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The Impact of Soil Lead Abatement on Urban Children's Blood Lead Levels: Phase II Results from the Boston Lead-In-Soil Demonstration Project

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The Boston Lead-In-Soil Demonstration Project was a randomized environmental intervention study of the impact of urban soil lead abatement on children's blood lead levels. Lead-contaminated soil abatement was associated with a modest reduction in children's blood lead levels in both phases of the project; however, the reduction in Phase II was somewhat greater than that in Phase I. The combined results from both phases suggest that a soil lead reduction of 2060 ppm is associated with a 2.25 to 2.70 μg/dl decline in blood lead levels. Low levels of soil recontamination 1 to 2 years following abatement indicate that the intervention is persistent, at least over the short-term. Furthermore, the intervention appears to benefit most children since no measurable differences in efficacy were observed for starting blood and soil lead level, race, neighborhood, gender, and many other characteristics. However, soil abatement did appear to be more beneficial to children in the higher socioeconomic classes, with low baseline ferritin levels, and who spent time away from home on a regular basis and lived in nonowner occupied housing, and with adults who had lead-related hobbies and almost always washed their hands before meals. Children who lived in apartments with consistently elevated floor dust lead loading levels derived almost no benefit from the soil abatement. It was not possible to separate the effects of the variables that had a beneficial impact on efficacy because they were closely correlated and the number of subjects was small. We recommend that further research be conducted to identify subgroups of children to whom soil lead abatement might be targeted.

INTRODUCTION

Children are exposed to lead through different pathways including air, water, dust, and soil (ATSDR, 1988). Primary and secondary prevention efforts have focused mainly on reducing the lead levels in air, water, and dust, but recently lead-contaminated soil has gained attention (ATSDR, 1988; Mielke *et al.*, 1983; Duggan and Inskip, 1985). Most available data on soil lead exposure come from cross-sectional studies often conducted in communities with smelters (ATSDR, 1988; Mielke *et al.*, 1983; Duggan and Inskip, 1985; Sayre *et al.*, 1974; Charney *et al.*, 1980; Clark *et al.*, 1985; Landrigan *et al.*, 1975; Rabinowitz *et al.*, 1985; Roels *et al.*, 1980). Recently, three prospective intervention studies were conducted in Boston, Baltimore, and Cincinnati to determine the impact of reducing soil lead levels among urban children (Weitzman *et al.*, 1993; U.S. EPA, 1993a,b).

Phase I of the Boston Lead-In-Soil Demonstration Project found that lead-contaminated soil abatement resulted in a modest but statistically significant re-

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duction in children's blood lead levels. Ten months after the soil abatement, the mean decline in blood lead levels was 2.44 μg/dl following soil lead reductions averaging 1790 parts per million (ppm) while the average declines in the two comparison groups were 0.91 and 0.52 μg/dl. The difference between the soil abatement and comparison groups ranged from 0.8 to 1.6 μg/dl when confounding variables including the preabatement blood lead level were controlled (Weitzman *et al.*, 1993). The individual studies in Baltimore and Cincinnati found little effect of the soil abatement on blood lead levels, perhaps because the preabatement soil lead levels were considerably lower than those in Boston (U.S. EPA 1993a,b).

The current report describes the results of Phase II of the Boston project, when soil abatement was conducted in the two comparison groups and follow-up was extended another year in order to assess the generalizability and persistence of the blood lead decline observed in Phase I and to determine the rate and extent of soil and dust recontamination over the 2-year follow-up period. The report also describes the results of exploratory analyses of demographic, behavioral, and environmental characteristics that influenced the efficacy of the abatement.

MATERIALS AND METHODS

Identification and Enrollment of the Study Population

Children screened for lead were considered eligible if they lived in the neighborhoods of Boston with a high incidence of lead poisoning, were under 4 years of age, and had a finger stick blood lead level from 10 to 20 μg/dl. Additional children up to 4 years of age living on the same premises were also identified for enrollment. Potential participants were required to meet the following eligibility criteria: (1) the amount of peeling paint was less than 30% of the exterior walls of the child's house or 40% of the exterior walls of adjacent buildings; (2) the child's house had a yard at least 10 square feet in size that was composed, at least partly, of accessible soil and/or grass; (3) the surface soil lead levels, 1 m from the house, averaged at least 1500 ppm; (4) the house had eight or fewer apartments; (5) the child was mobile and had never been lead poisoned; and (6) the family lived on the premises for at least 3 months and had no plans to move in the near future.

Children who met these criteria had venous blood lead determinations from September 1989 through January 1990 (N = 236). One hundred fifty-two children whose blood lead levels ranged from 7 to 24 μg/dl were enlisted and randomly assigned to the Study Group (N = 54), Comparison Group A (N = 51), or Comparison Group B (N = 47). During Phase I, the Study Group received soil and interior dust abatement and loose paint stabilization, Comparison Group A received interior dust abatement and loose paint stabilization, and Comparison Group B received only loose paint stabilization. During Phase II, soil abatement was conducted in Comparison Groups A and B, and residential lead-based paint removal was offered to participants in all three groups. Figure 1 describes the timing of the interventions in the three groups, hereafter called Groups S, A, and B.

Environmental Interventions

The soil abatement consisted of removing 6 in. of top soil from the entire yard,

	GROUP S	GROUP A	GROUP B	TOTAL
PHASE ONE				
Biological Sampling (9/89-1/90)				
	Blood Pb	*Blood Pb*	*Blood Pb*	*Blood Pb*
	N=54/54 (100%)	N=51/51 (100%)	N=47/47 (100%)	N=152/152 (100%)
Environmental Interventions (9/89-1/90)				
	Soil and Interior Dust Abatement Loose Paint Stabilization	Interior Dust Abatement, Loose Paint Stabilization	Loose Paint Stabilization	
	N=54/54 (100%)	N=51/51 (100%)	N=47/47 (100%)	N=152/152 (100%)
Biological Sampling* (7/90-11/90)				
	Blood Pb	Blood Pb	Blood Pb	Blood Pb
	N=54/54 (100%)	N=49/51 (96.1%)	N=46/47 (98.0%)	N=149/152 (98.0%)
PHASE TWO				
Environmental Interventions* (9/90-1/91)				
	———	Soil Abatement	Soil Abatement	Soil Abatement
		N=47/49 (95.9%)	N=42/46 (91.3%)	N=89/95 (93.7%)
	Paint Deleading	Paint Deleading	Paint Deleading	Paint Deleading
	N=23/54 (42.6%)	N=18/49 (36.7%)	N=16/46 (34.8%)	N=57/149 (38.3%)
Biological Sampling*+ (7/91-8/91)				
	Blood Pb	Blood Pb	Blood Pb	Blood Pb
	N=33/54 (61.1%)	N=32/49 (65.3%)	N=26/46 (56.5%)	N=91/149 (61.1%)

* Subjects who did not participate in an activity either refused, moved, or were lost to follow-up.

\+ Among children who received biologic sampling in 1991, 14 in Group S, 18 in Group A, and 14 in B received soil abatement alone.

FIG. 1. Timing and number of subjects at each study activity.

placing a water-permeable geotextile fabric over the exposed subsurface, and covering the fabric with 8 in. of clean soil and ground cover. The median lead concentration of the replacement soil was 100 ppm (range: undetectable to 620 ppm). The one-time interior dust abatement consisted of HEPA (High-Efficiency Particulate Aerosol Filter) vacuuming floors and rugs and wiping surfaces with wet cloths and furniture with oil-treated cloths. The one-time loose paint stabilization consisted of HEPA vacuuming and washing loose paint areas with trisodium phosphate and painting window wells with primer.

Fifty-seven participants also received residential lead-based paint removal during Phase II. Deleading consisted of removing leaded paint from mouthable surfaces below 5 feet, and making intact all paint above 5 feet inside the home, common areas of multiunit buildings, and exterior areas.

Environmental Measurements and Analysis

Soil. Soil sampling was conducted at baseline and two times thereafter to monitor the rate of recontamination. At baseline, an average of eight samples were taken throughout the yard using mainly a line source sampling pattern. Follow-up samples were taken at every other previously sampled location. Soil samples were analyzed by x-ray fluorescence (XRF) at the U.S. EPA Region 1 Laboratory using strict QA/QC procedures. The detection limit was 100 ppm; undetectable levels were assigned a value of 50 ppm for calculations.

Dust. Household dust sampling was conducted at baseline and three times thereafter to monitor the rate of recontamination. Dust was sampled using a hand-held dust vacuum unit (Sirchee-Spittler modified dust buster) that collected the sample in a fine mesh stainless steel screen. Up to six samples in each household were obtained from the window wells and floors of the kitchen, living room, and child's bedroom. The floor dust samples were later combined into a single sample because individual samples were often lighter (less than 10 μg) than considered optimal for accurate analysis. Before analysis, dust samples were passed through a 60-mesh sieve, and only the fines were analyzed. The U.S. EPA Region 1 Laboratory conducted the dust analyses by XRF using strict QA/QC procedures. The detection limit was 100 ppm; undetectable levels were assigned a value of 50 ppm for calculations.

Water. Two first flush water samples were taken by the parent from the cold water kitchen faucet. Water samples were analyzed by Hall-Kimbrell Environmental Services, Inc. (Lawrence, KS) using U.S. EPA test method 239.2. The detection limit was 1 μg/liter; undetectable levels were assigned a value of 0.5 μg/liter for calculations.

Paint. Portable XRF analyzers (Princeton Gamma Tech XK-3) were used to measure lead in paint. Up to six measurements were taken from the walls and woodwork in the kitchen, living room, and child's bedroom. The detection limit was 0.5 mg/cm^2; undetectable levels were assigned a value of 0.25 mg/cm^2 for calculations.

Child and Family Measures

Shortly after enrollment, trained staff members conducted standardized interviews with parents to obtain information on demographic characteristics, sources of lead exposure, and the children's behavior and play locales. Follow-up interviews, one at each subsequent round of biologic sampling, were conducted to assess any changes.

Outcome Measures

Three venous blood samples were taken over approximately a 2-year period. During Phase I, samples were obtained before abatement and, on average, 10 months after soil abatement. During Phase II, follow-up sampling took place an average of 9 months after soil abatement.

Blood lead levels were determined by ESA Laboratories (Bedford, MA) using graphite furnace atomic absorption (Miller *et al.*, 1987). The detection limit was 1 μg/dl and the coefficient of variation was 13.8% at 10 μg/dl. The laboratory participated in a strict quality control system overseen by the Centers for Disease Control and Prevention (CDC).

Follow-Up of Participants

Figure 1 gives the number of children at each round of biologic sampling and intervention activity. During Phase I, all 152 children received a baseline blood lead determination and their assigned interventions. Only 3 children dropped out. Another 19 moved, but were followed, and their postabatement blood lead levels determined.

Eighty-nine children in Groups A and B received soil abatement during Phase II. Six children did not have their yards abated because either the family was no longer interested in participating ($N = 1$), refused ($N = 1$), or had moved ($N = 4$). In addition, 57 children received residential lead-based paint abatement during Phase II. Among the 92 children who did not receive deleading, 44 refused, 43 had moved, 2 had dropped out, and 3 were lost.

By the end of Phase II, 91 children were still participating and living at the same premises as when they enrolled. All 91 had postabatement blood lead determinations during this phase. Forty-six of these children received only soil abatement, 44 received both soil abatement and deleading, and 1 refused both interventions.

Data Analysis

Complete sample: Comparison of Phase I and Phase II blood lead changes. Crude analyses were conducted to describe the change in blood lead levels from before to after soil abatement (1989 to 1990 for Group S and 1990 to 1991 for Groups A and B), and over the entire study (1989 to 1991 for all groups); 95% confidence intervals were used to assess the precision of the changes.

All children who received soil abatement alone and had blood lead determinations before and after abatement were eligible for this analysis (Table 1). Outliers were determined by examining the residual blood lead levels, that is, the difference between observed levels and those predicted from the linear regression (Draper 1966). Three children whose postabatement residual blood lead levels were more than three standard deviations from zero were excluded (2 Group S siblings with blood lead levels of 35 and 43 μg/dl in 1990 and 1 Group B child with

TABLE 1
GROUPS, PHASES, AND NUMBER OF SUBJECTS IN EACH ANALYSIS

Analysis	Groups	Phases	Number eligible	Number excluded	Final number
Comparison of phase I and II blood lead changes	S, A, B	I (S) II (A, B)	54 (S) 18 (A) 14 (B)	2 (S) 1 (B)	52 (S) 18 (A) 13 (B)
Characteristics influencing the soil abatement					
Repeated measures analysis	A, B	I (A, B) II (A, B)	18 (A) 14 (B)	1 (B)	18 (A) 13 (B)
Analysis of covariance	S, A, B	I (S, A, B)	54 (S) 49 (A) 46 (B)	2 (S)	52 (S) 49 (A) 46 (B)

a blood lead level of 23 μg/dl in 1991). Thus, 52 in Group S, 18 in Group A, and 13 in Group B were included in the final analysis. Twenty-nine Group S children who did not receive deleading during Phase II were also examined as a separate group.

Restricted sample: Characteristics influencing effectiveness of soil abatement. Exploratory analyses were conducted on two subsets of the study population to identify characteristics that influenced the effectiveness of the soil abatement. The main analysis consisted of a two-way analysis of variance (ANOVA) with repeated measures on one factor (Winer, 1971). This analysis was conducted among children in Groups A and B combined over Phase I (no soil abatement) and Phase II (soil abatement phase). Group S children were not included since they received the intervention during Phase I and had no "control" period. Although based on a relatively small number of children ($N = 31$, 20% of the enrolled population), this longitudinal analysis was a powerful test of the determinants of blood lead changes since the children served as their own controls.

In the repeated measures analysis, the two ANOVA factors were characteristic (e.g., age, race) and time, with time as the repeated measure at 1989 (beginning of Phase I), 1990 (end of Phase I), and 1991 (end of Phase II).

The model used was as follows:

$$Y_{ijt} = M + G_j + C_{i(j)} + T_t + \mathrm{GT}_{jt} + \mathrm{TC}_{ti(j)} + \mathrm{E}_{m(ijt)}$$

where Y_{ijt} = blood lead level for the ith child in the jth characteristic category at time t, M = grand mean of the blood lead levels over all categories of the characteristic and time, G_j = effect of characteristic category j, $C_{i(j)}$ = effect of ith child in the jth characteristic category, T_t = effect of time t, GT_{jt} = interaction effect between the jth characteristic category and time t, $\mathrm{TC}_{ti(j)}$ = interaction effect between time t and the ith child in the jth characteristic category, and $E_{m(ijt)}$ = random error nested within each observation Y_{ijt}.

The interaction of a particular characteristic and time was of primary importance since our main interest was in the comparison of blood lead levels over Phases I and II between different levels of the characteristic. Interaction terms whose P values were ≤ 0.15 were considered evidence of effect modification. This liberal significance level was arbitrarily chosen to avoid overlooking possible effect modifiers.

Characteristics examined included race, age, sex, socioeconomic status, mouthing behaviors, play locales, and the presence of other sources of lead (see Table 4 for complete list). To be included in these analyses, each category of a variable or, for variables measured twice, the joint level of each category had to be represented by at least 10% of subjects. All variables were categorized; most were dichotomized because the number of subjects was small. Cut points were based on the: (1) natural distribution (e.g., yes/no), (2) frequency distribution (e.g., 50th percentile), or (3) external considerations such as regulatory or clinical standards.

As a back-up, an analysis of covariance (ANCOVA) on Phase I data was conducted to determine the reliability of the repeated measures results and to provide information on low prevalence characteristics (Kleinbaum *et al.*, 1988). Based on a larger number of children ($N = 147$), the ANCOVA compared blood lead changes among Group S children who received the soil abatement with Group A and B children who did not.

The ANCOVA model included the postabatement blood lead level as the dependent variable, and the preabatement blood lead level, group assignment, a particular characteristic, and interaction between the characteristic and the group as independent variables. The beta coefficients were estimated using least squares methods. Interaction terms whose P values were ≤ 0.15 were again considered evidence of effect modification.

Thirty-two children from Groups A and B who received only soil abatement during Phase II and had all three blood lead determinations over both phases were eligible for the repeated measures analysis (Table 1). After the exclusion of 1 outlier in Group B, the final repeated measures analysis was conducted on 31 children. One hundred forty-nine children from Groups S, A, and B who had follow-up blood lead determinations during Phase I were eligible for the analysis of covariance (ANCOVA). After 2 Group S outliers were excluded, the final analysis of covariance was conducted among 147 children.

Soil and Dust Recontamination Assessment

The median soil lead level (ppm) was used to characterize each yard before soil abatement and 6–10 and 18–22 months later. Premises were the unit of this analysis, and all premises that received soil abatement and whose residents permitted soil sampling were included.

The floor and window well dust lead loading levels ($\mu g/m^2$) were used to characterize the living unit before and after soil abatement. Lead loading was calculated from the lead concentration (ppm) and dust loading (mg/m^2). A single composite sample was used to characterize the floors, and the median of the samples was used to characterize the window wells. Since the dust data were log-normally distributed, the raw results were transformed using natural logarithms. The apartment or house was the unit of this analysis, and all homes that received soil abatement but no deleading, and whose residents permitted dust sampling, were included. Paired t tests were used to assess the statistical significance of the dust changes from baseline levels.

RESULTS

Complete Sample: Comparison of Phase I and II Changes in Blood Lead Levels

During Phase II the mean decline following soil abatement in Groups A and B combined was larger than that seen in Group S and varied considerably between the two groups (Table 2). The results were virtually identical when the analysis was restricted to subjects whose blood samples were most clearly matched for season or to only one child from each family. When the data were adjusted for the starting blood lead level, the declines remained variable across groups (2.51 μg/dl in Group S (N = 29), 5.24 μg/dl in Group A (N = 18), 2.57 μg/dl in Group B (N = 13), and 4.18 μg/dl in Groups A and B combined (N = 31)).

When data from both phases and all three groups were combined, the mean declines were 2.89 and 3.34 μg/dl, depending on the number of Group S children included. While not an ideal comparison, mean blood lead levels declined by 0.64

TABLE 2
CRUDE DIFFERENCE IN BLOOD LEAD LEVELS BEFORE AND AFTER SOIL ABATEMENT IN PHASES 1 AND 2

Group	Mean blood lead level (μg/dl) before abatement[a]	Mean blood lead level (μg/dl) after abatement[b]	Difference between before and after blood lead levels (95% CI)
		Phase 1 (1989–1990)	
S (N = 52)	13.10	10.65	−2.44 (−3.32, −1.57)
S[c] (N = 29)	14.00	10.97	−3.03 (−4.44, −1.63)
		Phase 2 (1990–1991)	
A[c] (N = 18)	12.94	7.69	−5.25 (−6.51, −3.99)
B[c] (N = 13)	10.54	9.15	−1.39 (−4.03, +1.26)
A and B[c] (N = 31)	11.94	8.31	−3.63 (−5.05, −2.21)
		Phases 1 and 2 combined	
S, A, B[c] (N = 60)	12.93	9.59	−3.34 (−4.32, −2.37)
S, A, B[d] (N = 83)	12.66	9.77	−2.89 (−3.64, −2.13)

[a] 1989 level for Group S and 1990 level for Groups A and B.
[b] 1990 level for Group S and 1991 level for Groups A and B.
[c] Includes only those children whose homes were not deleaded during Phase II.
[d] Includes all 52 subjects from Group S irrespective of Phase II deleading status.

μg/dl in Groups A and B (N = 31) during Phase I (no soil abatement), and so soil abatement in all three groups combined was associated with an additional decline of 2.25 to 2.70 μg/dl.

When the crude changes in blood lead level between the first (1989) and last sampling round (1991) were examined, considerable variability among the three groups was again present; however, the crude blood lead decline among Groups A and B combined was quite similar to that observed in Group S (Table 3). When adjusted for the starting (1989) blood lead level, group differences were slightly diminished (−3.93 μg/dl in Group S, −5.45 μg/dl in Group A, −3.10 μg/dl in Group B, and −4.48 μg/dl in Groups A and B combined).

Restricted Sample: Characteristics of Soil Abatement Efficacy Population

The characteristics of children on whom the repeated measures analysis was based (N = 31) are described in Table 4. The majority had baseline blood lead levels of at least 10 μg/dl, were from minority and low socioeconomic groups, and were over 36 months of age when the soil abatement was conducted. Most yards had baseline soil lead levels greater than 2000 ppm. Other sources of lead exposure including water, paint, and dust were also common.

The mean declines in blood lead levels among the repeated measures analysis population (N = 31) were 0.64 (95% CI: −1.71, +0.42) during Phase I and 3.63 (95% CI: −5.05, −2.21) during Phase II. When these data were stratified according to the starting blood lead levels, the Phase I blood lead levels changed little among children with starting levels from 7 to 9 and 10 to 14 μg/dl (+0.30 and +0.18, respectively) but declined by 2.50 μg/dl for children with levels 15–22 μg/dl. The Phase II results confirmed the direct linear relationship between blood lead levels before and after abatement. The crude declines in blood lead levels were 1.45 (95% CI: −3.98, +1.08), 3.82 (95% CI: −6.86, −0.77), and 5.60 (95% CI: −7.22, −3.98), respectively, among children in each incremental starting blood lead category.

TABLE 3
CRUDE DIFFERENCES IN BLOOD LEAD LEVELS BETWEEN 1989 AND 1991

Group	1989 Mean blood lead level (μg/dl)	1991 Mean blood lead level (μg/dl)	Difference between blood lead levels (μg/dl) (95% CI)
S[a] (N = 14)	14.07	9.71	−4.36 (−6.71, −2.01)
A[a] (N = 18)	13.22	7.69	−5.53 (−7.39, −3.67)
B[a] (N = 13)	11.69	9.15	−2.54 (−5.48, +0.41)
A[a] and B[a] (N = 31)	12.58	8.31	−4.27 (−5.90, −2.65)
S,[a] A,[a] B[a] (N = 45)	13.04	8.74	−4.30 (−5.59, −3.01)

[a] Includes only those children whose homes were not deleaded during Phase II.

TABLE 4
CHARACTERISTICS OF THE REPEATED MEASURES ANALYSIS POPULATION

Characteristic	Distribution (%)
1989 Blood lead level (μg/dl) ($N = 31$)	
7–9	32.3
10–14	35.5
15–22	32.3
Race ($N = 31$)	
Black	54.8
Cape Verdean	22.6
Hispanic	6.5
White	3.2
Other	12.9
Age at abatement (months) ($N = 31$)	
25–36	19.4
37–48	35.5
≥49	45.2
Socioeconomic status[a] ($N = 31$)	
Classes 4, 5	67.7
Classes 1, 2, 3	32.3
Gender ($N = 31$)	
Male	48.4
Female	51.6
Place of residence ($N = 31$)	
Dorchester	74.2
Roxbury, Mattapan, Jamaica Plain	25.8
Primary language not English[b] ($N = 31$)	12.9
Lives in owner-occupied premises ($N = 31$)	74.2
Baseline ferritin level ≤15 ng/ml ($N = 30$)	16.7
Often/sometimes sucks thumb[i] ($N = 31$)	16.1
Puts mouth or tongue on window sill[i,d] ($N = 30$)	26.7
Puts favorite toy or blanket in mouth[i] ($N = 31$)	9.7
Puts miscellaneous other things in mouth[i,j] ($N = 31$)	32.3
Composite mouthing variable[i] ($N = 31$)	
Mouths items likely to be lead painted[e]	25.8
Mouths items unlikely to be lead painted,[f] or no mouthing	74.2
No. hours plays in yard per week[i] ($N = 31$)	
Less than 10	48.4
10 or more	51.6
Eats food outdoors[i] ($N = 31$)	58.1
No. hours plays on floor inside per week[i] ($N = 27$)	
1 or less	51.9
2 or more	48.1
Washes hands before meals[i] ($N = 31$)	
Almost always	83.9
Sometimes/almost never	16.1
Washes hands after being outdoors[i] ($N = 31$)	
Almost always	61.3
Sometimes/almost never	38.7
Eats imported canned foods ($N = 30$)	33.3
Spends time away from home[i,g] ($N = 31$)	61.3
Spends time outside study area[i] ($N = 31$)	12.9
Has household pets that go outdoors[i] ($N = 31$)	19.4

TABLE 4—*Continued*

Characteristic	Distribution (%)
Cigarette smoking among household members[i] (N = 31)	61.3
Lead jobs among household members[i] (N = 30)	16.7
Lead hobbies among household members[i] (N = 31)	67.7
Baseline yard soil lead level (ppm) (N = 31)	
≤2,000	41.9
2001–3000	25.8
>3000	32.3
Size of yard (sq. ft.) (N = 31)	
≤1000	25.8
1001–2000	35.5
>2000	38.7
Daily water lead intake[c] (μg) (N = 31)	
0–6.0	29.0
6.1–24.9	32.3
≥25.0	38.7
Paint lead variables	
Lead paint on wall[h,i] (N = 31)	32.3
Lead paint on woodwork[h,i] (N = 31)	67.7
Number of places lead paint found[h,i] (N = 31)	
None	22.6
1 or 2	51.6
3 or 4	25.8
Amount of chipping paint at baseline (sq. in.) (N = 29)	
≤50	58.6
>50	41.4
Dust lead variables	
Window wells	
Lead concentration[i] (ppm) (N = 31)	
≤4,000	35.5
≥4,001	64.5
Dust loading[i] (mg/m²) (N = 31)	
≤300	58.1
≥301	41.9
Lead loading[i] (μg/m²) (N = 31)	
≤600	29.0
≥601	71.0
Floors	
Lead concentration[i] (ppm) (N = 31)	
≤1000	58.1
≥1001	41.9
Dust loading[i] (mg/m²) (N = 31)	
≤30.0	45.2
≥30.1	54.8
Lead loading[i] (μg/m²) (N = 31)	
≤30.0	51.6
≥30.1	48.4

[a] According to the Hollingshead two-factor index.
[b] Includes Spanish and Portuguese.
[c] The maximum daily lead ingested from water (μg) was derived from the maximum of two available water lead levels (μg/liter) and the child's reported daily water intake (liter).
[d] Includes children who were reported to eat paint chips.
[e] Includes window sills, paint chips.
[f] Includes blankets, toys, coins, pacifiers, thumbs.
[g] Includes day care, preschool, baby sitters, relatives.
[h] Defined as an XRF reading greater than 1.2 mg/cm².
[i] As measured during Phase II.
[j] Includes children who were reported to put dirt or sand in their mouth.

TABLE 5

MEAN 1989, 1990, 1991 BLOOD LEAD LEVELS ACCORDING TO SELECTED DEMOGRAPHIC AND OTHER CHARACTERISTICS AMONG THE REPEATED MEASURES ANALYSIS POPULATION

Characteristic	Category	1989 Mean blood lead level (μg/dl)	1990 Mean blood lead level (μg/dl)	1991 Mean blood lead level (μg/dl)	P value[a]
Race	Black (N = 17)	12.29	11.18	7.03	>0.15
	Nonblack (N = 14)	12.93	12.86	9.86	
Socioeconomic status[b]	Classes 1–3 (N = 10)	12.80	11.60	6.35	0.07
	Classes 4–5 (N = 21)	12.48	12.10	9.24	
Age at abatement (months)	25–36 (N = 6)	11.00	12.00	8.83	0.08
	37–48 (N = 11)	13.27	13.27	7.50	
	≥49 (N = 14)	12.71	10.86	8.71	
Sex	Male (N = 15)	13.73	12.80	9.13	>0.15
	Female (N = 16)	11.50	11.13	7.53	
Baseline ferritin level (ng/ml)	≤15 (N = 5)	13.80	13.80	7.40	0.12
	>15 (N = 25)	12.16	11.52	8.62	
Eats imported canned foods	Yes (N = 10)	13.70	13.20	7.50	0.05
	No (N = 20)	11.95	11.40	8.83	
Mouths window sill	Yes–Yes[c] (N = 5)	14.80	14.80	9.00	>0.15
	Yes–No (N = 3)	10.33	11.33	9.00	
	No–Yes (N = 3)	13.67	12.00	12.33	
	No–No (N = 19)	12.42	11.58	7.55	
Mouths miscellaneous other items[d]	Yes–Yes[c] (N = 4)	15.75	13.75	8.75	0.08
	Yes–No (N = 4)	9.75	11.50	10.75	
	No–Yes (N = 5)	12.60	13.00	7.60	
	No–No (N = 17)	12.35	11.24	7.74	
Spends time away from home	Yes–Yes[c] (N = 16)	11.81	11.75	7.84	0.14
	Yes–No (N = 3)	13.33	11.33	7.67	
	No–Yes (N = 3)	18.33	18.00	9.67	
	No–No (N = 9)	11.78	10.44	8.89	
Baseline yard soil lead level (ppm)	≤2000 (N = 13)	12.54	12.92	8.31	>0.15
	2001–3000 (N = 8)	12.25	10.13	7.81	
	>3000 (N = 10)	12.90	12.10	8.70	
Floor dust lead loading (μg/m²)	≤30.0–≤30.0[c] (N = 10)	13.00	12.90	7.40	0.12
	≤30.0–≥30.1 (N = 6)	12.33	10.83	6.83	
	≥30.1–≤30.0 (N = 5)	15.80	15.60	10.00	
	≥30.1–≥30.1 (N = 7)	11.43	10.00	9.64	
Number of places lead paint detected	None (N = 7)	10.71	11.29	5.86	0.47
	1 or 2 (N = 16)	13.31	12.88	9.81	
	3 or 4 (N = 8)	12.75	10.63	7.44	

[a] P values associated with the interaction term between the characteristic and time in the repeated measures analysis.
[b] According to the Hollingshead two-factor index.
[c] The first value refers to the characteristic during Phase I and the second value refers to Phase II.
[d] Includes dirt, sand, furniture, coins.

According to the repeated measures analysis, soil abatement had a similar impact on children regardless of their race, sex, neighborhood, baseline yard soil lead levels, and the presence of most other sources of lead (Table 5, and Figs. 2–13). Characteristics for which differences in effectiveness were seen included socioeconomic status, age, ferritin level, consumption of canned foods imported from foreign countries, mouthing miscellaneous items, spending time away from home on a regular basis, and interior floor dust lead loading levels (Table 5). The soil abatement appeared to be more beneficial to children in the higher socioeconomic levels (Classes 1, 2, and 3 according to the Hollingshead Index, $P = 0.07$), with low baseline ferritin levels (≤ 15 ng/ml, $P = 0.12$), who ate canned foods imported from foreign countries ($P = 0.05$), or who spent time away from home on a regular basis (e.g., day care) ($P = 0.14$). On the other hand, children who lived in apartments with consistently elevated floor dust lead loading levels derived almost *no* benefit from the soil abatement ($P = 0.12$).

With regard to age, during Phase I blood lead levels increased for children aged 25–36 months, were stable for those aged 37–48 months, and decreased for those older than 48 months. During Phase II, the two younger groups appeared to benefit more from the soil abatement ($P = 0.08$).

No appreciable differences in efficacy were observed for children according to window sill mouthing habits ($P \geq 0.15$); however, children who mouthed other miscellaneous items including dirt during Phase II appeared to benefit more from the intervention ($P = 0.08$).

The analysis of covariance based on Phase I data identified several additional variables with a measurable impact on the response to soil abatement. Children who lived in nonowner occupied housing ($P = 0.09$), who lived with adults who had lead-related hobbies ($P = 0.10$), who spent time outside of the study area neighborhoods ($P = 0.14$), or who almost always washed their hands before meals

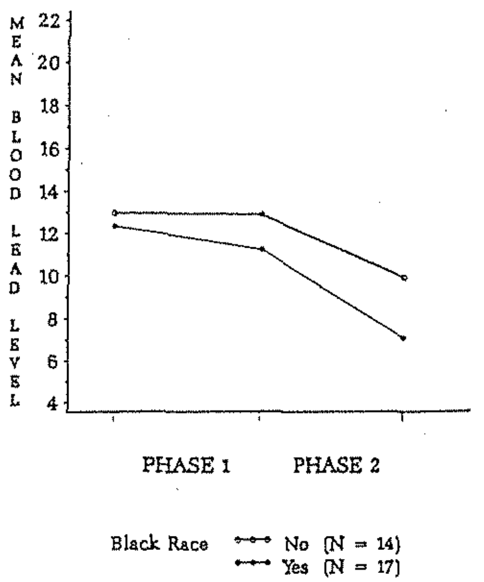

FIGURE 2

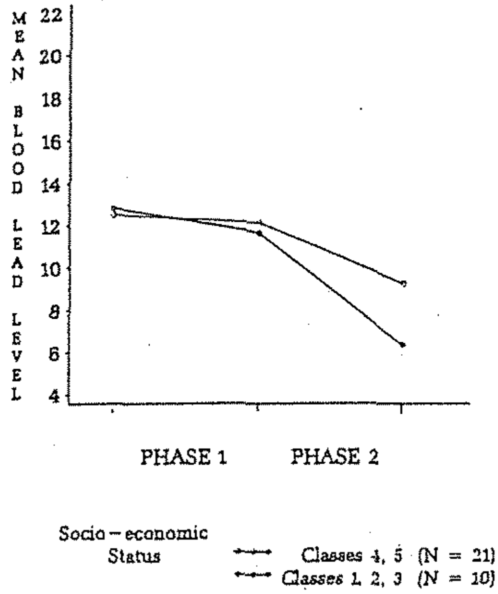

FIGURE 3

(P = 0.08) had a greater response to the intervention. The repeated measures analysis results for the former two variables were in a similar direction as described above but the P values for the interaction terms were quite large. The latter two variables were not examined in the repeated measures analysis because of small numbers.

When we examined the interrelationships between the potential effect modifiers, we found that socioeconomic status, ferritin level, and floor dust lead loading levels were associated with each other and most of the other variables. Children in the highest socioeconomic classes (Classes 1, 2, and 3) were *more* likely to have low ferritin levels, eat canned food from foreign countries, go outside of the study area, and live with adults who have lead-related hobbies. Children with persistently elevated floor dust lead loading levels were *less* likely to be members of the highest socioeconomic classes, live in nonowner occupied housing, have low ferritin levels, and go outside of the study neighborhoods. It was not possible to separate the effects of these variables due to small numbers of individuals in each category.

Recontamination of Soil and Dust

Many yards had evidence of recontamination both at 6–10 and 18–22 months after soil abatement; however, the recontamination was generally at a low level (Table 6). Follow-up median soil lead concentrations were, for the most part, less than 300 ppm.

At 6–12 months, mean floor lead loading levels declined markedly in Group S (P = 0.001),[1] but were relatively unchanged in Groups A and B (P = 0.95 and 0.15,

[1] The P values in this paragraph refer to the paired t tests comparing the differences from baseline to each follow-up, whereas Tables 7 and 8 describe the overall group results.

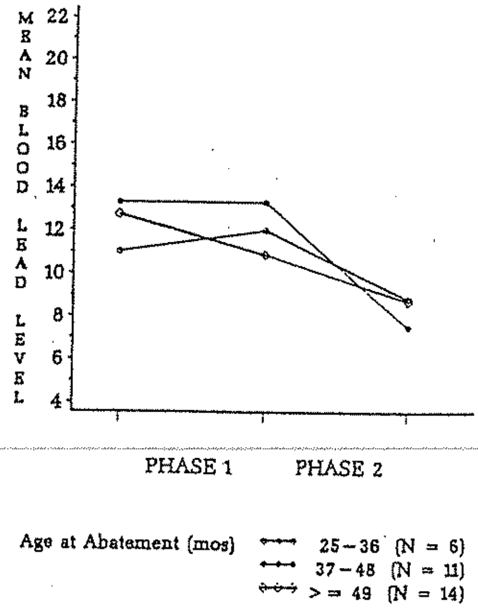

FIGURE 4

respectively) (Table 7). At 18–22 months, mean levels in Group S rose but still remained substantially below baseline ($P = 0.02$). At 6–12 months, mean window well dust lead loading levels fell slightly in Group A ($P = 0.77$), and rose in Groups S ($P = 0.02$) and B ($P = 0.21$) (Table 8). At 18–22 months, mean levels rose further in Group S ($P = 0.17$).

DISCUSSION

The results from Phase II of the Boston Lead-In-Soil Demonstration Project

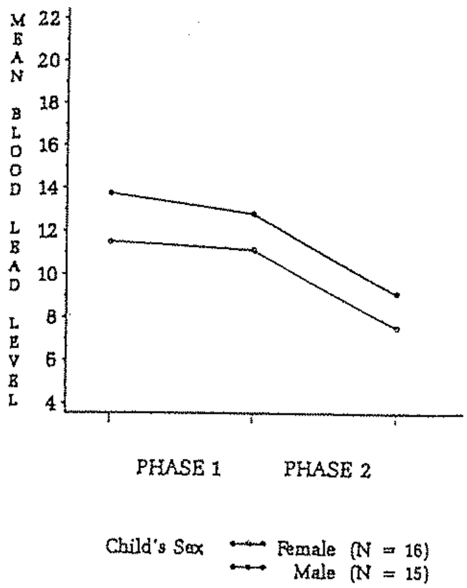

FIGURE 5

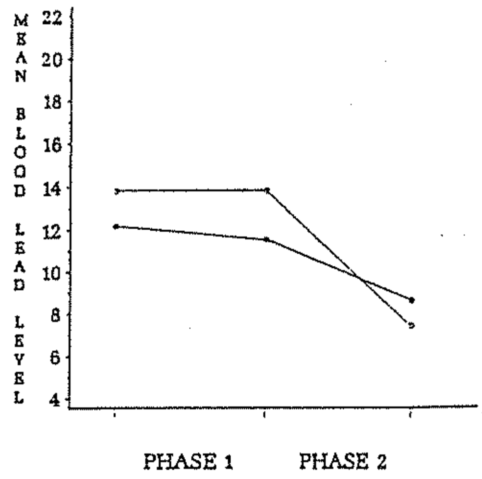

FIGURE 6

confirm that soil lead abatement is associated with a decline in the blood lead levels of urban children. The magnitude of the decline was greater than that seen during Phase I, and the combined results from both phases suggest that a soil lead reduction of 2060 ppm is independently associated with a 2.25 to 2.70 μg/dl decline in blood lead levels.

Before this association can be interpreted as causal, one must consider the possible influence of seasonal and secular changes and of aging on blood lead levels of participating children. With respect to seasonal changes, longitudinal

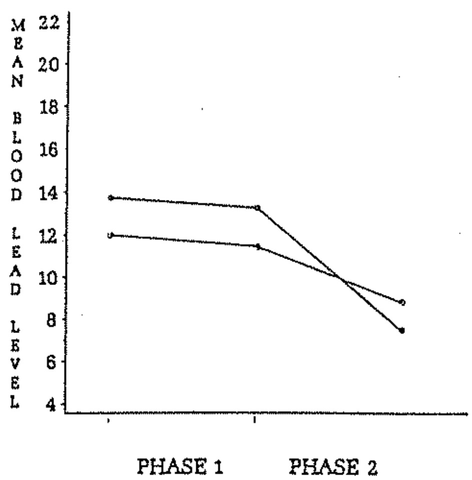

FIGURE 7

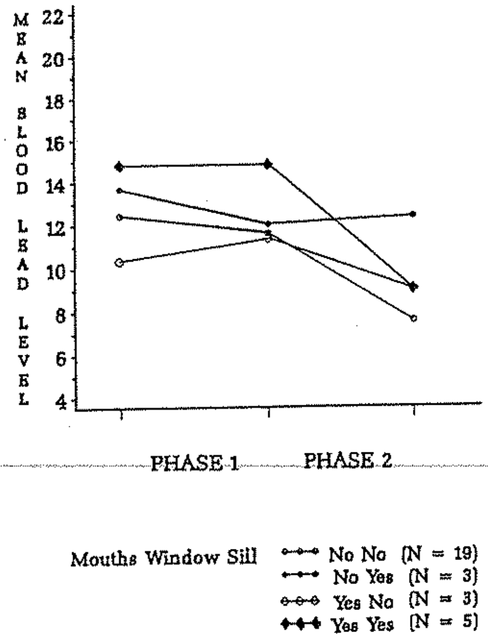

FIGURE 8

studies have shown that blood lead levels typically peak during the late summer months and are lowest during the late winter months (Billick *et al.*, 1979). While the pre- and postabatement blood sampling rounds in this study were roughly matched for season, individual samples were not taken exactly 1 year apart be-

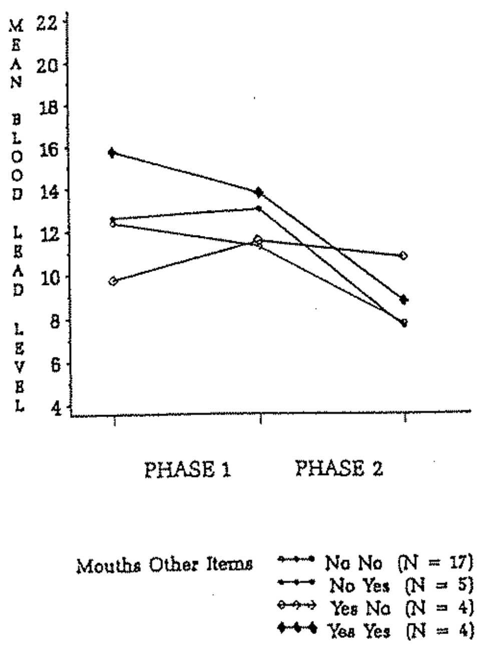

FIGURE 9

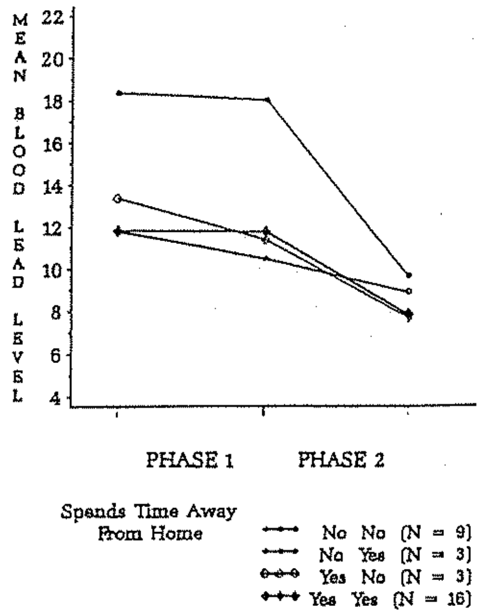

FIGURE 10

cause of difficulties in enrolling and contacting study participants and scheduling study activities. However, the findings were quite similar when the analysis was limited to subjects whose blood samples were most closely matched on calendar time.

As regards the interrelated secular changes and aging, since the 1970s U.S. blood lead levels have declined among all age groups, most likely because of decreases in lead in air and food (Annest *et al.*, 1983). In addition, studies have

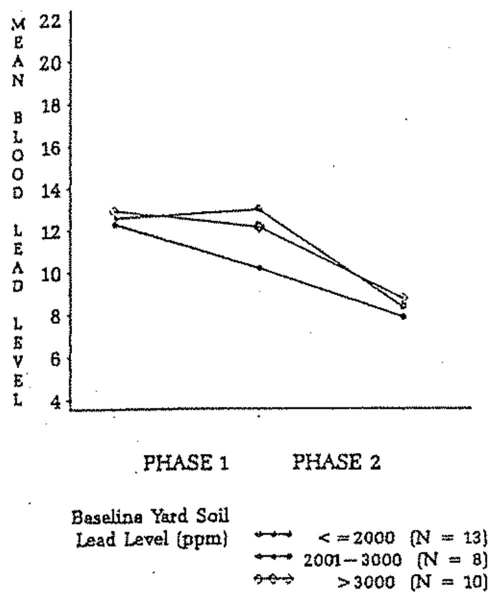

FIGURE 11

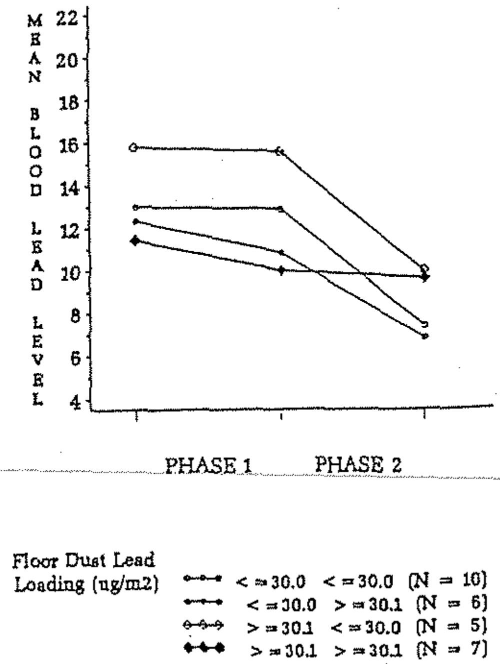

FIGURE 12

shown that blood lead levels among high risk children rise until ages 18 to 27 months, plateau, and then decline (McMichael *et al.*, 1985; Dietrich *et al.*, 1993). We estimated that these factors would lead to a 0.64 μg/dl blood lead decline over 11 months using children in Groups A and B. While not an ideal comparison

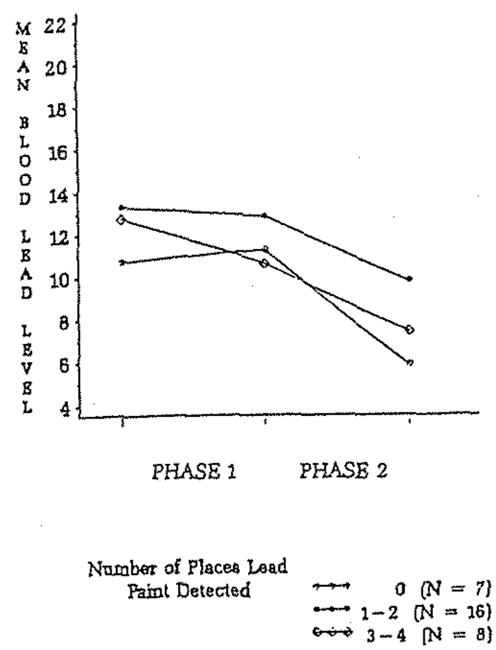

FIGURE 13

TABLE 6
DISTRIBUTION OF SOIL LEAD LEVELS[a] (ppm) AND EXTENT OF RECONTAMINATION OVER TIME AND ACCORDING TO GROUP

	Groups			
	S	A	B	Total
Before abatement[b]				
(*N*)	(35)	(31)[c]	(26)	(92)
Minimum	400	600	920	400
Median	2000	2200	1900	2075
Maximum	5500	5550	4900	5550
Mean	2206	2358	2299	2284
SD	1123	1203	1129	1141
6–10 months after abatement				
(*N*)	(35)	(32)[c]	(26)	(93)
Minimum	50	50	50	50
Median	50	90	200	50
Maximum	1800	780	540	1800
Mean	141	171	180	162
SD	299	172	127	218
% of Yards with Recontamination[d]	22.9	43.8	61.5	40.9
18–22 Months after abatement				
(*N*)	(34)	NA[e]	NA[e]	NA[e]
Minimum	50			
Median	175			
Maximum	430			
Mean	160			
SD	115			
% of yards with recontamination[d]	52.9			

[a] The median level was used to characterize the yard.
[b] These samples were taken just before soil abatement—1989 for Group S and 1990 for Groups A and B.
[c] One premises was not available for sampling just before abatement but was available 6–10 months afterward.
[d] Defined as a median yard lead level greater than 150 ppm.
[e] NA, not available.

because they also received some interventions, these children during Phase I represent the best available internal comparison for the calendar years under study. Even after taking this expected drop into account, there was an additional decline of 2.25 to 2.70 μg/dl after the lead contaminated soil was abated.

The low levels of soil recontamination 1 to 2 years following abatement indicate that the soil intervention is persistent, at least over the short-term. This is particularly reassuring given that lead-contaminated soil was removed only from single yards in densely populated neighborhoods composed mainly of old lead-painted frame homes with high yard soil lead levels. However, because the long-term persistence of the soil abatement remains unknown, we suggest that the abated yards be monitored periodically for many years to come.

The dust lead loading changes following soil abatement were less consistent.

TABLE 7
DISTRIBUTION OF LN FLOOR LEAD LOADING[a] ($\mu g/m^2$) AND EXTENT OF RECONTAMINATION OVER TIME AND ACCORDING TO GROUP

	Groups			
	S	A	B	Total
Before abatement[b]				
(*N*)	(21)	(22)	(22)	(65)
Minimum	2.037	1.641	−0.136[c]	−0.136[c]
Median	3.969	3.297	3.495	3.778
Maximum	8.842	5.111	5.111	8.842
Mean[d]	4.269	3.310	3.189	3.579
SD	1.606	1.003	1.433	1.429
6–12 Months after soil abatement				
(*N*)	(14)	(15)	(12)	(41)
Minimum	0.340	1.064	1.700	0.340
Median	2.087	3.351	3.523	3.082
Maximum	4.366	5.156	4.507	5.157
Mean[d]	2.193	3.375	3.311	2.953
SD	1.174	0.946	0.932	1.143
18–22 months after soil abatement				
(*N*)	(11)	NA[e]	NA[e]	NA[e]
Minimum	1.626			
Median	2.845			
Maximum	4.176			
Mean[d]	2.958			
SD	0.725			

[a] One composited floor dust sample was used to characterize the living unit.
[b] These samples were taken just before soil abatement—1989 for Group S and 1990 for Groups A and B.
[c] The unlogged value was less than 1 and so its natural log is negative.
[d] The geometric mean can be obtained by exponentiating the ln mean.
[e] NA, not available.

Floor levels declined in Group S but not Groups A and B. Window well levels declined in Group A but rose in Groups S and B. Several factors may account for these results. First, the soil abatement eliminated only one of many sources of interior dust lead. Second, the one-time loose paint abatement conducted in Phase I reduced, but did not eliminate, lead-based paint and so high concentrations of leaded paint were present in virtually all homes. Third, lead dust generating household activities (e.g., renovations, lead hobbies) and inconsistent housekeeping practices may have mitigated the impact of the abatement.

The soil abatement did appear to benefit most children since no measurable differences in efficacy were observed for the majority of characteristics examined including starting blood and soil lead levels, race, neighborhood, and gender. With respect to the starting soil lead level, random measurement errors and the small number of yards with relatively low levels may have made it difficult to detect a dose–response relationship.

The analysis did identify several characteristics that appeared to influence a

TABLE 8
DISTRIBUTION OF LN WINDOW WELL LEAD LOADING[a] ($\mu g/m^2$) AND EXTENT OF RECONTAMINATION OVER TIME AND ACCORDING TO GROUP

	Groups			
	S	A	B	Total
Before abatement[b]				
(*N*)	(19)	(22)	(21)	(62)
Minimum	1.346	4.274	3.923	1.346
Median	7.560	8.132	8.015	7.993
Maximum	10.617	10.406	10.384	10.617
Mean[c]	6.976	7.877	7.599	7.507
SD	2.589	1.688	1.762	2.029
6–12 Months after soil abatement				
(*N*)	(15)	(15)	(12)	(42)
Minimum	3.917	2.426	4.052	2.426
Median	7.682	6.847	8.492	7.723
Maximum	10.120	11.156	10.970	11.156
Mean[c]	7.891	7.267	8.148	7.741
SD	1.939	2.143	2.246	2.084
18–22 Months after soil abatement				
(*N*)	(11)	NA[d]	NA[d]	NA[d]
Minimum	5.457			
Median	7.851			
Maximum	10.273			
Mean[c]	7.979			
SD	1.339			

[a] The median of the ln window well levels was used to characterize the living unit.
[b] Samples were taken just before soil abatement—1989 for Group S and 1990 for Groups A and B.
[c] The geometric mean can be obtained by exponentiating the ln mean.
[d] NA, not available.

child's response to soil abatement. First, relatively younger children, those aged 25 to 48 months, benefitted more from the intervention. This difference may reflect age-related differences in mouthing activities and/or level of parental supervision, but the relationships between age, mouthing behaviors, and soil abatement efficacy were inconsistent. According to parental report, younger children were more likely to mouth window sills and other items likely to be lead painted, but were less likely to suck their thumbs and mouth other miscellaneous items such as dirt and sand. Furthermore, children who mouthed other miscellaneous items derived a greater benefit from the intervention, regardless of their age, while no differences in efficacy were seen for other mouthing variables. No information on the level of parental supervision was available.

Second, soil abatement was *not* effective among children with persistently elevated interior floor dust lead loading levels. This finding may have important implications for the manner in which the intervention is conducted for it may be necessary to perform interior dust abatement simultaneously, and perhaps repeatedly.

Several other characteristics appeared to enhance the soil abatement efficacy including higher socioeconomic status, living in nonowner occupied homes, low ferritin level, consumption of canned foods from foreign countries, consistently washing the child's hands before meals, spending time away from home on a regular basis, and the presence of adults in the home with lead-related hobbies. Unfortunately, most of these variables were closely correlated (the common threads were socioeconomic status and dust lead loading levels), and it was not possible to separate their effects because of small numbers.

For these reasons, we consider the analyses of possible effect modifiers exploratory and requiring confirmation from other investigations. If a consistent picture emerges, identified effect modifers could be used to target particular groups and geographic areas where soil abatement would be most effective. While information on some characteristics would be readily available to decision makers (e.g., age, socioeconomic status), obtaining information on others would require a special interview or laboratory test (e.g., mouthing behaviors, ferritin level). While no systematic surveys of soil lead concentrations have been conducted on a national basis, studies in selected areas in the U.S. and abroad suggest that high levels may be common in urban areas with older homes (Davies and Thornton, 1987a) where lead-based paint was used (Ter Haar and Aranow, 1974; Mielke *et al.*, 1984), and where heavy vehicular traffic (Mielke *et al.*, 1984) and lead-generating commercial activities are present (Davies and Thornton, 1987b).

On a population basis, even a modest decline could greatly reduce the number of children above the current action levels recommended by the CDC (Centers for Disease Control, 1991). However, the high cost of the abatement ($9600 per property in Boston) and soil disposal issues make it unlikely that this intervention will be conducted on a widescale basis. Thus, it is particularly important to identify subgroups to whom the intervention might be targeted and consider the cost-effectiveness of various interventions as we plan effective strategies for reducing lead exposure among children across the United States.

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