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Spatial analysis of bioavailable soil lead concentrations in Los Angeles, California

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ABSTRACT

Lead (Pb) poisoning causes permanent neurologic and developmental disorders and remains an important environmental health problem for US children, despite removal of Pb from gasoline and household paints. To better understand the contribution of Pb from historical traffic and residential Pb based paint to soil Pb concentrations in Los Angeles, we analyzed 550 soil Pb samples from south central Los Angeles County, CA, in relation to land-use patterns (commercial, industrial, residential, and parks and open areas) and proximity to freeways, highways, and major arterials. House age variables (surrogates of historical Pb-based paint) and traffic index variables (surrogates of historical traffic) were created at different buffer distances (10–5000 m).

Total and bioavailable Pb concentrations near freeways and major arterials were significantly higher than those collected elsewhere. Total and bioavailable Pb concentrations were highly correlated ($r=0.96$) after the removal of one outlier. Both parcel-age related variables and traffic variables were important predictors of current soil bioavailable Pb concentrations. Average age of parcels within 30 m and length of small streets within 3000 m explained 57% and 38% of the variance, respectively, in soil bioavailable Pb concentrations in residential areas away from freeways and major arterials ($N=44$). Road length of freeways within 750 m explained 28% of bioavailable Pb concentrations in parks and open areas ($N=26$). Multi-variable regression models predicted 16–61% of the variances in bioavailable Pb concentrations, depending on land-use type and spatial relationship to roadways. Based on these models a map of spatial distributions of soil Pb concentrations was created for the Los Angeles area that shows promise as a screening tool to evaluate continued Pb poisoning in children.

1. Introduction

Lead (Pb) poisoning causes permanent neurologic, developmental, and behavioral disorders (Cecil et al., 2008; Kalavska, 1992; Rosen, 1992; Wright et al., 2008). Pb was recognized as the single most significant environmental health threat to children in the United States in the 1980s and early 1990s, despite dramatic reductions in environmental Pb sources (i.e. leaded gasoline and household paint) since the late 1970s (National Research Council, 1993; Pirkle et al., 1998). Particularly high risks of Pb exposure were observed in children living in urban cities, minority groups (Macey et al., 2001), or with low socioeconomic standing (Mielke et al., 1999). For example, 15% of urban children exhibit blood Pb levels above 10 μg/dL compared with 2.2% nationally (Filippelli et al., 2005).

Lead in soils and house dust are the dominant contributors to continued Pb poisoning in young children, in addition to dietary sources (Laidlaw et al., 2005; Laidlaw and Filippelli, 2008; Mielke et al., 2007; Mielke and Reagan, 1998). When deposited onto soil, Pb from anthropogenic sources does not appreciably dissolve, biodegrade, or decay and is not rapidly absorbed by plants. Therefore, Pb remains in the upper 2–5 cm of undisturbed soil and can contaminate much greater depths in urban soils or other soils that have been turned under or otherwise disturbed (US Environmental Protection Agency, 2001b). Guidelines for soil Pb in the US are 400 ppm for playground soil and 1200 ppm for other bare soil (US Environmental Protection Agency, 2001a), compared with 40–150 ppm set by other nations such as Norway (Mielke et al., 2008).

Soil Pb concentrations reflect the historic deposition of metal dust from gasoline, leaded paint, and industrial activities (Mielke et al., 2008). Conclusions are mixed regarding the relative contributions from leaded paint and gasoline to the soil Pb contamination and subsequent childhood Pb poisoning

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(US Environmental Protection Agency, 1998). Some literature indicates that house paint was the major source of soil Pb contamination (Haar and Aronow, 1974; Jordan and Hogan, 1975; Schmitt et al., 1988), while others attribute leaded gasoline to high soil Pb concentrations at immediate proximity of freeways and major roadways (Filippelli et al., 2005; Francek, 1997; Johnson et al., 1976; Zupancic, 1999), and in surrounding areas (Lejano and Ericson, 2005; Mielke et al., 2008). Most of these studies did not quantify relative contributions from different sources. Isotopic ratios determined using X-ray fluorescence have been used in a few studies to distinguish different sources of soil and dust Pb concentrations (Adgate et al., 1998; Caravanos et al., 2006; Clark et al., 2006); however, these methods are expensive and results can be ambiguous since both Pb based paint and leaded gasoline have varied Pb isotopic compositions because of the wide variety of manufacturers of Pb-based paints and numerous locations of ore bodies for manufacturing Pb gasoline additive (Clark et al., 2006; Rabinowitz, 2005).

Land use has been associated with soil Pb concentrations in previous studies. Pb concentration in topsoil was found to decrease with increased distances from industrial sites (Linzon et al., 1976; Little and Martin, 1972; Maskall and Thornton, 1993). Pb concentrations in urban soils are likely higher than those found in rural areas (Markus and McBratney, 2001; Pouyat et al., 2007). Pouyat et al. (2007) reported soil chemical and physical properties by urban land-use and cover types. Although mean Pb concentrations were different by land-use type (up to a factor of thee), the differences were not statistically significant, possibly due to the small sample size (N=122). A complete understanding of source contributions to the spatial distribution of Pb in soil is crucial to reduce risk, mitigate impact, allocate responsibility, and help shape policies that more effectively protect the health of children. In this paper we quantify the contribution of emission sources (historical leaded paint, leaded gasoline, industrial emissions) to soil Pb contaminations by different land-use types (commercial, industrial, residential, and parks and open areas) and spatial relationship to roadways (near freeways and highways, near major arterials, and distant from freeways and major arterials) in urban areas of Los Angeles County. Regression models were developed to estimate soil Pb concentrations at high spatial resolution in the study area.

2. Methods

2.1. Study area

The study area is approximately 675 km^2 in south central Los Angeles County and northwest Orange County, loosely bounded by La Cinega Boulevard on the West, Hollywood Boulevard on the North, I-5 on the East, and US-91 on the South (Fig. 1). The area has high traffic densities with approximately 41,000 vehicles commuting on freeways and major arterials and the corresponding vehicle miles traveled (VMT) of 65 million miles. The study region contains about 3.3 million people, with 58% Hispanic, 18% African American, 14% White, and 8% Asian. Approximately 24% of the residents had incomes below the poverty line, and 11% of the residents were children younger than six years oldthe age group most vulnerable to Pb-related toxicity.

2.2. Field sampling

Soil samples were collected from July to September, 2004 in three categories: along freeways and highways, near major arterials, and in random stratified grids. Most of the mass fraction of vehicle-originated particulates deposit within 150 m distance of the road (Johnson et al., 1976; Lansdown et al., 1986; Zupancic, 1999). As a result the widest boundary of 300 m was selected in this study to cover the traffic influential zone, with three soil samples being collected on each side of the road approximately 0–10, 150–160, and 290–300 m away from the roadway. Soil samples were collected adjacent to freeways, major arterials, and at random grid locations (predominantly in residential areas away from freeways and major arterials). Freeway samples were taken along I-10, I-405, I-5, and I-710—major southern California freeways and highways in the study area. Arterial samples were taken alongside 23 major arterial roads, all of which had high traffic density and also linked up to expressways and freeways with interchanges. Continuous grids at a 1 km × 1 km resolution were created on the map of 2004 Los Angeles County Thomas Guide®. Centroids of all randomly selected grids (N=111) were chosen as the sampling locations of the grid samples.

At each sampling location, the field team identified suitable areas in the vicinity, avoiding physical barriers, areas where the soil was disturbed, and areas needing owner's permission. A 1 m^2 area was then marked, and soil samples from

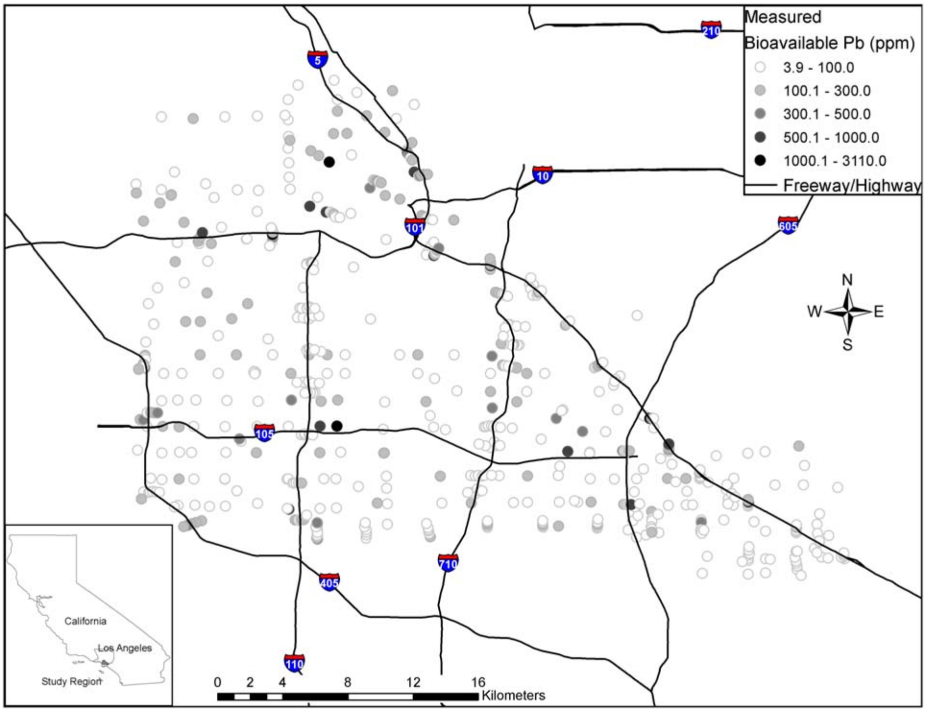

Fig. 1. Bioavailable soil Pb concentrations in the study region (N=490).

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four points (each 40 cm from the center of the square) were obtained by removing approximately an inch of soil (including vegetation cover) from a 10 cm × 10 cm square surface (Ericson and Gonzalez, 2003; Lejano and Ericson, 2005). Laboratory analysis was conducted using hotplate digestion with nitric acid (EPA SW-846 3050B) followed by analysis by Graphite furnace atomic absorption spectrophotometry (EPA SW-846 7421). Bioavailable Pb was measured using a weak acid (1 N) and total Pb by a concentrated acid (12 N). A total of 550 samples were collected. The location of each sample point was recorded using a global positioning system (GPS) unit in Universal Transverse Mercator (UTM) coordinate system.

2.3. Data sources

Detailed road maps (including minor surface streets) were obtained from the TeleAtlas street database (Reitscheweg, Netherlands), one of the most positionally accurate databases of its kind in the world. Annual average daily traffic (AADT) counts in 2005 were obtained from the California Department of Transportation (Caltrans) on freeways and major arterials. Digital land-use data for the study region were obtained from the Southern California Association of Government (SCAG). Tax parcel data were obtained from the Los Angeles County Assessor's Office, which contained parcel boundaries, age of the structures, use code, and square feet of the parcel structures. A parcel refers to a piece of land, regardless of size, under one ownership. Population density was obtained from 2000 Census block data. Elevation data at 10 m resolution were acquired from the United States Geological Survey (USGS) National Elevation Dataset. Lead emissions from Toxic Release Inventory (TRI) facilities were obtained from EPA's National Emissions Inventories back to 1988—the earliest year for which EPA has records (http://www.epa.gov/triexplorer/).

2.4. Spatial variables

A matrix of roadway and traffic index variables was created to represent historical traffic impact using ArcInfo GIS 9.1 (ESRI, Redlands, CA) software, and the TeleAtlas roadway and the Caltrans traffic data. A series of circular buffers were constructed with a radius from 10 to 5000 m (10, 20, 30, 40, 50, 75, 100, 300, 500, 750, 1000, 2000, 3000, 4000, and 5000 m) around each sampling location. Roadway length contained within the buffer and distance to the nearest roadway were generated for three types of roadways (primary interstate and state highways, major arterials, and minor surface streets). Traffic variables included distance-weighted traffic density, traffic count on the nearest roadway (by roadway type), and vehicle miles traveled (VMT) within a specific buffer.

SCAG land-use classifications (relatively coarse spatial resolution) and parcel use code were employed to categorize land-use patterns at or near each sampling site. The 108 SCAG land-use classes were classified into four major categories (commercial, industrial, residential, and parks and open areas). Similarly each parcel was classified into three categories (residential, commercial, and other structures) based on parcel use code. If there was a conflict between two sources in classification, higher priority was given to parcel data because of their higher spatial resolution. For example, a sampling site was classified as non-residential even if it was in a SCAG residential area, but the closest parcel was identified as a commercial structure.

For each sampling location and buffer size, average age of all structures within the buffer and age of those built before 1978 were computed. In addition, average structure ages weighted by the perimeter of parcel polygons were computed as separate variables as an estimate of exterior painted surfaces of a house. The cut point of 1978 for house ages was selected because the US Consumer Product Safety Commission banned the manufacture of house paint containing more than a trace amount (0.06%) of Pb in 1978. For each sampling site, we also assigned distance-weighted Pb emissions from nearby TRI facilities from 1988 to 2004, Census block population density, and elevation.

2.5. Statistical analyses

First we investigated the spatial autocorrelation of measured soil Pb concentrations using the Spatial Statistics Tools in ArcInfo GIS 9.1 (ESRI, Redlands, CA). Spatial autocorrelation was examined based on Moran coefficients and local indicators of spatial association (LISA) maps. Moran's I is a standard measure of spatial autocorrelation, with -1.0 indicating perfect negative correlation, 1.0 indicating perfect positive correlation, and 0 representing no spatial autocorrelation (Moran, 1950). Moran's I was calculated based on Euclidean distance between samples and weighted with inverse distance. LISA map illustrates the spatial autocorrelation of each individual sample based on local Moran statistics, with a p-value below 0.05 indicating that the sample is likely influenced by its neighborhood samples.

Since our samples showed low spatial autocorrelation, traditional statistical analyses were conducted using SAS, version 9.1.3 (SAS Institute Inc., Cary, NC). Since several previous studies (Cook and Ni, 2007; Griffith, 2002) and this study showed a log-normal distribution of soil Pb concentrations, the total and bioavailable Pb concentrations were log-transformed before the spatial analysis. Parametric multivariate analysis of variance (MANOVA) was conducted to determine whether soil Pb concentrations differ significantly by sample type and land-use type. Bivariate linear regressions were implemented to determine which variables were most strongly related to soil Pb concentrations. This first step tested over 200 independent variables as road, traffic, and parcel age variables not only had a large number of categories but also varied by buffer size. The single-variable models that considered no spatial autocorrelation were further compared to the corresponding spatial error models with the same variable.

Multiple linear regression models were developed using significant parameters from bivariate models with a forward selection process, based on the highest t-score for each variable. This process builds from the most significant variable, adding in the next significant variable until a model of maximum perdition is achieved. The variance inflation factor (VIF) was used to identify collinear variables. Variables with the highest VIF and variables with the lowest t-scores were removed until a parsimonious prediction model with the highest R^2 and acceptable collinearity was derived.

2.6. Prediction of bioavailable Pb concentrations in soil

To estimate spatial distribution of bioavailable soil Pb concentration, we divided the study area into 50 m × 50 m gridpoints. These gridpoints were further classified into 12 sub-categories based on their land-use type (commercial, industrial, residential, and park and open area) and spatial relationship to roadways (<300 m of a freeway, <300 m of a major arterial and ≥ 300 m from freeways, and other). For each sub-category the corresponding regression model in Table 5 was selected to predict the bioavailable Pb concentration at each gridpoint. The spatial distribution of Pb was rasterized using the estimated Pb at the 50-m gridpoints in the study area.

3. Results and discussion

3.1. Basic statistics

Out of the 550 soil samples, 299 were measured near freeways, 140 near major arterials, and 111 in random grids (mainly residential areas) (Table 1). Approximately 8% and 1% of our samples had total Pb concentrations exceeding the US EPA standards of 400 ppm for soils in play areas and 1200 ppm for soils in other areas, respectively. The median total soil Pb concentration of 81 ppm corresponded to an estimated median blood Pb level of 3.6 μg/dL (Mielke et al., 2007), greater than 2 μg/dL indicated for neurotoxicity (Lanphear et al., 2000) and myocardial infarction and stroke mortality (Menke et al., 2006).

Bioavailable Pb concentrations from soil samples were not reported in 58 near-freeway samples and 2 near-arterial samples, and were therefore not included in analyses. Mean bioavailable Pb concentration was 128 ppm, and mean total Pb concentration was 181 ppm. The standard deviation (SD) was much larger than the mean, indicating a large variation, particularly in total Pb concentrations with a right skewed distribution typical for log normal distributions. Among the three types of samples, median bioavailable and total Pb concentration were the highest near freeways (bioavailable Pb: 79 ppm; total Pb: 94 ppm), followed by arterials (bioavailable Pb: 56 ppm; total Pb: 89 ppm), which were both statistically significantly higher than the random grid samples (bioavailable Pb: 40 ppm; total Pb: 57 ppm). This indicates impact from historical traffic since freeways and major

Table 1
Basic statistics of total and bioavailable Pb concentrations (unit: ppm).

	Sample type	N	Min.	Max.	Mean	Median	SD
Total Pb	Overall	550	8.9	8150	181	81	463
	Arterial	140	9.6	4720	224	89	501
	Freeway	299	8.9	8150	189	94	518
	Grid	111	12.0	644	107	57	123
Bioavailable Pb	Overall	490	3.9	3110	128	60	253
	Arterial	138	3.9	3110	146	56	355
	Freeway	241	5.7	2570	142	79	228
	Grid	111	5.0	504	76	40	90

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arterials carry much higher traffic density than local residential streets. No significant difference was observed for lead concentrations near freeways and near major arterials. Pouyat et al. (2007) found that among different land uses residential land had the highest average total Pb concentration of 340 ppm, three times that in our random grid samples (frequently residential areas). Much higher total Pb concentrations in the residential areas of Baltimore may be caused by older homes in the Baltimore area compared with Los Angeles (Grove et al., 2006; Pouyat et al., 2007).

The percentage of bioavailable to total Pb was 0.68, 0.76, and 0.69 on average for samples near arterials, near freeways, and in random grids, respectively. Removal of one outlier (bioavailable Pb=114 ppm and total Pb=8150 ppm) significantly improved the correlation between the total and the bioavailable Pb concentrations, allowing development of a regression equation to predict bioavailable Pb from total Pb:

$$\text{bio\_Pb} = -1.2 + 0.74 \times \text{total\_Pb} \quad (N = 488; R^2 = 0.92)$$

The very high total Pb concentration compared with the bioavailable Pb at the outlier site was likely caused by some unknown reasons, e.g. collection of a small piece of metallic Pb waste in the soil, accidental collection of a paint chip, etc.

The functional form of the logarithmic transformation included a translation parameter, δ, rendering $\log(\text{Pb concentration}+\delta)$, where the translation term is a function of the minimum concentration measure (Griffith, 2002). We found an optimal δ value of -3.2 and -8.1 for bioavailable and total Pb concentrations, respectively. Shapiro–Wilk normality tests confirmed the normal distribution of the transformed data (W=0.997 with a p-value of 0.43 for bioavailable Pb and W=0.996 with a p-value of 0.18 for total Pb). All following spatial analyses were based on log-transformed data.

3.2. Spatial autocorrelation

In general we observed a weak spatial autocorrelation in our soil Pb samples, consistent with the weak spatial autocorrelation of soil Pb found in Syracuse, New York, and weak to moderate autocorrelation observed in other cities (Griffith, 2002). The Moran's I was 0.07 over all bioavailable Pb samples (z score=0.54, p-value=0.59), and 0.14 (z score=0.13, p-value=0.88), 0.12 (z score=1.83, p-value=0.07), and 0.33 (z score=2.82, p-value=0.01) in the arterial, freeway, and random grid samples, respectively. The LISA significance maps (Fig. 2) show that spatial autocorrelation was not present in all grid samples (N=111), and present only in 7 out of 140 near-arterial samples and 9 out of 239 near-freeway samples. Both Moran's I statistics and the LISA maps indicated weak spatial autocorrelation of samples in this study.

3.3. Single variable spatial analyses

The MANOVA tests showed that the differences of bioavailable Pb concentrations were significant by sample type (p-value: 0.04), by land-use type (p-value: 0.01), and by the combination of sample and land-use types (p-value: 0.01), indicating that both nearby roadway type and land-use type are important factors influencing bioavailable Pb concentrations. Results focus on bioavailable Pb since log transformed bioavailable and total Pb concentrations were highly correlated. All sampling sites in Orange County (N=35) were excluded from spatial analyses since they had missing parcel information. The remaining sites were located mostly in commercial areas (34%), followed by residential areas (33%), industrial areas (25%), and parks and open areas (8%). Table 2 lists names and descriptions of predictive variables used in the spatial analysis. Variables are denoted by variable type

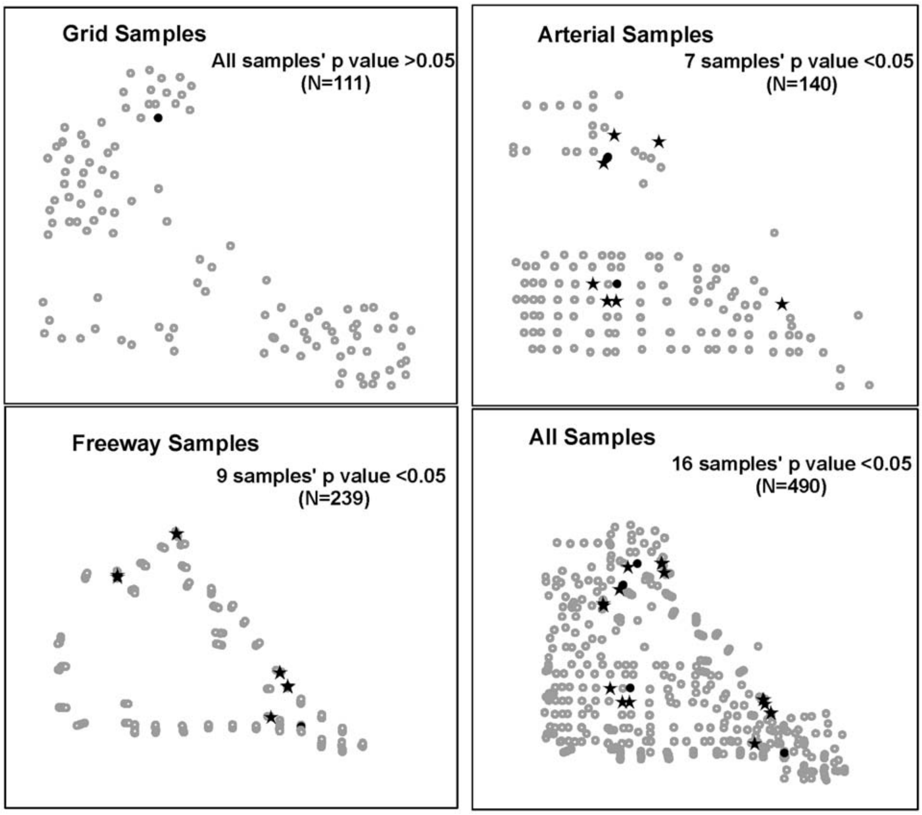

Fig. 2. LISA significance maps.
Note: solid star, solid circle, and hollow circle symbols represent samples with p-values <0.05, 0.06-0.10, and >0.10, respectively. Less than 0.05 p-value indicates that the samples are significantly influenced by their neighborhood samples. Weighting methods: inversed distance.

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followed by a period and then buffer size so that MaxAge.300 = the maximum age of parcels within 300 m buffer. We report only the regression results that considered no spatial autocorrelation because (1) weak spatial autocorrelation was observed in our samples and (2) using spatial error models did not greatly improve the explanatory power of most single variable models that considered no spatial autocorrelation (data not shown).

3.3.1. *Parcel-age related variables*

Table 3 summarizes the bivariate linear regression results and lists parcel, roadway, and traffic variables most associated with log-transformed bioavailable Pb concentrations by land-use type and spatial relationship to roadways. Due to a non-linear relationship between Pb concentration and the age of the nearest parcel, the square root of age (SRAge) correlated better with Pb concentrations than the age variable. In addition to SRAge, the other important parcel-age related variables included maximum parcel age, average parcel age over all parcels and over pre-1978 parcels weighted by parcel perimeter, and number of parcels. We observed stronger impact from parcels in residential area samples, especially those further away from freeways and major arterials, possibly due to reduced volume and speed of traffic in such areas leading to lower resuspension rates and contributions of dust from roadways. Fig. 3a shows a regression plot of bioavailable Pb concentrations and the average age of parcels within 30 m in residential area samples away from freeways and major arterials, with AvgAge1.30 predicting 54% of the variance in Pb concentrations ($N = 44$).

Table 2
Variable type definition.

Variable type	Description
SRAge	Square root of the age of the nearest parcel
MaxAge	Maximum age of parcels
AvgAge1	Average age of parcels
AvgAge2	Average age of parcels pre-1978 and weighted by parcel perimeter
NP	Number of parcel structures
Len1	Length of freeways and highways
Len2	Length of major surface roads
Len3	Length of small surface roads
Len4	Length of all surface roads, i.e. Len2+Len3
Len5	Length of all the roads
Dist1	Distance to freeway and highway
Dist2	Distance to major surface street
Dist3	Distance to small surface street
VMT	Vehicle miles traveled

Parcel-age related variables showed a relatively narrow impact zone in residential area samples (predictive variables: SRAge, MaxAge.20, and AvgAge1.30) but a much wider impact zone in commercial and industrial area samples with the predictor buffer size up to 750 m, likely because commercial and industrial areas have higher traffic speeds and traffic volumes, leading to greater dust resuspension, and soils are more likely to have been disturbed by construction activities. Adjacent older buildings with potentially higher Pb contamination contributed more to soil Pb contamination in residential area samples than samples in other areas possibly due to more frequent construction and renovation activities than residential areas.

Parcel-age related variables explained a higher fraction of variance in soil Pb concentrations further away from freeways and major arterials ($R^2 = 0.31$) than samples near freeways ($R^2 = 0.16$) and arterials ($R^2 = 0.13$), possibly due to the increased contributions from traffic related sources at locations closer to freeways and major arterials. In addition, adjacent parcels were on average closer in samples further away from arterials and freeways (2 m) compared with samples near arterials (5 m) or freeways (9 m), and the average age of the nearest parcel was much larger for samples further away from arterials and freeways (54 years) compared with samples near freeways (42 years) or major arterials (43 years; Table 4). Sampling locations near freeways and major arterials may have been disturbed more often than those further away due to newer constructions of adjacent parcel structures; thus the impact of historical leaded paint is more prominent in undisturbed areas away from freeways and major arterials. Similar results were also observed when restricted to only residential samples (Table 3). Although the average ages of and the distances to the nearest parcel were similar among the three groups of residential samples (Table 4), we expected more re-painting of houses or buildings near freeways and major arterials as more apartments and mixed types of residences were located near freeways (59%) and major arterials (41%) compared with random grid samples (32%). Apartments are mostly used for

Table 3
Parcel and traffic variables statistically significantly associated with bioavailable Pb concentrations in soil (only the highest *R*-value is shown).

Land-use type	Sample type	Parcel variables			Roadway and traffic variables		
		Variable name[a]	*N*	R^2	Variable name[a]	*N*	R^2
All	All	SRAge	458	0.12	Len5.10	459	0.06
All	Arterial	MaxAge.300	136	0.13	Len1.750	137	0.07
All	Freeway	SRAge	221	0.16	Len5.10	221	0.05
All	Grid	AvgAge2.2000	101	0.31	Len3.3000	101	0.20
Commercial	All	MaxAge.300	166	0.08	Len1.3000	166	0.09
Commercial	Arterial	Maxage.750	74	0.14	Len1.1000	74	0.09
Commercial	Freeway	AvgAge1.500	57	0.14	Len4.300	57	0.24
Commercial	Grid	AvgAge2.750	35	0.15	Len3.300	35	0.28
Industrial	All	SRAge	113	0.14	Len1.40	114	0.11
Industrial	Arterial	NP.100	20	0.24	Len4.500	20	0.25
Industrial	Freeway	AvgAge1.750	89	0.13	Dist1.300	78	0.14
Industrial	Grid	NA	5	NA	NA	5	NA
Park and open area	All	NP.30	26	0.22	Len1.750	26	0.28
Residential	All	SRAge	145	0.26	Len5.10	145	0.07
Residential	Arterial	MaxAge.20	32	0.34	VMT.5000	35	0.15
Residential	Freeway	SRAge	66	0.26	Dist2.1000	66	0.08
Residential	Grid	AvgAge1.30	44	0.55	Len3.3000	44	0.37

[a] Left-hand side of period denotes variable type and right-hand side denotes buffer size so that **Maxage.300** = the maximum age of parcels within 300 m buffer. Variable types are listed in Table 2.

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renting purposes, which may lead to more frequent re-painting when tenants move out. In general Pb would be less likely to be released to the environment from peeling paint chips when the old paint is repeatedly coated and protected by lead-free paint although scraping and sanding in more extensive renovation activities may lead to release of more Pb dust in some instances.

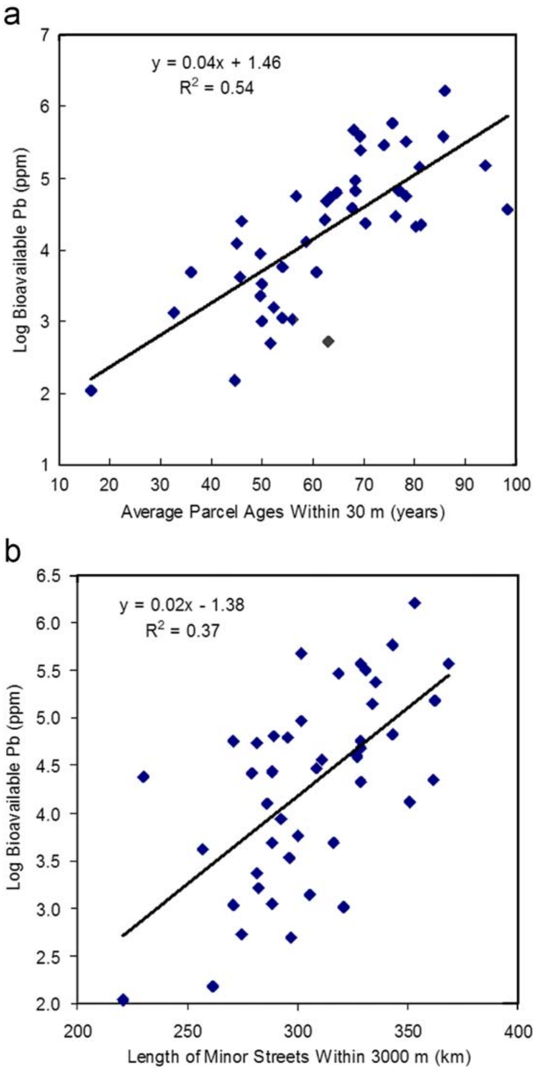

Fig. 3. Regression plots of bioavailable Pb concentrations in residential area random grid samples against average age of parcels within 30 m (a) and length of minor streets within 3000 m (b).

3.3.2. Roadway and traffic variables

In general, traffic variables had weaker associations with bioavailable Pb than parcel age variables did. The important predicative variables included total roadway length, length of freeways and highways, length of small surface roads, distance to the nearest freeway, highway, and major surface road, and total vehicle miles traveled. Similar to parcel variables, we observed the strongest association between Pb concentrations and traffic-related variables in residential samples away from freeways and major arterials. Fig. 3b shows the regression plot of bioavailable Pb concentrations and length of minor streets within 3000 m in residential samples away from freeways and major arterials, with Len3.3000 explaining 37% of the variance in Pb concentrations (N=44). In park and open area samples, Len1.750 predicted 28% of the variance in Pb concentrations (N=26). In commercial and industrial areas, traffic-related variables explained 9–28% of the variances in soil Pb concentrations.

The suite of roadway and traffic variables in the multi-variable regression models can be classified into three categories by the sizes of the buffer zones: (1) 10–40 m representing traffic in the immediate vicinity; (2) 300–1000 m representing neighborhood or community sources of traffic; and (3) 2000–5000 m representing regional traffic. The results clearly showed that both local and regional traffic contributed to soil Pb contamination. This is reasonable because smaller Pb particulate matter emitted from vehicle exhaust and resuspended dust from roadways may travel much further than larger Pb chips and dust from cracked and peeling house paint.

3.3.3. Other variables

Population density and elevation were not significant predictors when parcel-age and traffic-related variables were included. No single variable of Pb emissions from TRI facilities stood out, probably because (1) TRI relies on voluntary reporting and (2) the TRI emission data dated back only to 1988, and emission levels after 1988 were already much reduced from historical levels due to significant closures and relocations of facilities.

In addition to traffic index variables above, we used traffic count data to calculate distance-weighted traffic density (DWT) and dispersion of traffic-generated particulate matter based on the CALINE4 dispersion model developed by California Department of Transportation. However, both DWT and CALINE4 variables did not remain in the models when roadway length and distance to the nearest roadway were included. This is likely because traffic counts were available only in 2005 and only for freeways and major arterials but not neighborhood small streets. Emissions of Pb particulate matter per vehicle miles traveled can be much higher for traffic on the small streets due to relatively low speeds and frequent accelerations at stop lights and intersections. In addition, traffic activity patterns may change significantly after Pb was phased out in early 1980s, though the

Table 4
Statistics of the parcel characteristics near the sampling sites.

Land-use type	Sample type	N	Average distance to the nearest parcel (m)	Average age of the nearest parcel	Average age of parcels within 30 m	Average age of the nearest parcel built before 1978
All	All	459	6	45	48	56 (N=337)
All	Arterial	137	5	43	43	52 (N=100)
All	Freeway	221	9	42	47	54 (N=154)
All	Grid	101	2	54	55	63 (N=83)
Commercial	All	166	3	36	38	49 (N=104)
Industrial	All	114	13	34	37	46 (N=69)
Parks and open area	All	26	3	49	62	60 (N=20)
Residential	All	145	4	63	60	65 (N=138)
Residential	Arterial	36	3	66	59	67 (N=34)
Residential	Freeway	66	5	60	58	63 (N=62)
Residential	Grid	44	3	65	63	67 (N=42)

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roadway network may not change much in this established urban area.

3.4. Multi-variable regression analyses

Table 5 shows multi-regression models by land-use type and spatial relationship to roadways. Although adding independent variables can maximize R^2, we limited the number of independent variables to three due to the limited sample size in each sub-category. All VIFs ranged from 1.00 to 1.63, with the majority of the values less than 1.09. This indicated a low degree of correlation among independent variables; thus models did not have problems with multicollinearity. Both parcel age-related and traffic-related variables were significant for all models with soil Pb being positively associated with age of parcel and length of road contained in the buffer, and negatively associated with distance to the nearest freeway. Parcel-age related variables explained more of the variance than traffic-related variables in each model, with partial R^2 ranging from 0.03 to 0.52. The overall utility of the variables in explaining soil Pb concentrations was the lowest in commercial areas (R^2=0.16), and the highest in residential areas away from freeways and major arterials (R^2=0.61).

SRAge is the strongest predictor in all areas except for the randomly selected grid samples located away from major transportation corridors, where AgeAvg2 was the strongest. In areas where the source of contamination is dominated by leaded paint, soil concentrations may have been most sensitive to how many years prior to the cutoff date of 1978 the house existed, reflecting historical changes in Pb concentrations of leaded paint. Since road length variables were not significant, leaded paint sources appear to dominate in these areas.

Modeled bioavailable Pb concentrations at 276,155 uniformly distributed 50 m × 50 m gridpoints were compared to measurement data in each sub-category by land-use type and spatial relationship to roadway (Table 6). In general, modeled median Pb concentrations in each sub-category agreed reasonably well with the corresponding measured median concentration (R^2=0.93; N=9), particularly for areas near arterial streets and areas away

Table 5
Multi-variable models of bioavailable Pb concentrations in soil.

Land-use type	Sample type	*N*	Variables[a]	Beta	Std. error	*T*-value	*p*-value	VIF[b]	Partial R^2	R^2
All	All	458	SRAge	2.27×10^{-1}	2.50×10^{-2}	8.94	< 0.0001	1.00	0.13	0.23
			Len1.1000	1.08×10^{-4}	1.92×10^{-5}	5.64	< 0.0001	1.03	0.07	
			Len4.20	9.42×10^{-3}	2.25×10^{-3}	4.19	< 0.0001	1.03	0.03	
All	Arterial	136	MaxAge.300	1.87×10^{-2}	5.0×10^{-3}	3.75	0.0003	1.05	0.13	0.28
			SRAge	2.17×10^{-1}	5.34×10^{-2}	4.06	< 0.0001	1.05	0.08	
			Len1.750	1.89×10^{-4}	5.34×10^{-5}	3.54	0.0006	1.00	0.07	
All	Freeway	221	SRAge	2.25×10^{-1}	3.51×10^{-2}	6.43	< 0.0001	1.00	0.16	0.22
			Len1.1000	1.31×10^{-4}	3.93×10^{-5}	3.33	0.001	1.00	0.04	
			Len4.20	9.74×10^{-3}	3.62×10^{-3}	2.69	0.0077	1.00	0.03	
All	Grid	100	AgeAvg2.750	2.86×10^{-2}	8.14×10^{-3}	3.51	0.0007	1.63	0.31	0.41
			Len4.20	1.59×10^{-2}	4.52×10^{-3}	3.51	0.0007	1.07	0.06	
			Len3.3000	7.66×10^{-6}	3.19×10^{-6}	2.40	0.0183	1.55	0.04	
Commercial	All	166	MaxAge.300	1.20×10^{-2}	4.13×10^{-3}	2.91	0.0041	1.06	0.08	0.16
			Len4.10	2.93×10^{-2}	1.02×10^{-2}	2.89	0.0044	1.04	0.05	
			SRAge	1.16×10^{-1}	4.73×10^{-2}	2.45	0.0152	1.04	0.03	
Commercial	Arterial	74	MaxAge.300	2.00×10^{-2}	6.88×10^{-3}	2.91	0.0049	1.01	0.12	0.18
Commercial			Len1.1000	1.43×10^{-4}	5.23×10^{-5}	2.74	0.0078	1.01	0.06	
Commercial	Freeway	57	Len3.300	5.01×10^{-4}	1.49×10^{-4}	3.37	0.0014	1.09	0.24	0.36
Commercial			Len1.1000	2.03×10^{-4}	8.54×10^{-5}	2.38	0.0211	1.03	0.07	
Commercial			SRAge	1.59×10^{-1}	7.90×10^{-2}	2.01	0.0499	1.07	0.05	
Commercial	Grid	35	Len1.40	1.74×10^{-2}	6.17×10^{-3}	2.82	0.0082	1.00	0.17	0.32
Commercial			AvgAge2.750	2.86×10^{-2}	1.01×10^{-2}	2.84	0.0078	1.00	0.15	
Industrial	All	113	SRAge	1.77×10^{-1}	5.16×10^{-2}	3.43	0.0009	1.08	0.14	0.26
			Len1.40	5.48×10^{-3}	1.73×10^{-3}	3.16	0.002	1.03	0.08	
			AvgAge1.750	1.56×10^{-2}	6.85×10^{-3}	2.28	0.0244	1.09	0.04	
Industrial	Arterial	20	PN.100	4.00×10^{-2}	1.21×10^{-2}	3.31	0.0042	1.03	0.39	0.55
			SRAge	3.43×10^{-1}	1.42×10^{-1}	2.42	0.0271	1.03	0.16	
Industrial	Freeway	89	AvgAge1.750	1.70×10^{-2}	7.09×10^{-3}	2.40	0.0185	1.15	0.13	0.26
Industrial			Len1.40	5.14×10^{-3}	1.73×10^{-3}	2.97	0.0039	1.03	0.09	
Industrial			SRage	1.26×10^{-1}	5.48×10^{-2}	2.30	0.0238	1.14	0.05	
Park and open area	All	26	AvgAge2.750	4.75×10^{-2}	1.23×10^{-2}	3.85	0.0008	1.07	0.29	0.55
			Len1.500	7.80×10^{-4}	1.72×10^{-4}	4.52	0.0002	1.07	0.26	
Residential	All	144	SRAge	4.10×10^{-1}	5.58×10^{-2}	7.34	< 0.0001	1.02	0.26	0.33
			Dist2.1000	-1.32×10^{-3}	4.65×10^{-4}	-2.84	0.0051	1.01	0.04	
			Len4.10	2.34×10^{-2}	9.17×10^{-3}	2.56	0.0116	1.01	0.03	
Residential	Arterial	35	MaxAge.40	2.76×10^{-2}	8.48×10^{-3}	3.26	0.0027	1.00	0.22	0.31
			Len4.20	1.62×10^{-2}	7.65×10^{-3}	2.12	0.0421	1.00	0.10	
Residential	Freeway	66	SRAge	3.98×10^{-1}	7.37×10^{-2}	5.40	< 0.0001	1.02	0.26	0.36
			Len2.50	3.89×10^{-3}	1.22×10^{-3}	3.18	0.0023	1.02	0.10	
Residential	Grid	42	AvgAge1.30	4.71×10^{-2}	6.17×10^{-3}	7.63	< 0.0001	1.05	0.52	0.61
			Dist2.1000	$0-1.88 \times 10^{-3}$	6.48×10^{-4}	-2.90	0.0062	1.05	0.08	

[a] The variable keys are the same as those listed in Table 2.

[b] VIF: variance inflation factor.

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from freeways and arterial streets (Table 6). Regardless of land-use type, estimated median concentrations were lower at near-freeway gridpoint locations than our measured values taken near selected freeways. This is probably because our near-freeway measurement sites were selected deliberately near heavily traveled freeways while our near-arterial and random grid measurement sites were more representative of areas under the same sub-categories in the study region.

3.5. *Spatial distribution of bioavailable Pb concentrations in soil*

A raster map was constructed based on estimated Pb concentrations at 270k gridpoints and 50 m resolution (Fig. 4). To illustrate the contributions of parcel- and traffic-related variables, we selected and compared bioavailable Pb concentrations in four 1000-m buffer areas. Buffers A–C are centered on freeway I-101, I-105, and I-5, respectively; buffer D is centered on a hot spot of Pb concentrations. Much older building age and slightly longer roadway length in buffer A than buffer B contributed to 78 ppm higher Pb concentration in buffer A than in buffer B. Traffic-related variables explained 10 ppm higher Pb concentrations in buffer B than in buffer C since both buffers had the same average building age. Buffers A had slightly older building structures (3 years older) and slightly longer roadways (546 m) than buffer D, but the median Pb concentration in buffer A is 8 ppm lower than that in buffer D. This is probably because buffer D is located within 5000 m of a dense freeway network (I5, I-10, and I-101). In general, estimated Pb concentrations are more sensitive to parcel-age related variables than traffic-related variables, but both types of variables contribute to higher soil lead concentrations.

Table 6

Measured vs. modeled median bioavailable Pb concentrations in each sub-group by land-use type and spatial relationship to roadways (unit: ppm)

Land-use type	Sample type	Median measured concentration[a]	Median estimated concentration[b]
Commercial	Freeway	34.5	25.3
Commercial	Arterial	46.4	46.1
Commercial	Grid	30.8	34.1
Industrial	Freeway	90.2	84.1
Industrial	Arterial	53.5	53.1
Park and open area	All	20.4	19.4
Residential	Freeway	112.0	93.8
Residential	Arterial	98.0	109.1
Residential	Grid	40.0	44.8

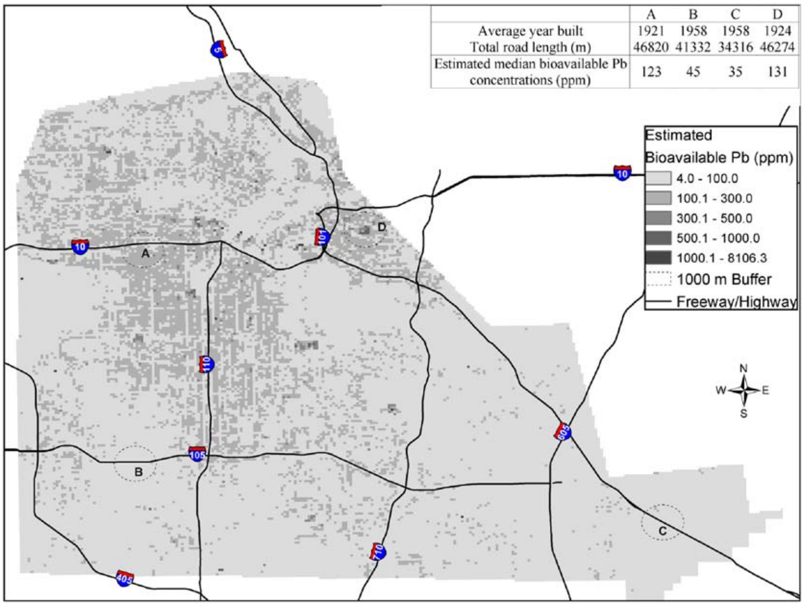
[a] Median value of bioavailable Pb concentration in each sub-category of measured data.

[b] Multi-variable models in Table 5 were used to estimate bioavailable Pb concentrations at uniformly distributed gridpoints (50 m × 50 m resolution) in the study region; the median estimated concentration represents median estimated values of all gridpoints in each sub-category.

4. Implications and recommendations

To our knowledge, this is the first study that quantitatively examined source contributions to soil Pb concentrations by land-use type and spatial relationship to roadways in south central Los Angeles County, CA. We first quantitatively examined source contributions to soil lead concentrations by land use type and spatial relationship to roadways in south central Los Angeles County, CA. Then, we developed multi-variable regression models to estimate the soil lead concentration and demonstrate the spatial distribution of soil lead concentration in the study area. The analyses showed that both historical traffic and leaded paint contributed to Pb contamination in soils. The traffic-related variables are somewhat less significant than parcel-related variables in explaining the variances in soil Pb concentrations. This may be partly due to more uncertainty in traffic-related variables since historical roadway and traffic count data were not available.

The multi-variable regression models performed well in predicting median soil lead concentration by land-use type and spatial relationship to roadways. These regression models are useful to identify areas where soil Pb concentrations would be expected to be higher, and where targeted Pb remediation efforts could be directed through focused investigations, pilot studies, and ultimately large-scale intervention based on the potential to expose nearby populations. The Pb concentration map would be of value not only to target remediation efforts but also to guide urban planning efforts in developing public playgrounds, or siting of new schools. For example, the Los Angeles County Unified School District employs risk assessment in



	A	B	C	D
Average year built	1921	1958	1958	1924
Total road length (m)	46820	41332	34316	46274
Estimated median bioavailable Pb concentrations (ppm)	123	45	35	131

Fig. 4. Map of estimated bioavailable soil Pb concentrations in the study region.

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screening potential sites, but lacks tools to consider multiple environmental contaminants in addition to air pollution. This study suggests that both historical lead-painted houses and historical traffic contribute to the current soil Pb contamination in south central Los Angeles. Although determinations of the extent to which each source (traffic, paint, or industry) contributes to these soil concentrations are less certain, these findings suggest that efforts at juvenile blood Pb testing are strengthened in areas such as south central Los Angeles.

The spatial distribution map of Pb concentration also highlights the disparate burdens of soil lead contamination experienced by lower income populations, and the relationship to ethnic population composition. For example, this study found that areas occupied by majority (population ratio larger than 50%) African American and Hispanic populations have higher soil lead concentrations than Non-Hispanic Whites (data not shown). This finding implies that minority groups in the study area have a higher potential for exposure to lead from soils. Considering the higher birth rates in minority populations, especially people of Hispanic descent, it is likely that lead from soils plays a greater role in childhood blood lead poisoning in children who live in these areas. Although further research is needed to fully elucidate these relationships, spatial maps of soil lead distributions can be used as tools by local administration and community based organizations to prioritize areas for greater promotion of blood lead testing in local communities and physician offices, and greater environmental sampling around residences.

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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.2010.02.004.

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