb additives after they enter the engine is based on estimates made by the U.S. EPA (1986).

1950–1982 Estimates	Bakersfield	Oxnrd– Vntur	Scrmnto	Rvrnsd–Sn Brnrdrn	San Jose	San Diego	Sn Frn– Okln	Metro LA	City sum	State total
Metric tons Pb in gasoline in 1982	31	65	152	156	223	296	534	1788	3244	5177
Proportion for each city	0.006	0.013	0.029	0.030	0.043	0.057	0.103	0.345	0.627	
Metric tons lead additives 1950–1982	2430	5167	12,113	12,388	17,725	23,583	42,562	142,383	258,351	<b>412,276</b>
<b>Pb emissions (75%)</b>	<b>1823</b>	<b>3875</b>	<b>9084</b>	<b>9291</b>	<b>13,294</b>	<b>17,687</b>	<b>31,922</b>	<b>106,788</b>	<b>193,764</b>	<b>387,527</b>
Particles med >10 µm local (40%)	972	2067	4845	4955	7090	9433	17,025	56,953	103,341	
Particles med <0.25 µm LRT (35%)	638	1356	3180	3252	4653	6190	11,173	37,376	67,817	
<b>Lead remaining in engine (25%)</b>	<b>608</b>	<b>1292</b>	<b>3028</b>	<b>3097</b>	<b>4431</b>	<b>5896</b>	<b>10,641</b>	<b>35,596</b>	<b>64,588</b>	<b>129,176</b>
Engine and exhaust system (15%)	365	775	1817	1858	2659	3537	6384	21,358	38,753	
Lead in the lubricating oil (10%)	243	517	1211	1239	1773	2358	4256	14,238	25,835	

conservative. Also, not all of the Pb emitted by vehicle traffic actually accumulated in the soils of each city. Lead aerosols from undetermined sources drifted large distances and even settled in Greenland and the Antarctic where ice cores disclose a geochemical record of the atmospheric Pb input from industrial development through many centuries (Murozami et al., 1969). For cities, tonnages of relatively coarse particles of Pb were probably dispersed in a small area, while tonnages of extremely small particles of Pb were scattered across the planet. Small particles of Pb may also collect on buildings, trees, and other vertical surfaces and wash down into the soil (Mielke et al., 1984; Mielke, 1999).

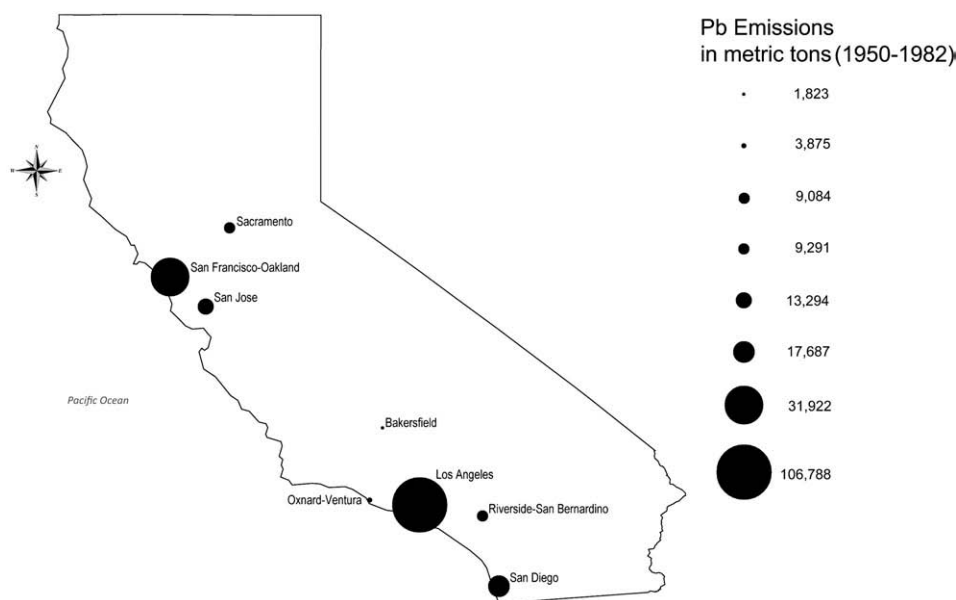
#### 4.3. 1950–1982 Estimates for eight urbanized areas

Fig. 3 illustrates the amount of Pb used in California during 1950–1982. From the data on the fuel consumed each year and the average amount of Pb additive per gallon, the calculated sum of Pb additives is about 412,300 metric tons in California from 1950 to 1982. The total amount of Pb additive used in the U.S. during the same period was about 4,639,000 metric tons; thus, the amount of Pb additive used in California was about 8.9% of the U.S. quantity of Pb additive in gasoline

from 1950 to 1982. Table 2 provides the estimated Pb additive for each city for 1950–1982 assuming the same proportions as 1982. The quantity of Pb additive accounted for by these UAs is around 258,400 metric tons of the total Pb additives 412,300, and because the 1982 proportions are assumed, this table accounts for about 63% of the Pb additive in California during 1950–1982. Note that the sum of two of the UAs, Riverside–San Bernardino plus Metro Los Angeles, in the South Coast Air Basin of California for 1950–1982 accounts for about 116,080 metric tons of Pb or nearly 6 times the 20,000 metric tons of Pb that Harris and Davidson (2005) indicated (from 1970 on) for the same region. Fig. 4 is a map of Pb aerosol emissions by the eight UAs of California included in this study. The connection between the legacy of Pb additives in gasoline and the current condition of UAs of California can be evaluated by reviewing soil Pb studies conducted in California.

#### 4.4. Background soil lead concentrations in California

Background soil Pb concentrations are described from several studies. At 11 California Air Force bases the soil Pb concentrations are 5.2 mg/kg (Hunter et al., 2005). For 50 benchmark California soils the



**Fig. 4.** Estimated lead aerosol emissions in metric tons, 1950–1982, were derived from proportions developed for 1982 that were applied to the calculated Pb additives in grams/gallon (Shelton et al., 1982) times gallons of gasoline sold in California from 1950 to 1975 (U.S. DOTb) and from 1975 to 1982 (Ethyl, 1982). The lead aerosol quantities are 0.75 the total amount of Pb additives in gasoline (U.S. EPA, 1986).

background is 20.6 mg/kg (University of California, 1996). The background was 23 mg/kg for 1300 surface soil samples collected from a 20,000 km<sup>2</sup> study area which includes the western slope of the Sierra Nevada, southern Sacramento Valley and the Coast Ranges of northern California (Goldhaber et al., 2009). Soil samples collected between 1919 and 1933 in the Southern California Air Basin had Pb concentrations of approximately 16 ± 0.5 mg/kg (Page and Ganje, 1970). Compared to UA soils these background soils are remarkably clean and readily accessible to UAs.

#### 4.5. Testable predictions about the legacy of lead additives in California's urbanized areas

The following discussion considers the testable consequences of the legacy of Pb additives in gasoline for 8 UAs of California listed in Tables 1 and 2.

##### 4.5.1. Soil Pb as a function of city size and inner-city vs. outer city location

Given the results of Tables 1 and 2, California UA soils probably have quantities of Pb correlated to city population, i.e., big cities are locations of larger traffic flows and larger emissions of Pb aerosols than smaller cities and towns. This prediction is based on studies conducted on larger and smaller cities and towns of Minnesota which noted that the amount of soil Pb was directly related to the size of the city, and small towns, regardless of age, had less soil Pb than larger towns and cities (Mielke et al., 1984/85, 1989). These city-size studies were replicated in Louisiana and compared with the Minnesota studies, and both studies support the hypothesis that the quantity of vehicle traffic is a major factor in dispersing Pb dust and defining the Pb footprint of urbanized areas (Mielke et al., 1984/85, 1989, 2008; Mielke, 1993). The same city-size characteristics are expected for UAs of California. A study published by the National Research Council in 1972 (NRC, 1972) noted that the Pb content in urban surface soil was 3357 mg/kg at MacArthur Park in Los Angeles, 560 mg/kg at Golden Gate Park San Francisco and 194 mg/kg at Balboa Park, San Diego.

Another characteristic concerning soil Pb quantity is the inner-city vs. outer-city soil Pb differences found in UAs. Laidlaw and Filippelli (2008) and Laidlaw, M.A.S. (Website) reviewed the quantity and distribution of soil Pb in numerous cities in North America, and to date, all North American cities exhibit the same distance decay characteristic of high soil Pb contamination in the inner city and decreasing contamination toward the outer parts of the city as initially identified in garden soils of Baltimore (Mielke et al., 1983). In California, soil studies in the heavily traveled neighborhood of the UCLA married student housing units in Los Angeles ranged between 673 mg/kg and 3633 mg/kg; the same study reports that soil samples from Lancaster, outside of Los Angeles, ranged between 42.5 and 98.4 mg/kg (Johnson et al., 1975). Goldhaber et al. (2009) observed that the UA of Sacramento including the cities of Stockton and Lodi has significantly higher soil Pb concentrations than adjacent rural and less populated areas. Pb concentrations are highest in the eastern Sacramento Valley where the preponderance of UAs and highways are located (Goldhaber et al., 2009). All of the above studies indicate that the major quantities of Pb accumulated in soil are associated with size of, and community location within, UAs of California.

##### 4.5.2. Soil pollution, lead-based paints and vehicle traffic

Given the results of Tables 1 and 2, soils of California UAs probably have soil Pb concentrations that are strongly interrelated with both age of housing units and vehicle traffic. The footprint of Pb in urban soils requires taking into account at least Pb-based paints and Pb additives to gasoline. This hypothesis was tested in Baltimore (Mielke et al., 1983), elaborated on in Minnesota (Mielke et al., 1984, 1989), and further refined for New Orleans (Mielke et al., 1997, 2008). In New Orleans, soil on properties of public housing constructed at the

same year with the same materials in the inner-city core and at the outskirts in the city had significantly ( $p$ -value < 0.001) different amounts of lead; the inner city (medians 158–386 mg/kg) had two to ten-fold more soil lead than public housing properties located in the outlying areas (medians 37–81 mg/kg) of the city (Mielke et al., 2008). The same study also indicated even larger amounts of lead on soils of residential properties within the inner city (medians 456–707 mg/kg) and the outer city (medians 96–178 mg/kg) (Mielke et al., 2008). Lead-based paint is particularly problematic as a source of pollution in New Orleans because of widespread power sanding. A study of one house was conducted where the paint was scraped and weighed to determine the potential quantity of Pb emanating as Pb dust if it were power sanded (Mielke et al. 2001a). The result was a one-time potential release of  $7.4 \times 10^9$  µg Pb dust which would have been released by power sanding compared to the annual emission of  $50 \times 10^9$  µg of Pb dust per 0.1 mile (0.16 km) from vehicle traffic on a nearby street during the peak (late 1960s–early 1970s; see Figs. 2 and 3) from Pb additives in gasoline (Mielke et al., 2001a).

In California both traffic and building-age related variables are similarly indicated as important variables for predicting soil Pb concentrations. Sutton et al. (1995) analyzed soil samples collected from 358 homes in Oakland, 343 homes in Los Angeles, and 232 homes in Sacramento, and median soil concentrations were 880 mg/kg in Oakland, 190 mg/kg in Los Angeles and 222 mg/kg in Sacramento; Sutton et al. (1995) also observed that homes built before 1920 were 10 times more likely to have soil Pb content ≥ 500 ppm compared to post-1950 homes; in Oakland, soil Pb concentrations exceeded 1000 mg/kg at 46% of the homes. A description of the location of the homes in each city is missing, but older homes are commonly located in inner-city communities while newer homes are located in communities toward the outskirts of UAs.

A review of California studies indicates that compared with background soil Pb away from urban areas, soils in UAs are highly contaminated by highway sources of Pb. In 2002, after Pb additives to gasoline had been completely phased out, Lejano and Ericson (2005) analyzed soil around Pacoima, California and found that both total and bio-available Pb were markedly higher in areas close to major highways. Similarly, elevated soil Pb occurred within a residential community in the proximity of Interstate 880, Alameda County, California (Teichman et al., 1993). Soils were collected from the yards of homes in communities adjacent to the freeway and within a one mile (1.6 km) radius; the possibility of Pb-based paint contributing to the contamination was minimized by collecting samples at least 20 ft (>6 m) from the homes. The soils closest to the highway contained amounts of Pb exceeding California's and EPA's criteria for hazardous waste, or >1200 mg/kg (Teichman et al., 1993). Wu et al. (2010) collected 550 surface soil samples from south central Los Angeles and found that mean total and bio-available Pb concentrations were highly correlated ( $r=0.96$ ); Pb concentrations near freeways and major arterials were significantly higher than soils collected at other locations.

Vehicle traffic continues to impact Pb loading of street dust. In addition to the past usage of Pb additives that have accumulated in UAs, Pb-based wheel weights used to balance tires contribute to Pb dust loading. Wheel weights are prone to dislodgement and on pavement they are ground into fine particles by the pounding forces of traffic (Root, 2000; U.S. EPA NLFWWI). California has passed legislation that was signed into law to eliminate Pb in wheel weights on cars intended for sale in California by July 31, 2009 (California lead-based wheel weight ban, Senate Bill #757). Pb however, still remains as a legacy of pollution associated with streets and highways.

##### 4.5.3. Soil lead as a source of exposure

Given the quantities of Pb shown in Tables 1 and 2, Pb dispersed and settled in soils of California UAs probably exposes children.

Children are exposed to soil Pb by dust being tracked into homes on shoes (Hunt et al., 2006) and family pets and via resuspension and deposition of Pb contaminated urban soil dust which penetrates interiors of homes and settles onto contact surfaces (Clark et al., 2004; Layton and Beamer, 2009; Laidlaw and Filippelli, 2008). Children are then exposed through hand-to-mouth activity (Ko et al., 2007). Soil Pb concentrations have been observed to be associated with children's blood Pb concentrations using multiple study designs—cross-sectional, ecological spatial, ecological temporal, prospective soil removal and isotopic (Filippelli et al., 2005; Laidlaw and Filippelli, 2008). Lead in soil is at least co-equal to Pb-based paint as an explanation for the urban pattern of Pb exposure of children (Mielke and Reagan, 1998). Children's hands at childcare centers were tested with wipes before and after outdoor play, and they had more Pb after playing outside than after playing inside (Viverette et al., 1996; Nielsen and Kristiansen, 2005). At private inner-city childcare centers the amount of Pb per hand exceeded the 6 µg Total Tolerable Daily Intake (TTDI) of Pb by a factor of 5 or more; in public Head Start childcare centers, where bare soil on play areas is covered with rubber mats, children's hands did not indicate Pb differences before and after outside play (Viverette et al., 1996; Nielsen and Kristiansen, 2005). Furthermore, a soil surface sampler (PLOPS) revealed that the Pb loading on the bare surface of soil containing 400 mg/kg, the EPA standard for Pb, exceeds the current guideline of Pb loading of 40 µg/ft<sup>2</sup> on interior floors by a factor of about 35 (Mielke et al., 2007b). Soil Pb on the play areas of elementary public schools follow the same trend as soil Pb in the entire city; however, soils on school grounds are significantly less Pb contaminated than soils of neighboring residential properties where the most vulnerable preschool children probably play before they attend school (Higgs et al., 1999).

Finally, vehicle interiors may also be a source of Pb exposure. In a case reported of car contamination from clothes of employees who work with Pb, Pb dust collected in vehicle upholstery and carpets may exist as another probable source of children's Pb exposure (Bernier et al., 2009; Yiin et al., 2002).

#### 4.5.4. Association between soil lead and blood lead

Given the results shown in Tables 1 and 2, blood Pb of California children probably respond directly to size of UAs and community location within a given UA. This and other predictions regarding blood Pb require obtaining full spectrum blood Pb surveillance rather than blood Pb results truncated at an arbitrary level (such as 15 µg/dL) as currently occurs in California. In Minnesota, the amount of Pb in the soil of a community was found to be strongly associated with blood Pb of children living in the same community, and this relationship was further refined for Louisiana (Mielke et al., 1989, 1997, 1999, 2007a). Levin et al. (2008) state that blood Pb levels increase 1–5 µg/dL for every 1000 mg/kg increase in soil Pb. However, the blood Pb response of children to soil Pb is curvilinear in New Orleans, LA (Mielke et al., 1997, 1999). Johnson and Bretsch (2002) also observed a similar curvilinear relationship between soil Pb and children's blood Pb in Syracuse, NY. The most recent New Orleans urban soil Pb and blood Pb study shows the following results: Below 100 mg/kg soil Pb children's blood Pb response is steep at 1.4 µg/dL per 100 mg/kg, while above 300 mg/kg soil Pb children's blood Pb response is a gradual 0.32 µg/dL per 100 mg/kg (Mielke et al., 2007a). Similar associations between soil Pb and blood Pb responses of children are expected in UAs of California.

In Los Angeles, Macey et al. (2001) concluded that proximity to transportation corridors was consistently the strongest indicator of environmental Pb exposure, while median home values were significantly and inversely associated with elevated blood Pb levels. In the UA of Sacramento, Deocampo and Orr (2006) observed that soil Pb concentrations ranged from 15 mg/kg (background) to over 1500 mg/kg and that the spatial distribution of soil Pb concentrations showed a possible relationship with children's blood Pb concentrations.

#### 4.5.5. Soil lead and seasonality

Given the results shown in Tables 1 and 2, blood Pb seasonality in California UAs will probably respond directly to climatic variables affecting Pb dust accumulated in each of the UAs. The Pb dust within major cities is so ubiquitous that seasonal weather patterns impact the blood Pb of the childhood population. For example, in Mexico City, Rosas et al. (1995) observed that during rainy seasons of the year, PM 10 dust was settled and atmospheric Pb concentrations were lower; during seasons with low rainfall PM10 and atmospheric Pb concentrations were higher. Laidlaw et al. (2005) extended this observation to include blood Pb and observed that during droughty periods when soil is dry and dusty, blood Pb increases; during rainy periods when soil is wet and dust is settled, blood Pb decreases. The suspended Pb dust apparently settles out and gradually recontaminates clean soil (Mielke et al., 2006b). Many studies indicate that urban Pb contaminated soils are being resuspended in the summer and autumn when evapotranspiration is at a maximum.

Average monthly blood Pb (BPb) values of children from urban areas tends to increase significantly in summer and autumn months (Haley and Talbot, 2004; Laidlaw et al., 2005; Yiin et al., 2000). Early work by Mielke et al. (1992), Johnson et al. (1996), and Johnson and Bretsch (2002) suggested that blood Pb seasonality may be related to the interaction between climate and Pb contaminated soils. Recent research strongly supports the relationship between soil resuspension and exposure and children's blood Pb levels. Laidlaw (2009) attempted to determine if the seasonal resuspension of soils into the atmosphere was related to seasonal changes in atmospheric Pb concentrations. Laidlaw (2009) tested the hypothesis that atmospheric Pb and atmospheric soil concentrations obtained from the Interagency Monitoring of Protected Visual Environments (IMPROVE, 2007) exhibit statistically significant correlations in Detroit, Birmingham and Pittsburgh. Results indicate that atmospheric soil and atmospheric Pb were correlated in Detroit between November 2003 and July 2005 ( $r=0.47$ ,  $p<0.001$ ); in Pittsburgh between April 2004 and July 2005 ( $r=0.40$ ,  $p<0.001$ ); and in Birmingham between May 2004 and December 2006 ( $r=0.35$ ,  $p<0.001$ ). Laidlaw concluded that soil and atmospheric Pb follow seasonal patterns with highest concentrations during the summer and/or autumn, and that atmospheric Pb and atmospheric soil concentrations are correlated due to resuspension of urban Pb contaminated soils. Laidlaw (2009) suggested that this Pb may be causing seasonal variations in children's blood Pb levels. In Milwaukee, Wisconsin, Havlena et al. (2009) observed that blood Pb levels followed a seasonal pattern with peaks in the summer and autumn. They also observed that particulate matter less than 2.5 µm (PM<sub>2.5</sub>) correlated with the seasonal variation in 10 month old children's blood levels, and suggested that the Pb in the PM<sub>2.5</sub> was causally related to seasonal variations in children's blood Pb levels.

The assumption that soil Pb is being resuspended and is responsible for a large portion of the Pb in the atmosphere is supported by isotopic analysis of atmospheric Pb in Yerevan Armenia (Kurkijan et al., 2002) which indicated that following elimination of the use of Pb in gasoline, 75% of atmospheric Pb in the Yerevan atmosphere was derived from resuspended soil. Similarly, Kamenov (2008) analyzed Pb isotopic ratios of teeth in Sofia Bulgaria and found that remarkable isotopic similarities between the teeth and the Pb additive to gasoline in the local soils and concluded that soil and/or soil-borne dust inhalation and/or ingestion are the most probable pathway for incorporation of soil Pb in the local population. Kurkijan et al.'s (2002) and Kamenov's (2008) observations are supported by Pingitore et al. (2009) who used synchrotron-based XAFS (x-ray absorption fine structure) to quantify the Pb species in the air of El Paso. Pingitore found that Pb-humate was the dominant form of Pb in contemporary El Paso air and that Pb-humate is the major Pb species in El Paso soils. Pingitore et al. (2009) concluded that the soil must be the dominant source, and it was being resuspended into the atmosphere.

Lankey et al. (1998) based on 1989 data, estimated that leaded gasoline use was responsible for approximately 50% of the overall lead emissions. Harris and Davidson (2005) calculated that the Pb particles that were deposited in the Southern California Air Basin (SOCAB) during the years of Pb additives in gasoline use are being resuspended into the atmosphere and responsible for generating approximately 54,000 kg of airborne Pb each year. The Harris and Davidson (2005) study used an average soil concentration of 79 mg/kg as an input into their resuspension model, while Wu et al. (2010) has calculated that the median soil concentration in Los Angeles is 180 mg/kg. Thus Harris and Davidson's (2005) SOCAB Pb resuspension estimate may be conservative. Nevertheless, Harris and Davidson (2005) concluded that soil contamination contributes most of the total airborne Pb currently measured in the SOCAB and is likely to continue to do so for many years. Young et al. (2002) studied resuspended roadside soils and Pb enriched smelter soils and observed that the Pb in the particulate matter less than 10  $\mu\text{m}$  (PM10) was enriched by 5.36–88.7 times compared with uncontaminated California soils.

Seasonal weather patterns differ markedly between southern and northern California and these differences are expected to influence children's blood Pb responses. Sabin and Schiff (2008) took measurements of metal dry deposition fluxes weekly on a north–south transect along the coast of southern California between Santa Barbara and San Diego over a four-month period during summer and fall 2006. Lead fluxes varied between 0.52 and 14  $\mu\text{g}/\text{m}^2/\text{day}$  with the highest Pb fluxes occurring at the San Diego and Los Angeles sites. They also commented that model estimates and measurement data in Los Angeles have found metal dry deposition flux rates which may increase during Santa Ana wind conditions by as much as factors of two to eight (Sabin and Schiff, 2008). Atmospheric metal concentrations at three sites in Santa Barbara and one site in Riverside showed evidence of seasonal variations whereby outdoor concentrations of metals were higher in the warmer months than in the cooler months (Polidori et al., 2009). Similarly, children's blood Pb in South Central Los Angeles ( $N=3679$ ) from 1991 to 1994 displayed a significant seasonal effect with the lowest blood Pb during late winter and early spring, and the highest blood Pb levels occurring in summer (Rothenberg et al., 1996).

#### 4.5.6. School performance and soil lead

Lead is the most intensively studied toxin, and the neurotoxic impact of childhood Pb exposure is strongly associated with societal problems that are extremely costly to society including learning deficits, socialization and violent behavior (Chandramouli et al., 2009; Muennig, 2009; Nigg et al., 2008; Reyes, 2007; Zahran et al., 2009). Given the results shown in Tables 1 and 2, California school children probably have school performance responses that are associated with the amount of Pb dust accumulated in various communities of UAs. The bases for this prediction are studies on tooth Pb and school performance by Needleman et al. (1979) followed up by empirical studies conducted in Minnesota and New Orleans. The hypothesis that the amount of Pb in soils of a community is associated with the performance of 4th grade children attending local schools was first hinted at by the observation in Minnesota of an association between dropout rates of high school students and city size (Mielke et al., 1989). The New Orleans studies refined the research to include the association between school achievement test scores and community soil Pb and other metals (Mielke et al. 2005b; Mielke and Berry, 2007, pp 116–123), and then between blood Pb and achievement test scores as an indicator of neurotoxicity at New Orleans attendance district schools (Zahran et al. 2009). Zahran et al. (2009) support Landrigan et al. (2002) and Stefanak et al. (2005) concerning the insidious costs that environmental Pb imposes on urban society. The finding also supports other reports (Chandramouli et al., 2009; Nigg et al., 2008). Patterson (1980, pp 271–272) expressed the problem as follows: "Extrapolating from present information, ...probably... it will be

shown in the future that average American adults experience a variety of significant physiological and intellectual dysfunctions caused by long-term chronic lead insult to their bodies and minds which results from excess exposures to industrial lead that are five hundred-fold above natural levels of lead exposure, and that such dysfunctions on this massive scale may have significantly influenced the course of American history."

Other important findings regarding soil pollutants and health are the correlations between multiple metals first described in Baltimore and also noted in New Orleans (Mielke et al., 1983, 2000). Lead, zinc, cadmium, manganese, chromium, nickel, vanadium and copper are strongly correlated with each other in soil, and the strongest correlations are among Pb, Zn, Cu, and Cr respectively (correlation coefficients above 0.8) (Mielke et al., 2000). The extremely strong correlation between Pb and Zn is probably because both metals are connected with vehicle traffic (Pb in gasoline and Zn in tires). Mixtures of multiple metals and various poly aromatic hydrocarbons (PAHs) are also elevated in soils in the inner city compared with soils in outlying communities (Mielke et al., 2001b; Wang et al., 2004). The toxicological impact of chemical mixtures is poorly understood but it probably influences the toxic characteristics of inner-city soils compared with soils in outlying communities of New Orleans, and these characteristics suggest a chemical basis for issues regarding health disparities and environmental justice (Campanella and Mielke, 2008; Mielke et al., 2004). Thus, school performance response by California children will probably be complicated by environmental chemistry characteristics and seasonality differences within the eight UAs included in this study.

#### 4.5.7. Treating the urban lead pollution problem

Currently U.S. exposure reduction efforts are focused on interior residential Pb dust, and especially on Pb-based paints (Dixon et al., 2009; Gaitens et al., 2009; Levin et al., 2008; Roberts et al., 1999). Given the results of Tables 1 and 2, prevention of Pb exposure in California UAs with emphasis on Pb-based paint alone will not successfully curb low blood Pb exposures (i.e. 5–10  $\mu\text{g}/\text{dL}$  or less) among children. In California a soil Pb standard of 80 mg/kg is proposed for residential properties to protect children from Pb (California 2009). This Pb standard is the same as empirically derived in New Orleans which assumed that the policy is to protect most children from a blood Pb exposure  $\geq 10 \mu\text{g}/\text{dL}$  (Mielke et al., 1999). If the policy is changed to prevent exposure of most children to a blood Pb  $< 5 \mu\text{g}/\text{dL}$  or lower, then the soil Pb standard must be reduced to substantially less than 80 mg/kg (Zahran et al., 2010). Because of the inherent size of the reservoir, soil Pb has been described as the "elephant in the playground" (Filippelli and Laidlaw, 2010). Soil mapping assists with developing priority for treatment and an empirical means for visualizing the environmental quality of any given city (Mielke, 2002). Some soil Pb mapping has been reported for UAs of California, but the surveys are not as extensive as maps of New Orleans (Mielke, 1991, 1994; Mielke et al., 2005a) or Syracuse (Griffith et al., 2009). California urban survey data are probably not of sufficient density to guide remediation efforts.

Examples of treating contaminated urban soil as a method for preventing exposure and reducing blood Pb began in Minneapolis (Mielke et al., 1992) and was advanced in New Orleans by using the soil Pb map as a guide (Mielke, 1994). Fresh sediments of the Mississippi River flow by the city at the average rate of 300 tons per minute, and they are remarkably clean ( $\sim 5 \text{ mg Pb}/\text{kg}$ ) and therefore it is a valuable natural resource to use for covering contaminated soils in the city (Mielke, 2005; Mielke et al., 2006a,b). Precedence for a national clean soil effort has been established by Norway to prevent exposure to accumulated Pb dust and other pollutants in urban environments. Norway's clean soil program conducts testing and cleanup of contaminated soils at all childcare centers, elementary schools and parks in the ten largest cities of the nation (Ottesen et al.,



2008). The scientific basis for developing the program was motivated in part by the mapping and statistical analysis applied to New Orleans research on soil Pb and children's health response (Ottesen et al., 2008).

## 5. Conclusions: emerging precautionary approaches to primary exposure prevention

Lead is a well known toxin, and its neurotoxic impact on children is strongly associated with problems that are extremely costly to society, including learning deficits, socialization, violent behavior and other health problems. Urban soil geochemistry research began with a map and statistical analysis of the clustering of high Pb concentrations in garden soils of inner-city Baltimore and the method has been developed into a tool for predicting the exposure of children to Pb. Emerging issues include finding the ways and means to reduce the continuing influence of Pb dust on children's health and wellbeing. Young children have no possibility for creating Pb-safe environments for themselves—this is an adult responsibility. There are many ways to make the environment safer for children. Currently, following Norway's precedence, an exterior mapping and clean soil program at childcare centers, elementary schools and playgrounds provides a path toward primary Pb exposure prevention for young children. By following the same precedence, California's children would benefit from an urban soil Pb mapping and clean soil program.

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## References

- ALRA. Airborne Lead Reduction Act of 1984, S. 2609. A bill to amend the clean air act with regard to mobile sources emission control. U.S. Senate Hearing Committee on Environment and Public Works. Washington, D.C.: U.S. Government Printing Office; 1984.
- Bernier T, Lee S, May A, Frohberg E, Smith A, Kennedy C, et al. Childhood lead poisoning associated with lead dust contamination of family vehicles and child safety seats. *MMWR* 2009;58(32):890–3.
- Bridbord K, Hanson D. Personal perspective on the initial federal health-based regulation to remove lead from gasoline. *Environ Health Perspect* 2009;117(8):1195–201.
- California lead-based wheel weight ban, Senate Bill #757 [http://www.leginfo.ca.gov/pub/09-10/bill/sen/sb\\_0751-0800/sb\\_757\\_bill\\_20091011\\_chaptered.pdf](http://www.leginfo.ca.gov/pub/09-10/bill/sen/sb_0751-0800/sb_757_bill_20091011_chaptered.pdf).
- California. Office of Environmental Health Hazard Assessment Revised California Human Health Screening Level for Lead (Review Draft) May 14, 2009; 2009. <http://oehha.ca.gov/risk/pdf/LeadCHHSL51809.pdf>. [Accessed December 1, 2009].
- Campanella R, Mielke HW. Human Geography of New Orleans' urban soil lead contaminated geochemical setting. *Environ Geochem Health* 2008;30(6):531–40. doi:10.1007/s10653-008-9190-9.
- Caravanos J, Weiss AL, Jaeger RJ. An exterior and interior leaded dust deposition survey in New York City: results of a 2-year study. *Environ Res* 2005;100(2):159–64.
- Chandramouli K, Steer CD, Ellis M, Emond AM. Effects of early childhood lead exposure on academic performance and behaviour of school age children. *Arch Dis Child* 2009;94:844–8.
- Clark S, Menrath W, Chen M, Succop P, Bornschein R, Galke W, et al. The influence of exterior dust and soil lead on interior dust lead levels in housing that had undergone lead-based paint hazard control. *J Occup Environ Hyg* 2004;1:273–82. doi:10.1080/15459620490439036.
- Deocampo DM, Orr W. Geochemistry of environmental lead in Sacramento, California. *GSA Abstracts with Programs*, 38. ; 2006. p. 152.
- Dixon SL, Gaitens JM, Jacobs DE, Strauss W, Nagaraja J, Pivetz T, et al. Exposure of U.S. children to residential dust lead, 1999–2004: II. The contribution of lead-contaminated dust to children's blood lead levels. *Environ Health Perspect* 2009;117:468–74. doi:10.1289/ehp.11918 available via <http://dx.doi.org/>.
- Ethyl. Ethyl Corporation Yearly Report for Gasoline Sales by States, 1982. Ethyl Petroleum Chemicals, 2 Houston Center, Suite 900, Houston, Texas 77010; 1982.
- Filippelli GM, Laidlaw MAS. The elephant in the playground: confronting lead-contaminated soils as an important source of lead burdens to urban populations. *Perspect Biol Med* 2010;53(1):31–45.
- Filippelli GM, Laidlaw M, Latimer J, Raftis R. Urban lead poisoning and medical geology: an unfinished story. *GSA Today* 2005;15:4–11.
- Gaitens JM, Dixon SL, Jacobs DE, Nagaraja J, Strauss W, Wilson JW, et al. Exposure of U.S. children to residential dust lead, 1999–2004: I. Housing and demographic factors. *Environ Health Perspect* 2009;117:461–7. doi:10.1289/ehp.11917.
- Goldhaber MB, Morrison JM, Holloway JM, Wanty RB, Helse DR, Smith DB. A regional soil and sediment geochemical study in northern California. *Appl Geochem* 2009;24:1482–99.
- Griffith DA, Johnson DL, Hunt A. The geographic distribution of metals in urban soils: the case of Syracuse. *NY Geojournal* 2009;74(4):275–91.
- Haley VB, Talbot TO. Seasonality and trend in blood lead levels of New York State children. *BMC Pediatr* 2004;4:8.
- Harris AR, Davidson CI. The role of resuspended soil in lead flows in the California South Coast Air Basin. *Environ Sci Technol* 2005;39(19):7410–5.
- Havlena J, Kanarek MS, Coons M. Factors associated with the seasonality of blood lead levels among preschool Wisconsin children. *WMJ* 2009;108(3):151–5.
- Higgs FJ, Mielke HW, Brisco M. Soil lead at elementary public schools: comparison between school properties and residential neighbourhoods of New Orleans. *Environ Geochem Health* 1999;21:27–36.
- Hunt A, Johnson DL, Griffith DA. Mass transfer of soil indoors by track-in on footwear. *Sci Total Environ* 2006;370:360–71.
- Hunter PM, Davis BK, Roach BK. Inorganic chemicals in groundwater and soil: background concentrations at California Air Force bases. 44th Annual Meeting of the Society of Toxicology. New Orleans, Louisiana; 2005.
- IMPROVE (Interagency Monitoring of Protected Visual Environments), 2007. Available: <http://vista.cira.colostate.edu/improve/> Accessed [15 November 2007].
- Johnson DL, Bretsch JK. Soil lead and children's blood lead levels in Syracuse, NY, USA. *Environ Geochem Health* 2002;24:375–85.
- Johnson DE, Tillery JB, Prevost RJ. Levels of platinum, palladium and lead in the population of Southern California. *Environ Health Perspect* 1975;12:27–33.
- Johnson D, Mcdade K, Griffith D. Seasonal variation in pediatric blood levels in Syracuse, NY, USA. *Environ Geochem Health* 1996;18:81–8.
- Kamenov GD. High-precision Pb isotopic measurements of teeth and environmental samples from Sofia (Bulgaria): insights for regional lead sources and possible pathways to the human body. *Environ Geol* 2008;55(3):669–80. doi:10.1007/s00254-007-1017-y.
- Ko S, Schaefer PD, Viacario CM, Binns HJ. Relationships of video assessments of touching and mouthing behaviors during outdoor play in urban residential yards to parental perceptions of child behaviors and blood lead levels. *J Expo Sci Environ Epidemiol* 2007;17:47–57.
- Kovarik W. Ethyl-leaded gasoline: how a classic occupational disease became an international public health disaster. *Int J Occup Environ Health* 2005;11:384–97.
- Kurkjian R, Dunlap C, Flegal R. Lead isotope tracking of atmospheric response to post-industrial conditions in Yerevan, Armenia. *Atmos Environ* 2002;36(8):1421–9.
- Laidlaw MAS. 2010 Website. Association between soil lead and blood lead—evidence <http://www.urbanleadpoisoning.com>.
- Laidlaw MAS. Correlation of atmospheric soil and atmospheric lead in three North American cities: can re-suspension of urban lead contaminated soil be a major source of urban atmospheric lead and cause seasonal variations in children's blood lead levels? 24th International Applied Geochemistry Symposium (IAGS). New Brunswick, Canada: Fredericton; 2009. June 1st to June 4th, 2009.
- Laidlaw MAS, Filippelli GM. Resuspension of urban soils as a persistent source of lead poisoning in children: a review and new directions. *Appl Geochem* 2008;23:2021–39.
- Laidlaw MAS, Mielke HW, Filippelli GM, Johnson DL, Gonzales CR. Seasonality and children's blood lead levels: developing a predictive model using climatic variables and blood lead data from Indianapolis, Indiana, Syracuse, New York and New Orleans, Louisiana (USA). *Environ Health Perspect* 2005;113(6):793–800.
- Landrigan PJ, Schecter CB, Lipton JM, Fahs MC, Schwartz J. Environmental pollutants and disease in American children: estimates of morbidity, mortality, and costs for lead poisoning, asthma, cancer, and developmental disabilities. *Environ Health Perspect* 2002;110:721–8.
- Lankey RL, Davidson CI, McMichael FC. Mass balance for lead in the California south coast air basin: an update. *Environ Res* 1998;78:86–93.
- Layton D, Beamer P. Migration of contaminated soil and airborne particulates to indoor dust. *Environ Sci Technol* 2009;43:8199–205.
- Lejano RP, Ericson JE. Tragedy of the temporal commons: soil-bound lead and the anachrony of risk. *J Environ Plann Manage* 2005;48(2):301–20.
- Levin R, Brown N, Kashtock ME, Jacobs DE, Whelan EA, Rodman J, et al. Lead exposures in U.S. children, 2008: implications for prevention. *Environ Health Perspect* 2008;116:1285–93.
- Macey G, Her X, Reibling ET, Ericson JE. An investigation of environmental racism claims: testing environmental management approaches with a geographic information system. *Environ Manage* 2001;27(6):893–907.
- Mielke HW. Mapping lead in residential soils of urban environments: overview of the New Orleans metals assessment project. *Water Air Soil Pollut* 1991;57:57–58: 111–9.
- Mielke HW. Lead dust contaminated USA communities: comparison of Louisiana and Minnesota. *Appl Geochem* 1993;8(Suppl 2):257–61.
- Mielke HW. Lead in New Orleans soils: new images of an urban environment. *Environ Geochem Health* 1994;16(3/4):123–8.
- Mielke HW. Lead in the inner-cities. *Amer Scientist* 1999;87:62–73.

- Mielke HW. Research ethics in pediatric environmental health: lessons from lead. *Neurotoxicol Teratol* 2002;24(4):467–9.
- Mielke HW. Lead's toxic urban legacy and children's health. *Geotimes* 2005;50(5):22–6.
- Mielke PW, Berry KJ. *Permutation Methods: A Distance Function Approach*. 2nd ed. New York: Springer-Verlag; 2007. 439 pp.
- Mielke HW, Reagan PL. Soil is an important source of childhood lead exposure. *Environ Health Perspect* 1998;106(Supplement 1):217–29.
- Mielke HW, Anderson JC, Berry KJ, Mielke Jr PW, Chaney RL, Leech M. Lead concentrations in inner-city soils as a factor in the child lead problem. *Am J Public Health* 1983;73(12):1366–9.
- Mielke HW, Blake B, Burroughs S, Hassinger N. Urban lead levels in Minneapolis: the case of the Hmong children. *Environ Res* 1984;34:64–76.
- Mielke HW, Burroughs S, Wade R, Yarrow T, Mielke Jr PW. Urban lead in Minnesota: soil transect results of four cities. *J Minn Acad Sci* 1984/85;50(1):19–24.
- Mielke HW, Adams JL, Reagan PL, Mielke Jr PW. Soil-dust lead and childhood lead exposure as a function of city size and community traffic flow: the case for lead contaminated soil abatement in Minnesota. (Supplement to volume 9) *Lead in soil: issues and guidelines* Environ Geochem Health; 1989. p. 253–71. ISBN 0-905927-92-3.
- Mielke HW, Adams JE, Huff B, Reagan PL, Peppersack J, Stoppel D, et al. Dust control as a means of reducing inner-city childhood Pb exposure. *Trace Subst Environ Health* 1992;25:121–8.
- Mielke HW, Dugas D, Mielke PW, Smith KS, Smith SL, Gonzales CR. Associations between lead dust contaminated soil and childhood blood lead: a case study of urban New Orleans and rural Lafourche Parish, Louisiana, USA. *Environ Health Perspect* 1997;105(9):950–4.
- Mielke HW, Smith MK, Gonzales CR, Mielke Jr PW. The urban environment and children's health: soils as an integrator of lead, zinc and cadmium in New Orleans, Louisiana, U.S.A. *Environ Res* 1999;80(2):117–29.
- Mielke HW, Gonzales CR, Smith MK, Mielke Jr PW. Quantities and associations of lead, zinc, cadmium, manganese, chromium, nickel, vanadium, and copper in fresh Mississippi alluvium and New Orleans alluvial soils. *Sci Total Environ* 2000;246(2–3):249–59.
- Mielke HW, Powell E, Shah A, Gonzales C, Mielke Jr PW. Multiple metal contamination from house paints: consequences of power sanding and paint scraping in New Orleans. *Environ Health Perspect* 2001a;109:973–8.
- Mielke HW, Wang G, Gonzales CR, Le B, Quach V, Mielke Jr PW. PAH and metal mixtures in New Orleans soils and sediments. *Sci Total Environ* 2001b;281(1–3):217–27.
- Mielke HW, Wang G, Gonzales CR, Powell ET, Le B, Quach VN. PAHs and metals in soils of inner city and suburban New Orleans, Louisiana USA. *Environ Toxicol Pharmacol* 2004;18(3):243–7.
- Mielke HW, Gonzales C, Powell E, Mielke Jr PW. Changes of multiple metal accumulation (MMA) in New Orleans soil: preliminary evaluation of differences between Survey I (1992) and Survey II (2000). *Int J Environ Res Public Health* 2005a;2(2):84–90.
- Mielke HW, Berry KJ, Mielke Jr PW, Powell ET, Gonzales CR. Multiple metal accumulation as a factor in learning achievement within various New Orleans communities. *Environ Res* 2005b;97(1):67–75.
- Mielke HW, Powell ET, Gonzales CR, Mielke Jr PW, Ottesen RT, Langedal M. New Orleans soil lead (Pb) cleanup using Mississippi River alluvium: need, feasibility and cost. *Environ Sci Technol* 2006a;40(08):2784–9.
- Mielke HW, Powell ET, Gonzales CR, Mielke Jr PW. Hurricane Katrina's impact on New Orleans soils treated with low lead Mississippi River alluvium. *Environ Sci Technol* 2006b;40(24):7623–8.
- Mielke HW, Gonzales CR, Powell E, Morten J, Mielke Jr PW. Nonlinear association between soil lead and blood lead of children in metropolitan New Orleans, Louisiana: 2000–2005. *Sci Total Environ* 2007a;388:43–53.
- Mielke HW, Powell ET, Gonzales CR, Mielke Jr PW. Potential lead on play surfaces: evaluation of the "PLOPS" sampler as a new tool for primary lead prevention. *Environ Res* 2007b;103:154–9.
- Mielke HW, Gonzales C, Powell E, Mielke Jr PW. Urban soil lead (Pb) footprint: comparison of public and private housing of New Orleans. *Environ Geochem Health* 2008;30(3):231–42. doi:10.1007/s10653-007-9111-3.
- Muennig P. The social costs of childhood lead exposure in the post-lead regulation era. *Arch Pediatr Adolesc Med* 2009;163(9):844–9.
- Murozami M, Chow TJ, Patterson CC. Chemical concentration of pollutant lead aerosols, terrestrial dusts and sea salts in Greenland and Antarctic snow strata. *Geochim Cosmochim Acta* 1969;33:1247–94.
- NRC (National Research Council). *Airborne Lead in Perspective*. Washington, DC: National Academy of Sciences; 1972.
- Needleman HL, Clair Patterson and Robert Kehoe: two views of lead toxicity. *Environ Res* 1998;78(2):79–85.
- Needleman HL, Gunnoe C, Leviton A, Reed R, Peresie H, Maher C, et al. Deficits in psychological and classroom performance of children with elevated dentine lead levels. *N Engl J Med* 1979;300:689–95.
- Nielsen JB, Kristiansen. Remediation of soil from lead-contaminated kindergartens reduces the amount of lead adhering to children's hands. *J Expo Anal Environ Epidemiol* 2005;15:282–8. doi:10.1038/sj.jea.7500403.
- Nigg JT, Knottnerus GM, Martel MM, Nikolas M, Cavanagh K, Karmaus W, et al. Low blood lead levels associated with clinically diagnosed attention-deficit/hyperactivity disorder and mediated by weak cognitive control. *Biol Psychiatry* 2008;63:325–31. doi:10.1016/j.biopsych.2007.07.013.
- Ottesen RT, Alexander J, Langedal M, Haugland T, Høygaard E. Soil pollution in day-care centers and playgrounds in Norway: national action plan for mapping and remediation. *Environ Geochem Health* 2008;30:623–37. doi:10.1007/s10653-008-9181-x.
- Page AL, Ganje TJ. Accumulations of lead in soils for regions of high and low motor vehicle traffic density. *Environ Sci Technol* 1970;4:140–2.
- Patterson CC. Lead in the human environment: An alternative perspective—lead pollution in the human environment: Origin, extent, and significance. National Research Council, National Academy of Sciences. Washington, DC, National Academy Press 1980; pp 265–349.
- Pingitore Jr NE, Clague JW, Amaya MA, Maciejewska B, Reynoso JJ. Urban airborne lead: X-ray absorption spectroscopy establishes soil as dominant source. *PLoS ONE* 2009;4(4):e5019. doi:10.1371/journal.pone.0005019.
- Polidori AKL, Cheung M, Arhami RJ, Delfino J, Schauer J, Sioutas C. Relationships between size-fractionated indoor and outdoor trace elements at four retirement communities in Southern California. *Atmos Chem Phys* 2009;9:4521–36.
- Post RC. *Urban Mass Transit: The Life Story of a Technology*. Greenwood Publishing Group; 2007. 181 pp.
- Reyes JW. Environmental policy as social policy? The impact of childhood lead exposure on crime. *B E J Econ Anal Policy* 2007;7(1). doi:10.2202/1935-1682.1796 Article 51. Available at: <http://www.bepress.com/bejeap/vol7/iss1/art51>.
- Roberts JW, Clifford WS, Glass G, Hummer PG. Reducing dust, lead, dust mites, bacteria, and fungi in carpets by vacuuming. *Arch Environ Contam Toxicol* 1999;36(4):477–84.
- Root RA. Lead loading of urban streets by motor vehicle wheel weights. *Environ Health Perspect* 2000;108:937–40.
- Rosas I, Belmont R, Jauregui E. Seasonal variation of atmospheric lead levels in three sites in Mexico City. *Atmósfera* 1995;8:157–68.
- Rosner D, Markowitz G. A 'Gift of God?': the public health controversy over leaded gasoline during the 1920s. *AJPH* 1985;75(4):344–52.
- Rothenberg SJ, Williams Jr FA, Delrahim S, Khan F, Kraft M, Lu M, et al. Blood lead levels in children in south central Los Angeles. *Arch Environ Health* 1996;51:383–8.
- Sabin LD, Schiff KC. Dry atmospheric deposition rates of metals along a coastal transect in southern California, USA. *Environ Sci Technol Atmos Environ* 2008;42:6606–13.
- Shelton EM, Whisman ML, Woodward PW. Long-term historical trends in lead in gasoline properties are charted. *Oil Gas J* 1982;80:95–9.
- Stefanak M, Diorio J, Frisch L. Cost of child lead poisoning to taxpayers in Mahoning County, Ohio. *Public Health Rep* 2005;120:311–4.
- Sutton PM, Athanasoulis M, Flessel P, Guirguis G, Haan M, Schlag R, et al. Lead levels in the household environment of children in three high-risk communities in California. *Environ Res* 1995;68(1):45–57.
- Teichman J, Coltrin D, Prouty K, Bir WA. A survey of lead contamination in soil along Interstate 880, Alameda County, California. *Am Ind Hyg Assoc J* 1993;54:557–9.
- Thomas VM, Socolow RH, Fanelli JJ, Spiro TG. Effects of reducing lead in gasoline: an analysis of the international experience. *Environ Sci Technol* 1999;33(22):3942–8.
- TTI—Texas Transportation Institute. Congestion data in your city. Excel spreadsheet (XLS) of the base statistics for 90 urbanized areas and population group summary statistics; 2009. Available: [http://mobility.tamu.edu/ums/congestion\\_data/](http://mobility.tamu.edu/ums/congestion_data/). [Accessed 10 May 2010].
- U.S. Census Bureau. 1970 Census of Population, Volume 1—Characteristics of the Population, Part 1—United States Summary, Table 20—Population and Land Area of Urbanized Areas, 1970 and 1960 (issued June, 1973); 1990 Census of Population and Housing, Summary Population and Housing Characteristics, United States, Table 8—Land Area and Population Density: 1990.
- U.S. Census Bureau. 1990 Census of Population and Housing, Summary Population and Housing Characteristics, United States, Table 8—Land Area and Population Density: 1990.
- U.S. DOTa. Department of Transportation, Federal Highway Administration, Office of Highway Policy Information. Vehicle miles of travel, highway motor fuel use and miles per gallon for all vehicles; 1987. Available: <http://www.fhwa.dot.gov/ohim/onh00/line9.htm> [Accessed 11 May 2010].
- U.S. DOTb. Department of Transportation, Federal Highway Administration, Highway Statistics Summary to 1985. Washington DC: Government Printing Office; 1987. April.
- U.S. EPA. U.S. Air Quality Criteria for Lead, 1986, Volume II. Washington DC: US Government Printing Office; 1986. p. 5–14.
- U.S. EPA NLFWWI. National Lead Free Wheel Weight Initiative. Available: <http://www.epa.gov/waste/hazard/wastemin/nlfwwi.htm> [Accessed 10 May 2010].
- U.S. Geological Survey (USGS). Lead end use statistics. 140Historical statistics for mineral and material commodities in the United States: U.S. Geological Survey Data Series; 2005. Available: <http://pubs.usgs.gov/ds/2005/140/>. [Accessed 10 May 2010].
- University of California, Riverside and DTSC. Background concentrations of trace and major elements in California soils. Kearney Foundation of soil science, Division of Agriculture and Natural Resources. March, 1996.
- Viverette L, Mielke HW, Brisco M, Dixon A, Schaefer J, Pierre K. Environmental health in minority and other underserved populations: benign methods for identifying lead hazards at day care centers of New Orleans. *Environ Geochem Health* 1996;18(1):41–5.
- Wang G, Mielke H, Quach V, Gonzales C, Zhang Q. Determination of polycyclic aromatic hydrocarbons and trace metals in New Orleans soils and sediments. *Soil Sediment Contam* 2004;13:313–27.
- Wu J, Edwards R, He Xueqin (E), Liu Z, Kleinman M, Wu J. Spatial analysis of bioavailable soil lead concentrations in Los Angeles, California. *Environ Res* 2010;309–17. doi:10.1016/j.envres.2010.02.004.
- Yiin L-M, Rhoads GG, Liou PJ. Seasonal influences on childhood lead exposure. *Environ Health Perspect* 2000;108:177–82.
- Yiin L-M, Rhoads GG, Rich DQ, Zhang J, Bai Z, Adgate JL, et al. Comparison of techniques to reduce residential lead dust on carpet and upholstery: the New Jersey

- assessment of cleaning techniques trial. Environ Health Perspect 2002;110:1233–7 <http://ehpnet1.niehs.nih.gov/docs/2002/110p1233-1237yiii/abstract.html>.
- Young TM, Heeraman DA, Sirin G, Ashbaugh LL. Resuspension of soil as a source of airborne lead near industrial facilities and highways. Environ Sci Technol 2002;36:2484–90.
- Zahran S, Mielke HW, Weiler S, Berry KJ, Gonazles C. Children's blood lead and standardized test performance response as indicators of neurotoxicity in metropolitan New Orleans elementary schools. NeuroToxicol 2009;30:888–97, [doi:10.1016/j.neuro.2009.07.017](https://doi.org/10.1016/j.neuro.2009.07.017).
- Zahran S, Mielke HW, Gonzales CR, Powell ET, Weiler S. New Orleans before and after Hurricanes Katrina/Rita: a quasi-experiment of the association between soil lead and children's blood lead. Environ Sci Technol 2010, [doi:10.1021/es100572s](https://doi.org/10.1021/es100572s).