Available online at www.sciencedirect.com
SCIENCE DIRECT®
Environmental Research 92 (2003) 221–231
Environmental Research
http://www.elsevier.com/locate/envres

Hierarchical sampling of multiple strata: an innovative technique in exposure characterization ☆

Jonathon E. Ericson[a,*] and Elisabeth J. Gonzalez[b]

[a] *Department of Environmental Analysis and Design, University of California, Irvine, 258 Social Ecology I, Irvine, CA 92697-7070, USA*
[b] *Divisions of Environmental Health and Disease Control & Epidemiology, Orange County Health Care Agency, 2009 E. Edinger Ave., Santa Ana, CA 92705, USA*

Received 10 December 2001; received in revised form 7 October 2002; accepted 18 December 2002

Abstract

Sampling of multiple strata, or hierarchical sampling of various exposure sources and activity areas, has been tested and is suggested as a method to sample (or to locate) areas with a high prevalence of elevated blood lead in children. Hierarchical sampling was devised to supplement traditional soil lead sampling of a single stratum, either residential or fixed point source, using a multistep strategy. Blood lead ($n = 1141$) and soil lead ($n = 378$) data collected under the USEPA/UCI Tijuana Lead Project (1996–1999) were analyzed to evaluate the usefulness of sampling soil lead from background sites, schools and parks, point sources, and residences. Results revealed that industrial emissions have been a contributing factor to soil lead contamination in Tijuana. At the regional level, point source soil lead was associated with mean blood lead levels and concurrent high background, and point source soil lead levels were predictive of a high percentage of subjects with blood lead equal to or greater than 10 μg/dL (pe 10). Significant relationships were observed between mean blood lead level and fixed point source soil lead ($r = 0.93$; $P < 0.05$; $R^2 = 0.72$ using a quadratic model) and between residential soil lead and fixed point source soil lead ($r = 0.90$; $P < 0.05$; $R^2 = 0.86$ using a cubic model). This study suggests that point sources alone are not sufficient for predicting the relative risk of exposure to lead in the urban environment. These findings will be useful in defining regions for targeted or universal soil lead sampling by site type. Point sources have been observed to be predictive of mean blood lead at the regional level; however, this relationship alone was not sufficient to predict pe 10. It is concluded that when apparently undisturbed sites reveal high soil lead levels in addition to local point sources, dispersion of lead is widespread and will be associated with a high prevalence of elevated blood lead in children. Multiple strata sampling was shown to be useful in differentiating among sources by site-specific association to mean blood lead and the prevalence of elevated blood lead at the regional level.

Keywords: Exposure characterization; Hierarchical sampling; Lead point sources; Spatial analysis

1. Introduction

For a decade, lead has been recognized as the single most significant environmental health threat to children in the United States (NRC, 1993; CDC, 1991), and at least 20 US government reports have recognized soil and dust lead as major exposure sources (Mielke and Reagan, 1998; Reagan, 1997). In children, blood lead levels (BLLs) above 10 μg/dL but less than 25 μg/dL have been associated with decrements in cognitive functioning for more than 20 years (CDC, 1991; Needleman and Bellinger, 1991; ATSDR, 1988; USEPA, 1986; Needleman et al., 1979). More recently, increasing evidence that BLLs below 10 μg/dL are associated with cognitive deficits has been reported (Lanphear et al., 2000; Walkowiak et al., 1998; Schwartz, 1994; Schwartz and Otto, 1991).

Reviews have described the association between lead exposure and adverse health effects as demonstrating a quantitative dose–response relationship (NRC, 1993; ATSDR, 1993; USEPA, 1990). However, the strength of

☆ Funding sources: This research was supported by USEPA collaborative agreement CR824353-01-0, UC MEXUS, UCI Global Peace and Conflict Studies, UCI Center for Occupational and Environmental Health, and the Regents of the University of California. Human Subjects Compliance: The USEPA/UCI epidemiological study was previously approved and assigned HS# 94-410. The present study was reviewed administratively and classified as exempt research by the University of California, Irvine Institutional Review Board Administration (HS# 2001-1709) in accordance with 45 CFR 46.101.

* Corresponding author. Fax: +1-949-824-2056.
E-mail address: jeericso@uci.edu (J.E. Ericson).

0013-9351/03/$ - see front matter
doi:10.1016/S0013-9351(02)00088-9

the correlation between environmental lead exposure and children's blood lead levels varies between studies (Manton et al., 2000; Bornschein et al., 1985; Lanphear and Matte, 1998), and the relative contribution of lead in soil and dust to children's blood lead levels remains an issue. Lead concentrations in soil, gasoline, and food have been correlated with children's blood lead concentrations at the population level (Mielke and Reagan, 1998). Nutritional status, intensity of hand-to-mouth behavior, differences in quantity and concentration of ingested lead, and variation in clearance rates of blood Pb by the kidneys determine the magnitude of individual variation in blood lead levels from environmental media (Mahaffey, 1998).

Soil serves as both a sink and a source of long-term lead contamination. Soils that remain undisturbed retain lead deposited from the atmosphere in the upper 2–5 cm (USEPA, 1986). Baseline samples, representing concentrations from apparently undisturbed areas removed from anthropogenic activity, have recently been estimated at 10–50 μg/g (Lioy and Pellizzari, 1995). Several different transfer processes contribute to soil contamination—direct release from combustion processes, wet and dry deposition from air, transfer to soil via contaminated water for irrigation, farming, or home gardens and lawns (Layton et al., 1993), and resuspension. Of particular concern is the combustion of leaded gasoline, from which some 75% is emitted in exhaust as fine lead dust of particle size ranging from 0.25 to 15 μm (Mielke et al., 1999). Soil lead assessment has its drawbacks, particularly with regard to difficulties in assessing temporal factors of lead deposition. Nonetheless, soil lead is extremely useful to determine current exposure potential of the population and may be used in modeling future exposure risk.

At the population level, two recent studies found strong associations between soil lead and blood lead. Sargent et al. (1997) found an R^2 of 0.83 in a recent study of Rhode Island children in a multiple regression model. In a Louisiana study, the reported correlation coefficient for blood lead and soil lead was 0.69 (Mielke et al., 1999). The latter report found a steep rise in children's blood lead levels at soil lead concentrations approaching 100 μg/g (Mielke et al., 1999). This critical finding supports the conclusion that children are not only especially sensitive to lead exposure; they are especially sensitive to low levels of environmental lead (CDC, 1997; Brody et al., 1994; Mushak et al., 1989), as found in this study.

Accumulated soil lead in the urban environment has been shown to be a highly significant source of exposure for children as evidenced by a significant relationship between soil lead levels and age of housing as a crude measure of the correlation of blood lead and lead exposure variables (Mielke et al., 1999). The total tolerable daily ingestion limit of lead for children has been estimated at 6 μg/day (Mielke and Reagan, 1998). Increasing soil lead concentrations from a baseline (<80 μg/g) to 400 μg/g was recently estimated to produce an increase in the percentage of children with blood lead exceeding 10 μg/dL by 11.6% (Lanphear and Matte, 1998). It has been estimated that the slope of blood lead to soil lead ranges from 0.6 to 6.8 μg/dL per 1000 μg/g of soil lead (USEPA, 1983); such variability indicates the possibility of a misspecification problem with some models. The validity of these predicted values are dependent on age of subjects, specific covariates used, and overall appropriateness of the model. For example, the impact of soil lead abatement was found to be more beneficial to certain subgroups of children in a Boston study (Aschengrau et al., 1994). However, even when research utilizes similar lead sources, exposure pathways, and populations there is considerable variability in study results. The National Research Council has reported that "the fact that current evidence on some toxicants, most notably lead, does not clearly reveal a safe threshold has raised concern that the threshold model might reflect the limits of scientific knowledge, rather than the limits of safety" (NRC, 1993). An important limiting factor is that studies to date of the association between soil lead and blood lead have utilized a single sampling stratum, either point source or residential sites.

Despite the prevalence of hierarchical structure observed in environmental research, previous studies have not addressed this issue in sampling methodology. Hierarchical, or multistep, sampling of multiple strata (various activity areas and exposure sources) has been developed and tested in this study. Hierarchical sampling was used to differentiate among site types by specific association to mean blood lead and prevalence levels. Site types included in this analysis include a background (or baseline) survey, followed by surveys of fixed point sources, schools and parks, and residential soil from study subjects' homes. Sampling of multiple soil strata has been tested and is suggested as a method to locate areas with a high prevalence of elevated blood lead in children.

Residential soil containing lead is regulated under Section 403 of the Toxic Substances Control Act and is set at 400 μg/g. This legislation, 40 CFR Part 745, has received bipartisan support and represents the first national standard aimed at lead in dust or soil and from deteriorated paint in the residential environment. Within the United States, an estimated 18% of privately owned housing units have soil lead levels exceeding 500 μg/g (USEPA, 1993). It is critical to note that exposure to residential soil containing lead levels between 50 and 150 μg/g has been shown to pose a significant risk to young children and pregnant mothers (Reagan and Silbergeld, 1989). House dust and residential soil have been reported as the major sources of lead exposure in recent studies (Lanphear and Matte, 1998; Mielke et al., 1999). A new study by Lanphear et al. (2002) determined that lead-contaminated house dust, soil, and water were significant contributors to lead intake during the first 2 years of life, after adjusting for dietary iron and calcium intake. Although most of the potential residential lead sources can be eliminated or greatly reduced, soil lead represents a long-term problem even with phasing out and control in the United States and other countries. The problems that we observe will continue given that the turnover or half-life of undisturbed soil lead is 400–3000 years depending on the soil type and environmental condition (Lansdown and Yule, 1986).

Despite the attenuation in childhood Pb exposure in the United States since 1980, the problem remains pervasive (Mielke et al., 1999). Due to rapid industrialization during the latter half of the 20th century in Mexico, exposure to lead has become an increasingly significant public health problem (Romieu et al., 1997). Urban Mexico, both Mexico City and Tijuana, have provided the opportunity to study variant Pb exposures and their health effects due to increased levels of Pb observed in Mexican populations (Romieu et al., 1994; Rothenberg et al., 1995). The rapid industrialization observed in Tijuana has highlighted the potential for exposure to lead, and childhood exposures are of particular concern. Rural populations assessed on the Arizona–Sonora border Mexico region had higher geometric mean blood lead levels than did US children (Ericson and Baker, 1999). The Arizona–Sonora group of 3–5-year-olds had a geometric mean of 3.8 μg/dL (Esteban and Hart, 1998) compared to NHANES III data which showed a mean of 2.5 μg/dL for that age group among US children (Pirkle et al., 1998).

In general, airborne Pb exposures of Mexican populations may be assumed to have been higher in recent years than those of US populations due to the phasing out in the United States of Pb additives in gasoline (Ericson and Baker, 1999). Exposure to the combustion products of leaded gasoline was identified as one of the two major sources of Pb exposure in Mexico City (Romieu et al., 1995). Although Pb additives to gasoline are now being phased out in Mexico, leaded gasoline remains as a fuel since it is cheaper than unleaded alternatives and older automobiles still use leaded gasoline. In effect, citizens of Mexico have used leaded gasoline for 17 years longer than US consumers (Ericson and Baker, 1999). Other sources of current lead exposure in Mexico include lead-glazed ceramics, the paint used to cover some toys and school equipment, and lead-soldered cans that may still be available (Romieu et al., 1994). Until recently there has been limited information on blood lead levels in this region (Esteban and Hart, 1998).

2. Materials and methods

The USEPA/UCI Tijuana Lead Project was a cross-border collaborative study of childhood lead exposure within the largest urban area along the US–Mexican border. In 1991, the Mexican federal government indicated its commitment to reducing lead in the environment by signing the Agreement for Joint Actions and by establishing a committee in the Health Ministry to prevent the use of lead. The committee established regulations to reduce and control exposure to lead by reducing lead in gasoline, requiring pigments and glazes to carry a warning label if they contain lead, and disallowing the use of lead-soldered cans, among other initiatives (Romieu et al., 1994).

The project was a 3-year study supported by the US Environmental Protection Agency (with input from the National Center for Environmental Health) and the Centers for Disease Control and Prevention with the permission of the Secretaria de Salud, Mexicali, Baja California, Mexico, the Municipality of Tijuana, and six health-care sectors. Between May 1997 and September 1998, an epidemiological survey of childhood lead exposure of children, ages 1.5–6.9 years, was conducted in the City of Tijuana, Baja California. A geographically representative sample using sampling sites at preschools and clinics throughout the region was selected. Teams of local professionals (nurses and doctors) conducted the survey. A total of 1719 randomly selected subjects were included in the study. The mean age among subjects was 4.0 ± 1.5 years. All of the subjects were Hispanic, and 49.3% were female (Ericson and Baker, 1999).

The overall mean blood lead level in Tijuana was 6.2 ± 3.4 μg/dL. In accordance with CDC and Mexican guidelines, 9.8% of subjects had BLLs between 10.0 and 19.9 μg/dL, and 1% had levels between 20 and 43 μg/dL (the maximum level found in this study). By comparison, the CDC's NHANES III survey (the primary source for monitoring BLLs in the US population) found that the mean BLL among 1–5-year-olds was 2.7 μg/dL and that 4.4% had levels equal to or exceeding 10 μg/dL (Pirkle et al., 1998). Multivariate regression of the key risk factors for children with blood lead level $\geqslant 10$ μg/dL revealed that elevated blood lead was significantly associated with social class and with the use of ceramic pots for cooking. There are estimated to be at least 37,000 children with BLL $\geqslant 10$ μg/dL (both ceramic- and non-ceramic-using) in the City of Tijuana of the total estimated population of 344,000 (Ericson and Baker, 1999).

Hierarchical strata sampling was devised to precede and supplement residential soil sampling. The strata were organized in a step-wise process: first, background soil lead levels (undisturbed locations apparently removed from anthropogenic activity), schools/parks (based upon identification of all sites in Tijuana with sampling sites randomly chosen throughout the city), and point sources (preselected industrial sites identified in the field as current emitters of lead) (Bocco and Sanchez, 1997) to further investigate pathways of soil lead exposure.

Initially, background soil collection (Survey 1 sampling) was undertaken by University of California at Irvine (UCI) researchers in undisturbed and natural areas of the city to assess the baseline levels of lead in Tijuana by analyzing these soil samples. These samples were expected to be of much lower lead concentration than those samples collected in the proximity of lead point sources, at schools and parks, and at homes. Therefore, rigorous quality control standards were followed both in the collection and in the analysis of these samples. The sampling design utilized a 2- by 2-km square grid system superimposed over a map of the Greater Tijuana area. Within each grid, sample sites were preselected based upon topological information indicating areas of sparse urbanization. In January 1995, the UCI team collected samples from 68 sites in duplicate ($n = 136$) from predesignated, undisturbed locations. Site selection was verified in the field, and each site was referenced by geographic positioning satellite instrumentation. Samples were selected from locations that were at least 150 m away from any structure or transportation access. Objects that would be prone to disturb wind patterns or sampling sites in proximity to roadways, waste areas, or burned areas were also avoided. Low-lying areas were also avoided as collection points due to possible lead accumulation from water drainage. On site, team members who changed disposable gloves and cleaned the collection implements with distilled water between samples collected approximately 400 g of soil to a depth of 4 cm. The samples were imported into the United States under a US Department of Agriculture (USDA) soil collection permit and were analyzed in the Environmental Health Science Cleanroom Laboratory at UCI. Results of the three surveys are reported in the following Table 1.

Schools and parks (Survey 2) were sampled in June 1996. A total of 44 duplicate sets of samples were collected from sites that were randomly distributed across the city. The final analysis of these 44 samples was completed by Fayette Environmental Services, Inc., consistent with the remaining sample analyses.

In March 1997, UCI researchers were deployed to the identified fixed point sources (Survey 3 sites) within the city. In the field, teams determined the type of industry or source at each location before collecting samples and had the opportunity to sample at apparent sources, which had not been previously identified. A total of 76 samples from 14 sites were collected with geolocational information and have been analyzed. Included were 18 point source samples collected from subjects' homes in the vicinity of 3 major fixed point sources (smelting sites) in the area. Samples from subjects' homes were obtained in conjunction with the USEPA/UCI Tijuana Lead Project. Home soil and dust were collected for 365 subjects, 160 of whom had been designated case management subjects.

Table 1
USEPA/UCI study: Soil lead sampling results

Survey	No. of samples	Geometric mean (μg/g)	Standard deviation	Standard error of the mean
Background: Survey 1	68	7.87	1.02	0.12
Schools/parks: Survey 2	44	19.09	0.92	0.14
Fixed point sources: Survey 3	76	37.52	1.63	0.19
Residential soil	190	24.28	1.30	0.09
Residential dust	310	30.89	1.18	0.07

The background samples were analyzed following the protocol of Ericson and Mishra (1991), which is used to quantify total extractable lead. All other environmental samples were analyzed following the protocol of Mielke et al. (1983), which is used in an attempt to extract "bioavailable" lead only. A total of 688 soil and dust samples have been analyzed. Using the Mielke et al. (1983) protocol, the samples were prepared by removing approximately 20 g (soil) or 3 g (dust) from each double-bagged sample, placing the sample in a Fisher PTFE 250-ml beaker, and oven drying at 65°C for 48 h. The dried sample was then sieved through a 20-mesh (0.85-mm) screen, and 3 g were recovered and transferred to the PTFE beaker. The samples were chemically extracted with 0.1 M nitric acid (Mielke et al., 1983) and analyzed by atomic absorption spectrometry using Perkin–Elmer SIMAA 6000 instrumentation. Internal calibration prior to each run was performed using a blank and Fisher Scientific analytical Pb standard. Standardization was based upon a four-point linear calibration curve.

3. Results

The expected trend of increasing mean soil lead levels was observed among sampling sites as follows: Background (11.9 μg/g) → Schools and Parks (33.3 μg/g) → Residential Soil (63.4 μg/g) and Residential Dust (77.0 μg/g) → Point Sources (243.8 μg/g). The practice of using fill soil or sand at public schools in Tijuana was

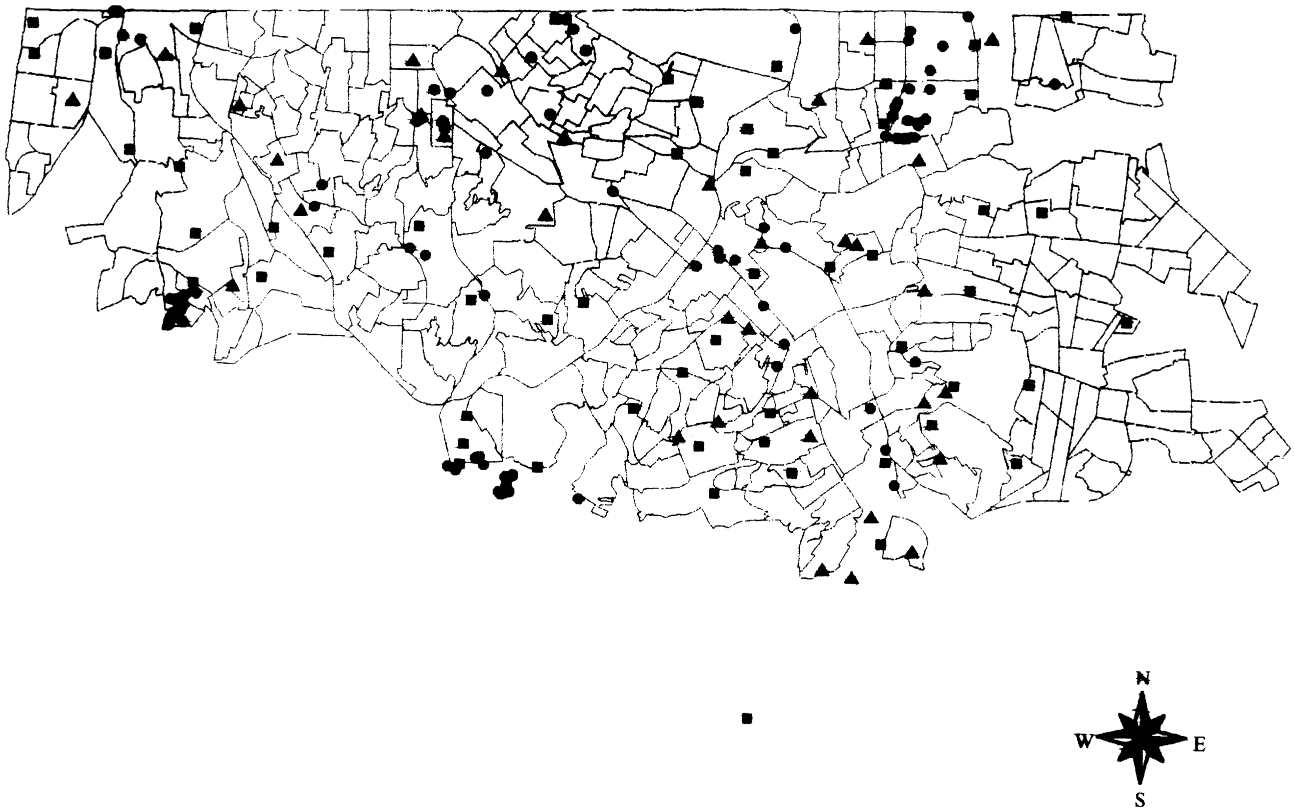

Fig. 1. Composite soil lead sampling sites. ■, Survey 1, background samples; ▲, Survey 2, schools and parks; •, Survey 3, point sources.

observed, producing the abrupt increase in lead levels in soil of schoolyards. Sand or silt was used for fill of clay or silt parent soil. This practice causes the School sampling (Survey 2) to be less valid with regard to generalizing to other sites not sampled, particularly the La Gloria region where no school sites were identified. Nevertheless, fill soil or sand is still an exposure source, whether low or high, for children at the schools from the surrounding tracts. The fixed point source samples were observed to vary widely in lead concentration. It is assumed that this is due to the fact that they were taken as judgement samples in the field or were due to sampling at varying distances from sites when necessary.

The soil lead sampling results presented in Table 1 were georeferenced and entered into ArcView for analysis of spatial relationships. Fig. 1 illustrates the relative soil lead concentrations across Tijuana, as a composite of three soil lead strata (background, schools and parks, and fixed point sources). Data analysis of each stratum was performed separately for comparison to blood lead at the regional level. The regional analysis was performed using the predetermined regions within Tijuana under the USEPA/UCI Project. Eight of the nine regions were composed of 33–49 census tracts each. The La Gloria region was not delineated on the city map as the area was not mapped for the 1995 census; however, it includes 25 main study subjects clustered contiguous to the southwest region, within an area equal to an estimated 20–25 census tracts in Tijuana. Of the 1189 non-ceramic-using subjects in Tijuana, 1141 were determined to reside within regional borders and were included in the data analysis at the regional level, presented in Table 2. There were no significant differences in mean blood lead levels across regions by analysis of variance ($P = 0.35$). The data in Table 3 reveal significant differences in the means across regions for Surveys 1 ($P = 0.04$) and 3 ($P < 0.005$), but not for Survey 2 ($P = 0.14$) (Kruskal–Wallis test). There are no significant correlations between the soil surveys at the 0.05 level; however, the correlation of 0.54 for Surveys 1 (background) and 3 (fixed point sources) is noteworthy. Finally, there was no significant difference in the proportion of subjects with BLL$\geqslant$10 μg/dL across regions by χ^2 test ($P = 0.40$), despite the considerable range in proportion of subjects with BLL$\geqslant$10 μg/dL (presented in Table 4). The larger range of prevalence vs geometric mean BLL is believed to be due to the relatively higher blood lead levels for cases and the frequency of noncases with BLL of 7 μg/dL observed in other regions relative to the data for the La Gloria region.

The results of the residential soil lead analyses appear in Table 5. A total of 190 residential soil samples were collected. Results for the residential soil sampling by

Table 2
Regional blood lead means

Region	No. of subjects	Geometric mean BLL	Standard deviation	Variance	Standard error of the mean
Northeast	126	5.25	0.40	0.16	0.04
Southeast	169	4.95	0.46	0.21	0.04
North	127	5.47	0.41	0.17	0.04
East	83	4.90	0.50	0.20	0.05
West	188	5.18	0.43	0.19	0.03
Northwest	157	5.22	0.43	0.18	0.03
Southwest	131	5.37	0.45	0.20	0.04
South	135	5.07	0.44	0.20	0.04
La Gloria	25	6.04	0.57	0.33	0.11

Table 3
Regional soil lead survey statistics

	No. of samples	Geometric mean	Standard deviation	Variance	Standard error of the mean
Survey 1					
Northeast	11	12.58	1.45	2.10	0.44
Southeast	11	8.10	1.00	1.10	0.30
North	11	6.40	0.67	0.45	0.20
East	3	1.75	0.90	0.90	0.52
West	8	4.97	0.56	0.31	0.20
Northwest	7	4.11	0.81	0.65	0.38
Southwest	7	7.12	0.71	0.50	0.27
South	8	8.39	0.98	0.96	0.29
La Gloria	2	86.19	0.20	0.04	0.71
Survey 2					
Northeast	10	13.68	0.83	0.68	0.26
Southeast	9	10.86	0.66	0.43	0.22
North	8	24.36	0.76	0.58	0.27
East	0				
West	6	41.38	1.48	2.18	0.60
Northwest	3	21.44	0.28	0.08	0.16
Southwest	0				
South	8	30.90	0.60	0.40	0.21
La Gloria	0				
Survey 3					
Northeast	22	71.67	1.73	2.99	0.37
Southeast	1				
North	4	76.70	1.00	1.00	0.50
East	0				
West	21	9.32	0.93	0.86	0.20
Northwest	3	30.57	0.49	0.24	0.28
Southwest	5	108.11	1.73	3.01	0.77
South	3	22.09	0.80	0.64	0.46
La Gloria	17	118.27	1.00	1.00	0.24

region were generated using weighted data analysis techniques. Weighted data were used because subjects for whom residential lead samples were collected were not all selected with equal probability; therefore results were weighted to conform to the proportion of cases to noncases for each region. Differences across means were significant at the 0.02 level (Kruskal–Wallis test). At the regional level, there is a significant relationship between residential soil lead and fixed point source soil lead (Survey 3). However, data sets from only five of the eight regions were available to evaluate the relationship between residential soil lead and Survey 3 and therefore the association is described given its limitations. The Spearman correlation is 0.90 (significant at the 0.05 level); $R^2 = 0.86$. This cubic fit was modeled by curve estimation; however, the association between residential soil lead and Survey 3 is emphasized rather than noted to be a causative relationship. Correlations with residential soil lead were limited by several factors. All of the La Gloria home soil samples were collected as point source samples under the USEPA/UCI study. The explanation for no association found between mean

Table 4
Regional percentage of subjects with BLL ≥ 10 μg/dL and soil survey means

Region	Proportion with BLL ≥ 10 μg/dL	Mean weighted residential soil	Geometric mean Survey 1	Geometric mean Survey 3
Northeast	4.00	18.56	12.58	71.67
Southeast	6.50	15.86	8.10	n/a
North	7.10	n/a	6.40	76.70
East	7.20	10.83	1.75	n/a
West	8.00	9.62	4.97	9.32
Northwest	8.30	41.58	4.11	30.57
Southwest	8.40	56.29	7.12	108.11
South	8.90	15.78	8.39	22.09
La Gloria	20.00	n/a	86.17	118.27

Table 5
Regional weighted residential soil lead means

Region	Proportion with BLL ≥ 10 μg/dL	Geometric mean BLL	Mean LN weighted residential soil
Northeast	4	5.25	18.56
Southeast	6.5	4.95	15.86
North	7.1	5.47	n/a
East	7.2	4.9	10.83
West	8	5.18	9.62
Northwest	8.3	5.22	41.58
Southwest	8.4	5.37	56.29
South	8.9	5.07	15.78
La Gloria	20	6.04	n/a

blood lead levels and weighted residential soil lead means may be attributed to a significant degree to missing data.

The relationship between mean blood lead level per region and Survey 3 for the seven regions with point source data is shown in Fig. 2, which displays the quadratic relationship between blood lead and point source soil lead at the regional level. The Spearman correlation coefficient for this relationship is 0.93 (significant at the 0.05 level); $R^2 = 0.72$. The quadratic fit was modeled by curve estimation. Despite the small number of observations ($n = 7$) used to model the association between blood lead and fixed point source soil lead at the regional level, the quadratic curve estimation procedure graphically displayed in Fig. 2 reveals a strong association. Medians were evaluated in addition to means, and the Spearman correlation for the association between the two medians was 0.79 ($P = 0.034$), which lends further support to the association.

Measures of central tendency are appropriate for estimating overall risk to the population, but reliance on these measures alone have been shown to obscure the existence of more highly exposed individuals bearing unacceptable levels of risk (Brownson, 1998). The proportion of subjects with blood lead equal to or greater than 10 μg/dL (pe 10) within each region was also analyzed as a dependent variable (see Fig. 3). These results reveal the variability in correlating soil lead and blood lead for the eight regions with relatively low pe 10 and low background soil lead in addition to the higher values observed for the La Gloria region in pe 10 and mean blood lead levels.

The La Gloria region showed a striking relationship between elevated soil lead sampling site types, particularly fixed point source and background soil levels, and pe 10. As Table 4 indicates, La Gloria is the only region with combined elevated background and point source soil lead, and it has the highest level of pe 10 among the regions.

4. Discussion and conclusions

These bivariate relationships between soil lead and blood lead are consistent with the previously cited study which found a steep rise in children's blood lead levels at soil lead concentrations approaching 100 μg/g (Mielke et al., 1999). Among non-ceramic-exposed children aged 1.5–6.9 years, 20,440 are predicted to have blood lead greater than or equal to 10 μg/dL in Tijuana (Gonzalez et al., 2002). At the regional level, significant relationships between mean blood lead level and fixed point source soil lead level and between residential soil lead and fixed point source soil lead were found. These relationships are reported with the caveat that the model is considered preliminary due to relatively small data set. Despite stated limitations, results show that, at the regional level, point source soil lead level is associated with mean blood lead level and that concurrent high

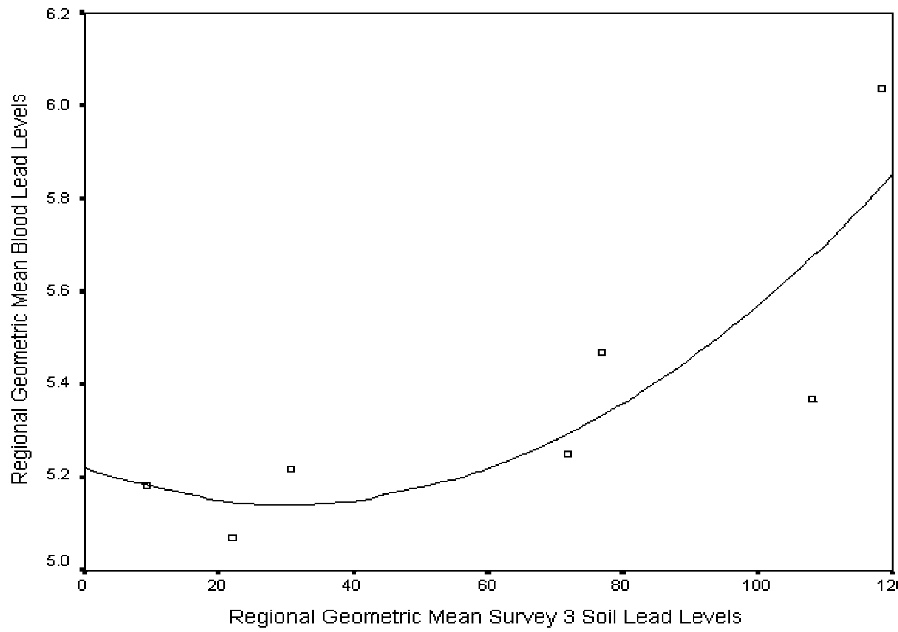

Fig. 2. Relationship between survey 3 soil lead and mean blood lead at the regional level.

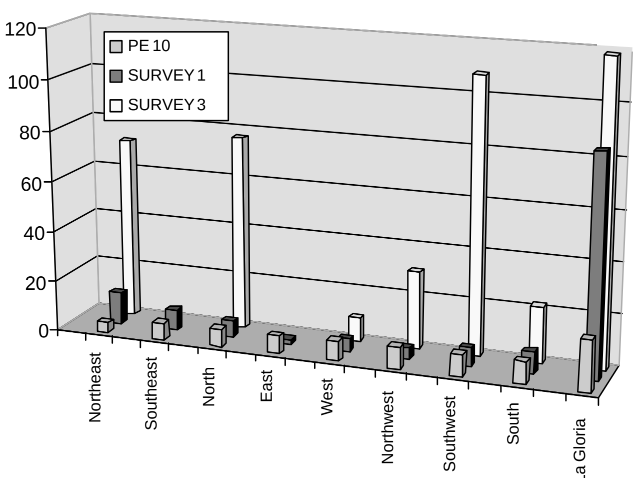

Fig. 3. Relationship between proportion of non-ceramic-using subjects with BLL$\geqslant$10 μg/dL and Surveys 1 and 3 soil lead.

background and point source soil lead level may be predictive of a high pe 10.

Variables in addition to soil or dust lead exposure which have been found to be significantly related to children's blood lead levels include race, hand-to-mouth behaviors, and age (Charney et al., 1980; Rabinowitz et al., 1985; Lanphear et al., 1996). Age was not a risk factor for the Tijuana study, suggesting that exposure is not reduced with increasing age or that nutritional deficiencies may be factors. Race was considered to be homogenous for the study participants. Age, race, and socioeconomic status have all been shown to modify the effects of lead exposure on blood lead level (Lanphear and Matte, 1998). Socioeconomic status may be an indicator of several other factors, including adequate nutrition or proximity to a hazardous waste site. Specifically, children whose diets do not include sufficient calcium and iron have been found to be more susceptible to the effects of lead exposure than better-nourished children (Elhelu, 1995; Marcus and Schwartz, 1987; Mahaffey and Goyer, 1972).

The risk posed by soil contaminated by lead exposure may be ameliorated by abatement and prevention strategies. Measures that have proven effective include educating parents and childcare providers about contaminated play areas, planting ground or plant cover on soils, and replacing contents of contaminated sand boxes (Hilts, 1996). However, Rust et al. (1999) estimate that lead abatement practices which reduce childhood exposure by 50% may produce only a 25% decline in blood lead 1 year later; the authors speculate that this may be due to mobilized bone lead stores. It is also possible that the intervention strategy was not completely successful in removing the source of exposure. Projects in the United States and British Columbia, Canada which have been implemented to control interior dust combined with soil lead exposure prevention strategies have achieved decreases in local childhood blood lead levels. The projects demonstrate that covering soils in play areas with grass, rubberized matting, gravel, wood chips, or cement is effective in preventing or reducing exposure and that river sediment can be used to cover contaminated soils (Mielke et al., 1999). During the field sampling of schools and parks in Tijuana, the research team observed that most of the schools had brought in sand or soil containing very low concentrations of lead to play areas with only a few exceptions. School officials effectively reduced exposure of their students.

The USEPA's National Risk Management Research Laboratory has recently reported that by adding phosphorous to lead-contaminated soil, lead can be effectively bound into pyromorphite, a stable compound which is rarely absorbed if ingested. Hydroxyapatite has been utilized as a source of phosphorous that binds to lead, thus reducing bioavailability (USEPA, 2001). The USEPA has been awarded a patent for its hydroxyapatite in situ inactivation technique, which has been tested in field studies in Region VII. The cost for this method was reported as thousands of dollars per acre–foot of treated soil, which is significantly lower than the traditional treatment costs of more than a million dollars per acre–foot (USEPA, 2001).

The question of when the economic benefits of a soil lead survey will exceed the costs of this undertaking remains a consideration. The preferred sampling method for a given community will depend in part upon observed variability within census tracts or regions in different environmental sampling sites, which could be estimated with preliminary sampling. The contribution of lead in various environmental media to blood concentrations should be evaluated on a city-wide (or regional) basis with regard to pinpointing significant fixed point sources. Abatement for highly contaminated areas may be accomplished by practices such as the USEPA's patented hydroxyapatite in situ inactivation technique at a considerably lower cost than that of traditional soil lead treatment (USEPA, 2001).

Consistent use of a single sampling method (random or stratified random) throughout Tijuana could potentially give a more accurate representation of total exposure sources, but this would by definition require a larger number of soil samples than those of the other sampling strategies and would not be cost effective. As a basis for comparison, blood lead surveys may be targeted or universal and the benefit of screening depends upon the prevalence of elevated blood lead levels. Universal screening can detect all cases of lead poisoning and is the most cost-effective strategy for populations with a high prevalence of elevated blood lead levels. The benefit of universal blood lead screening has been observed to increase when 11–17% of children have elevated blood lead levels (Briss, 1996). However the cost per case detected is less using targeted screening rather than universal screening in populations with low to medium prevalence, (Kemper et al., 1998), i.e., pe $10 \leqslant 10\%$ (CDC, 1997).

There are limitations in quantifying and comparing the association between soil lead and blood lead within and across studies. The relatively small number of samples analyzed for each type of stratum and the relatively small number of regions for which statistically significant results are reported are limitations of this study. Further, the measurement of soil lead concentrations will always be variable due to several factors. The nature of soil as a complex mixture and the total vs the bioavailable lead must be considered. Error (sampling, analytical, and measurement) must be considered in addition to the inherent variation of soil lead that will be found in a random soil sample.

Targeted soil sampling surveys are appropriate when blood lead testing of a random sample reveals a prevalence that is significantly higher for a region compared to the rest of the city or for a community compared to the national average. In the absence of information on the prevalence of elevated blood lead levels for a community, soil lead sampling should be undertaken in an iterative approach. Approximately 1 sample per km^2, or about 150 samples, was observed to be sufficient to characterize the extent of background soil lead contamination in an area the size of Tijuana. Next, fixed point sources should be identified and sampled in a denser grid circumventing each source, with a goal of collecting approximately 10 samples per source. Sampling should proceed radially outward from the source for a minimum of 1 km and be designed to capture potential human exposure by sampling in inhabited areas and in areas proximal to the source. This strategy would allow for a comparison of background soil lead levels to fixed point source lead levels. When significantly elevated background levels are observed in an area of confirmed point source emissions, blood lead analyses should proceed at the census tract level. Universal screening would be appropriate in this scenario and should be undertaken in recognition of prevailing winds or other geographic phenomena which are expressed as spatial trends in soil sampling.

In Tijuana, the La Gloria region has a pe 10 of 20% among non-ceramic-using subjects and is the location of a secondary lead smelter. These conditions justify universal blood lead screening and soil lead abatement policies. The most cost-effective soil sampling strategy suggested by this study for a geographically and/or demographically similar area would be stratified random sampling targeted at background and point source sites. For Tijuana, the foregoing results suggest that as few as 300 soil samples could reveal the dispersion of background and point source soil lead for this population of approximately one million. For regions with low to medium pe 10, targeted soil lead sampling is appropriate to monitor urban areas which are exposed to both industrial and past or current vehicular emissions containing lead.

This study revealed that industrial emissions have been a contributing factor to soil lead contamination in Tijuana. We have previously shown that point sources of lead in Tijuana are a highly significant variable, but will underestimate the number of subjects at risk (Gonzalez et al., 2002). This study suggests that point sources alone are not sufficient for predicting the relative risk of exposure to lead in the urban environment.

These findings have implications for the United States also, where higher Pb exposures occur disproportionately within the inner cities among children of lower socioeconomic status (Brody et al., 1994; Pirkle et al., 1994) and 60% of African Americans and Hispanics live in communities proximal to toxic waste sites (ATSDR, 1988). Further, within the United States,, controversy ensues over the current primary source of lead exposure to children: residual lead from gasoline emissions (Mielke et al., 1999) or lead-based paint in residential housing (USEPA, 1998). The issue appears to be population specific, as either source may dominate depending on housing stock and numerous environmental variables.

The results of this study will be useful in the absence of data on the prevalence of lead poisoning in a given locale by defining regions for targeted or universal soil lead sampling by site type. These findings suggest the utility of multiple strata sampling in differentiating among sources by site-specific association to mean blood lead and the prevalence of elevated blood lead at the regional level. This study revealed high background soil lead levels in addition to local point sources, indicating that dispersion of lead is widespread. This phenomenon is associated with a high prevalence of elevated blood lead in children. Recent findings that children are especially sensitive to low levels of environmental lead (CDC, 1997; Brody et al., 1994; Mushak et al., 1989) are supported by the results of this study.

Acknowledgments

We acknowledge Dean B. Baker, M.D., M.P.H., co-Principal Investigator of the USEPA/UCI Tijuana Childhood Lead Project. We thank Haiou Yang, Ph.D. and Stacey Kojaku for project support and the student volunteers of E164L (Spring 1995) and E100 for field assistance. This research was supported by USEPA collaborative agreement CR824353-01-0, UC MEXUS, UCI Global Peace and Conflict Studies, UCI Center for Occupational and Environmental Health, and the Regents of the University of California.

References

Agency for Toxic Substances and Disease Registry (ATSDR), 1988. Toxicological profile for lead. Washington, DC.

Agency for Toxic Substances and Disease Registry (ATSDR), 1993. Toxicological profile for lead. Report No: ATSDR/TP-92/12; NTIS No: PB93-182475. US Department of Health and Human Services, Public Health Service, Atlanta, GA.

Aschengrau, A., Beiser, A., Bellinger, D., Copenhafer, D., Weitzman, M., 1994. The impact of soil lead abatement on urban children's blood lead levels: phase II results from the Boston lead-in-soil demonstration project. Environ. Res. 67, 125–148.

Bocco, G., Sanchez, R., 1997. Identifying potential impact of lead contamination using a geographic information system. Environ. Manage. 21 (1), 133–138.

Bornschein, R.L., Succop, P.A., Dietrich, K.N., 1985. The influence of social and environmental factors on dust lead, hand lead, and blood lead levels in young children. Environ. Res. 38, 108–118.

Briss, P.A., 1996. Childhood blood lead screening: how do the costs and benefits compare? abstract. Ahsr. Fhsr. Annu. Meeting Abstr. Book 13, 114–115.

Brody, D.J., Pirkle, J.L., Kramer, R.A., Flegal, K.M., Matte, T.D., Gunter, E.W., Paschal, D.C., 1994. Blood lead levels in the US population: phase 1 of the third national health and nutrition examination survey (NHANES III, 1988 to 1991). J. Am. Med. Assoc. 272, 277–283.

Brownson, R.C., Petitti, D.B., 1998. Applied Epidemiology. Oxford University Press, NY.

Centers for Disease Control and Prevention (CDC), 1991. Strategic Plan for the Elimination of Childhood Lead Poisoning, Developed for the Risk Management Subcommittee, Committee to Coordinate Environmental Health and Related Programs, United States Department of Health and Services.

Centers for Disease Control and Prevention (CDC), 1997. Screening Young Children for Lead Poisoning: Guidance for State and Local Public Health Officials, Centers for Disease Control and Prevention, Atlanta, GA.

Charney, E., Sayre, J.W., Coulter, M., 1980. Increased lead absorption in inner city children: where does the lead come from? Pediatrics 65, 226–231.

Elhelu, M.A., 1995. Lead in inner-city soil and its possible contribution to children's blood lead. Arch. Environ. Health 50, 2.

Ericson, J.E., Mishra, S.I., 1991. Soil lead concentrations and prevalence of hyperactive behavior among school children in Ottawa, Canada. Environ. Int. 16, 247–256.

Ericson, J.E., Baker, D.B., 1999. Report to the US Environmental Protection Agency, US Centers for Disease Control and Prevention, XVI Ayuntamiento of City of Tijuana, Childhood Lead Assessment in Tijuana, Baja California, Mexico.

Esteban, E., Hart, R., 1998. Pediatric Lead Assessment on the United States–Mexico Border: A Binational Study in the Arizona–Sonora Region. CDC Report, National Center for Environmental Health.

Gonzalez, E.J., Pham, P.G., Ericson, J.E., Baker, D.B., 2002. Tijuana childhood lead risk assessment revisited: validating a GIS model with environmental data. Environ. Manage. 29, 559–565.

Hilts, S.R., 1996. A cooperative approach to risk management in an active lead/zinc smelter community. Environ. Geochem. Health 18, 17–24.

Kemper, A.R., Bordley, W.C., Downs, S.M., 1998. Cost-effectiveness analysis of lead poisoning screening strategies following the 1997 guidelines of the centers for disease control and prevention. Arch. Pediatr. Adolescent Med. 152 (12), 1202–1208.

Lanphear, B.P., Matte, T.D., 1998. The contribution of lead-contaminated house dust and residential soil to children's blood lead levels. Environ. Res. 79, 51–68.

Lanphear, B.P., Weitzman, M., Eberly, S., 1996. Racial differences in environmental exposures to lead. Am. J. Public Health 86, 1460–1483.

Lanphear, B.P., Dietrich, K.N., Auinger, P., Cox, C., 2000. Cognitive deficits associated with blood lead levels $\geq 10\,\mu g/dl$ in US children and adolescents. Public Health Rep. 115, 521–529.

Lanphear, B.P., Hornung, R, Ho, M., Howard, C.R., Eberly, S., Knauf, K., Eberle, S., 2002. Environmental lead exposure during early childhood. J. Pediatr. 140, 40–47.

Lansdown, R., Yule, W., 1986. Lead Toxicity: History and Environmental Impact. Johns Hopkins University Press, Baltimore, MD.

Layton, D.W., McKone, T.E., Knezovich, J.P., Wong, J.J., 1993. In: Brusick, D.J. (Ed.), Assessment of Exposures to Genotoxic Substances. Methods for Genetic Risk Assessment. Ann Lewis Publishers, Arbor, MI, pp. 29–63.

Lioy, P.J., Pellizzari, E., 1995. Conceptual framework for designing a national survey of human exposure. J. Exposure Anal. Environ. Epidemiol. 5, 425–444.

Mahaffey, K.R., Goyer, R.A., 1972. The influence of iron deficiency on tissue content and toxicity of ingested lead in the rat. J. Lab. Clin. Med. 79, 128–136.

Mahaffey, K.R., 1998. Predicting blood lead concentrations from lead in environmental media. Environ. Health Perspect. 106 (Suppl. 6), 1485–1493.

Manton, W.I., Angle, C.R., Stanek, K.L., Reese, Y.R., Kuehnemann, T.J., 2000. Acquisition and retention of lead by young children. Environ. Res. 82, 60–80.

Marcus, A.H., Schwartz, J., 1987. Dose response curves for erythrocyte protoporphytin vs. blood lead: effects on iron status. Environ. Res. 44, 221–727.

Mielke, H.W., Reagan, P.L., 1998. Soil is an important pathway of human lead exposure. Environ. Health Perspect. 106 (Suppl. 1), 217–229.

Mielke, H.W., Anderson, J.C., Berry, K.J., MIelke Jr., P.W., Chaney, R.L., 1983. Lead concentrations in inner city soils as a factor in the child lead problem. Am. J. Public Health 73, 1366–1369.

Mielke, H.W., Gonzales, C.R., Smith, M.K., Mielke, P.W., 1999. The urban environment and children's health: soils as an integrator of lead, zinc, and cadmium in New Orleans, Louisiana, USA. Environ. Res. 81, 117–129.

Mushak, P., Davis, J.M., Crocetti, A.F., Grant, L.D., 1989. Prenatal and postnatal effects of low level lead exposure: integrated summary of a report to the US congress on childhood lead poisoning. Environ. Res. 50, 11–36.

National Research Council (NRC), Committee on Measuring Lead in Critical Populations, 1993. Measuring Lead Exposure in Infants, Children and Other Sensitive Populations (NTIS No: PB-122256). National Academy Press, Washington, DC.

Needleman, H.L., Gunnoe, C., Leviton, A., Reed, R., Peresie, H., Maher, C., Barrett, P., 1979. Deficits in psychologic and classroom performance of children with elevated dentine lead levels. New Engl. J. Med. 300 (13), 689–695.

Needleman, H.L., Bellinger, D., 1991. The effects of low level exposure to lead. Annual Rev. Public Health 12, 111–140.

Pirkle, J.L., Brody, D.J., Gunter, E.W., Kramer, R.A., Paschal, D.C., Flegal, K.M., Matte, T.D., 1994. The decline in blood lead levels in the United States: the national health and nutrition examination surveys (NHANES). J. Am. Med. Assoc. 272, 284–291.

Pirkle, J.L., Kaufmann, R.B., Brody, D.J., Hickman, T., Gunter, E.W., Paschal, D.C., 1998. Exposure of the U.S. population to lead, 1991–1994. Environmental Health Perspectives 106 (11), 745–750.

Rabinowitz, M., Leviton, A., Needleman, H., Bellinger, D., Waternaux, C., 1985. Environmental correlates of infant blood lead levels in Boston. Environ. Res. 38, 96–107.

Reagan, P.L., 1997. Direct Quotations of Government Reports on Lead in Dust of All Types. St. Paul, MN: Midwest Environmental Education and Research Association (MEERA).

Reagan, P.L., Silbergeld, E.K., 1989. Establishing a health based standard for lead in residential soils. 50 (2), Lead Coalition, St. Paul, MN.

Romieu, I., Palazuelos, E., Hernandez, A., Mauricio, R., Camilo, J., Cahero, G., 1994. Sources of lead exposure in Mexico City. Environ. Health Perspect. 102, 4.

Romieu, I., Carreon, T., Lopez, L., Palazuelos, E., Rios, C., Manuel, Y., Hernandez-Avila, M., 1995. Environmental urban lead exposure and blood lead levels in children of Mexico City. Environ. Health Perspect. 103, 103–1040.

Romieu, I., Lacasana, M., McConnell, R., 1997. Lead exposure in Latin America and the Caribbean. Environ. Health Perspect. 105, 398–405.

Rothenberg, S.J., Karchmer, S., Schnaas, L., Perroni, E., Zea, F., Alba, J.F., 1995. Changes in serial blood lead levels during pregnancy. Environmental Health Perspectives 102, 876–880.

Rust, S.W., Kumar, P., Burgoon, D.A., Niemuth, N.A., Schultz, B.D., 1999. Influence of bone lead stores on the observed effectiveness of lead hazard intervention. Environ. Res. 81, 175–184.

Sargent, J.D., Bailey, A., Simon, P., Blake, M., Dalton, M.A., 1997. Census tract analysis of lead exposure in Rhode Island children. Environ. Res. 74, 159–168.

Schwartz, J., Otto, D., 1991. Lead and minor hearing impairment. Arch. Environ. Health 46, 300–305.

Schwartz, J., 1994. Low-level lead exposure and children's IQ: a meta analysis and search for a threshold. Environ. Res. 65, 42–55.

US Environmental Protection Agency (USEPA), 1983. Office of Research and Development. Air Quality Criteria for Lead, Vol. I, EPA Report 600/83-028A. Research Triangle Park.

US Environmental Protection Agency (USEPA), 1986. Environmental Criteria and Assessment Office. Air Quality Criteria for Lead. Report No. EPA/600/8-83/028aF. Research Triangle Park.

US Environmental Protection Agency (USEPA), 1990. Air Quality Criteria for Lead: Supplement for the 1986 Addendum. Report No: EPA-600/8-89/048F; NTIS No.: PB91-138420. Research Triangle Park, NC: Environmental Criteria and Assessment Office, US Environmental Protection Agency.

US Environmental Protection Agency (USEPA), 1993. Data Analysis of Lead in Soil and Dust. EPA-747-R-93-011. Office of Pollution Prevention and Toxics.

US Environmental Protection Agency (USEPA), 2001. Reducing the Risks Associated with Lead in Soil. EPA/600/F-01/014.

Walkowiak, J., Altmann, L., Kramer, U., Sveinsson, M., Turfeld, M., Weishoff-Houben, M., Winneke, G., 1998. Cognitive and sensorimotor functions in 6-year-old children in relation to lead and mercury levels: adjustment for intelligence and contrast sensitivity in computerized testing. Neurotoxicol. Teratol. 20, 511–521.