Estimating the Effects of Soil Remediation on Children’s Blood Lead near a Former Lead Smelter in Omaha, Nebraska, USA

Dongni Ye,1 James S. Brown,1,2 David M. Umbach,1,3 John Adams,4 William Thayer,5 Mark H. Follansbee,4,5 and Ellen F. Kirrane2,6

1Oak Ridge Institute for Science and Education, Oak Ridge, Tennessee, USA
2Center for Public Health and Environmental Assessment, Office of Research and Development, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, USA
3Biostatistics and Computational Biology Branch, National Institute of Environmental Health Sciences, Research Triangle Park, North Carolina, USA
4SRC, Inc., Syracuse, New York, USA
5HTSC, LLC, Syracuse, New York, USA

BACKGROUND: Lead exposures from legacy sources threaten children’s health. Soil in Omaha, Nebraska, was contaminated by emissions from a lead smelter and refinery. The U.S. Environmental Protection Agency excavated and replaced contaminated soil at the Omaha Lead Superfund Site between 1999 and 2016.

OBJECTIVES: The goal of this study was to assess the association of soil lead level (SLL) and soil remediation status with blood lead levels (BLLs) in children living near or on the site.

METHODS: We linked information on SLL at residential properties with children’s BLLs and assigned remediation status to children’s BLL measurements based on whether their measurements occurred during residence at remediated or unremediated properties. We examined the association of SLL and remediation status with elevated BLL (EBLL). We distinguished the roles of temporal trend and the intervention with time-by-intervention-status interaction contrasts. All analyses estimated odds ratios (ORs) with a generalized estimating equations approach to ensure robustness under the complex correlations among BLL measurements. All analyses controlled for relevant covariates including children’s characteristics.

RESULTS: EBLL (>5 μg/dL) was associated with both residential SLL [e.g., OR = 2.00; 95% confidence interval (CI): 1.83, 2.19; >400–800 vs. ≤200 ppm] and neighborhood SLL [e.g., OR = 1.85 (95% CI: 1.62, 2.11; >400–800 vs. ≤200 ppm)] before remediation but only with neighborhood SLL after remediation. The odds of EBLL were higher before remediation [OR 1.52 (95% CI: 1.34, 1.72)]. Similarly, EBLL was positively associated with preremediation status in our interaction analysis [interaction OR = 1.18 (95% CI: 1.02, 1.37)].

DISCUSSION: Residential and neighborhood SLLs were important predictors of EBLLs in children residing near or on this Superfund site. Neighborhood SLL remained a strong predictor following remediation. Our data analyses showed the benefit of soil remediation. Results from the interaction analyses should be interpreted cautiously due to imperfect correspondence of remediation times between remediation and comparison groups. https://doi.org/10.1289/EHP8657

Introduction

Children’s blood lead levels (BLLs) in the United States have decreased steadily over the last several decades, due largely to the phaseout of lead in gasoline and consumer products such as paint. In October 2021, the U.S. Centers for Disease Control and Prevention (CDC) lowered the blood lead reference level (BLRV) for identifying children with BLLs that are much higher than that of most children to 5 μg/dL. This BLRV of 5 μg/dL was set in 2012 based on the 97.5th percentile blood lead concentration of U.S. children (1–5 y old) during the period 2005–2018 (Ruckart et al. 2021). The previous BLRV of 10 μg/dL was set in 2012 based on the 97.5th percentile blood lead concentration of U.S. children (1–5 y old) during the period 2007–2010 (ACCLPP 2012). Before 2012, the CDC had designated a BLL of concern at 10 μg/dL.

Even low-level lead exposures are associated with decrements in cognitive function in young children; specifically, effects on cognition are observed in populations with group mean BLLs <5 μg/dL (ATSDR 2020; U.S. EPA 2013). Although contemporary BLLs in the United States are lower on average than they were in the past, lead from anthropogenic sources persists in the environment (Kennedy et al. 2016; Raymond and Brown 2017), and children are potentially exposed from legacy sources. No threshold for lead-related cognitive effects in children has been identified.

The Omaha Lead Superfund Site (OLSS) was contaminated by emissions from a lead smelter and refining facility that operated for approximately 125 y until its closure in 1997. Other sources of lead contamination at the site include a former paint manufacturer, lead battery plant, and lead-based paint. The Agency for Toxic Substances and Disease Registry (ATSDR) conducted a public health assessment from July 2000 through August 2002 and found that 9.7% of the children 0–6 y old in Omaha had BLLs greater than 10 μg/dL (ATSDR 2005), whereas this proportion was 3.1% in U.S. children overall at the time (Meyer et al. 2003). In 2003, the OLSS was officially designated a Superfund site under the Comprehensive Environmental Response Compensation and Liability Act and was included on the National Priorities List of contaminated sites.

In this study, we estimated the associations of soil lead levels (SLLs) and soil remediation status (i.e., soil excavation and replacement) with BLLs among children living on or near the OLSS. To answer our research questions, we leveraged large databases that were collected for surveillance and tracking purposes. Among the key challenges was to understand the potential biases stemming from use of these databases. We also sought to differentiate the effect of soil remediation from the temporal decline in BLLs that occurred for other reasons, as well as from the expected decline in BLLs as children grow older. Consistent with Steenland et al. (2020) and Savitz et al. (2019) who describe the merits of comparing results from different epidemiological methods that are vulnerable to different hypothesized biases, we adopted a modeling...
strategy that juxtaposed different epidemiological approaches, allowing us to tackle our research questions from several angles.

Evaluating the effectiveness of remediation actions and understanding the factors that contribute to elevated BLLs (EBLLs) are crucial due to the costs associated with cleanup activities and the significant public health concern posed by EBLLs. Focusing on the OLSS allowed us to examine whether one of the largest operations in the history of the Superfund program (U.S. EPA 2018) attained its goals. Literature on the effectiveness of soil remediation actions is sparse, and studies on interventions to mitigate exposure and detrimental health effects have produced mixed findings (Nussbaumer-Streit et al. 2016, 2020; Yeoh et al. 2012, 2008). Our study addresses an important research need by assessing soil-based environmental interventions on children’s BLLs. In addition, our research advances understanding of factors that influence BLLs, potentially guiding future decisions about remediation efforts to protect public health.

Methods
Data Sources and Description

To conduct this study, we linked information from a U.S. EPA database on the SLLs measured between 1999 and 2016 at residential properties in Omaha with blood lead surveillance data from the Douglas County Health Department (DCHD) for the same time period. The study protocol was reviewed and approved by the institutional review board (IRB) of the University of North Carolina at Chapel Hill. Because data were collected by another agency under their informed consent provisions and the risk of a privacy breach was considered extremely minimal, the U.S. EPA requested and received a waiver of informed consent in its entirety from the IRB. A Data Use Agreement between the DCHD and the U.S. EPA allowed a temporary use of the blood lead surveillance data for the time required to conduct the study.

The blood lead collection program was a public health screening effort; it was not designed for evaluating the effectiveness of soil remediation. In conformance with relevant guidelines (Nebraska DHHS 2012; CDC 1997; Council on Environmental Health 2016), blood lead screening using capillary tests was typically conducted in children at 12 and 24 months of age and in children between 36 and 72 months of age if they were not tested at earlier ages. Children residing in Omaha tended to be screened with capillary samples more frequently than children with a lower risk of lead exposure; hence, multiple capillary samples per child were available. Because capillary tests tend to overestimate BLL (Wang et al. 2019), confirmatory venous tests were scheduled when a capillary test showed an EBLL (>10 μg/dL) before 2012 and >5 μg/dL from 2012 to 2016). Children with EBLLs confirmed by venous tests were generally followed using venous tests until their BLLs were no longer elevated, at which point they might have been rescreened periodically using capillary samples. The children with venous samples were likely to include some with false positive elevated capillary BLLs and some whose guardians opted for venous BLLs. In general, BLLs between 5 and 10 μg/dL would be underrepresented in confirmatory venous samples until 2012 when the CDC reference value was lowered to 5 μg/dL.

The DCHD database maintained all capillary and venous blood lead test results, sampling dates, and clinics where the measurement was made, as well as children’s residential addresses at sample collection, their birth dates, sexes, races, and ethnicities (Table 1). Blood samples were analyzed with varying limits of detection (LOD), and we did not have a separate LOD associated with each blood lead measurement. Consequently, we assumed an LOD of 3.3 μg/dL, which was the most common and the highest known LOD in our data set with 74.9% of capillary samples and 43.9% of venous samples below this LOD. We specified two binary outcome variables indicating EBLL, EBLL5, and EBLL10, by dichotomizing blood lead concentrations at thresholds BLL >5 μg/dL and BLL >10 μg/dL, respectively.

Residential soil sampling for lead contamination was performed at the OLSS since 1999 by a variety of different organizations and contractors, all with U.S. EPA oversight and/or funding. Details of the field sampling and analysis methods are part of standard operating procedures described in U.S. EPA (2010). Briefly, yards were divided into quadrants (generally front, back, and two sides) and a “drip zone” that consisted of the area within approximately 3 ft of the house or structure. Multiple soil samples were collected from each quadrant of the yard and from the drip zone. Composite samples representing each of the five areas were analyzed in the field using hand-held X-ray fluorescence (XRF) technology. No fewer than 5% of the samples were sent to a laboratory for confirmation using inductively coupled plasma (ICP) metal analysis. ICP measurements less than 1,000 parts per million (ppm) were 1.16 times greater than the corresponding XRF measurements but the data were well correlated ($r^2 = 0.83$) (U.S. EPA 2010). Soils were air-dried in a controlled environment before sieving to provide bulk samples (particle size < 2 mm) for standard soil lead concentration analyses (U.S. EPA 2009b).

Excavation and replacement actions at the OLSS began in 1999 and continued through 2016, the end of our study period. The approach to soil sampling and remediation, including which properties were prioritized, was documented in the Record of Decision (U.S. EPA 2009a). Briefly, upon agreement of the property owner, soil from quadrants and the drip zone of eligible properties was excavated and replaced. Childcare centers and child-occupied residences where the maximum midyard SLLs (i.e., soil samples > 6 ft from the foundation) exceeded 400 ppm or where a child’s BLL exceeded the CDC reference level (i.e., 10 μg/dL until lowered to 5 μg/dL in 2012) were treated as an immediate threat. Soil excavation and replacement was also initiated to address the most highly contaminated residential properties (i.e., with maximum midyard SLLs exceeding 1,200 ppm) regardless of whether a child resided there. Nonresidential-type properties such as schools, churches, parks, vacant lots in residential neighborhoods, and other noncommercial/industrial properties where exposure could occur were also remediated during this phase of the cleanup action. As cleanups were completed at these highly contaminated properties, the SLLs required to qualify a property for soil excavation and replacement was adjusted downward to 800 ppm in 2005 and to 400 ppm in 2009. Decisions regarding soil sampling priorities during later phases of OLSS cleanup, and in the absence of an immediate threat (i.e., approximately after 2005), were made in collaboration with community stakeholders. The drip zone, even if exceeding 400 ppm, was not remediated unless one of the yard quadrants also exceeded 400 ppm. The U.S. EPA recorded measured SLLs and the dates of soil excavation and replacement. The replacement soil lead concentration (mean 14 ppm) was reported to the U.S. EPA.

We used two approaches to link the U.S. EPA and DCHD databases and assign a SLL to children with BLLs based on their reported address and the date of the BLL. First, we employed ArcMap (version 10.6) to geocode the residential addresses in the blood lead surveillance database so that their longitudes and latitudes could be projected onto the state plane coordinate system used to locate properties in the U.S. EPA database. This approach entailed obtaining a match based on the distance between a property and its geocoded address. For addresses that were not matched using this approach, the address format in multiple hand-entered U.S. EPA data tables was standardized to U.S. postal code norms for abbreviations and numbering and then matched to the address in the blood lead surveillance database.
We identified a set of covariates that are known to be associated with EBLL as potential confounders [i.e., year, season, age, sex, race, socioeconomic status (SES), and the presence of lead-based interior paint in the home] (Egan 2021; Raymond and Brown 2016, 2017; U.S. EPA 2013). Children’s characteristics (date of birth, sex, and race) were reported by the caregiver and recorded with each BLL measurement. Age at each BLL measurement was calculated from date of birth. The other potential confounders, i.e., SES and the likely presence of lead-based paint in the home, were not directly reported with the blood lead surveillance data. To control for these covariates, we derived census tract–level variables for median income and percentage of housing built before 1940, using data from the 2010 American Community Survey (www.census.gov/programs-surveys/acs) and assigned those values to BLLs according to the child’s current address. To evaluate the effect of season in our data and derive appropriate indicator variables, we examined the relationship between EBLL and month of the year of the measurement (see Figure S1). Based on this analysis and observations in the published literature (Raymond and Brown 2016, 2017; U.S. EPA 2013), we defined a binary variable that indicated BLL measurement during the summer months (June–August) to adjust for season. We explored alternative functional forms for the year variable (i.e., categorical with each year as one category, continuous, and continuous using a cubic function). We also considered alternative control for season by specifying month as a categorical variable.
Because our data set was large, comprising BLLs for 74,537 children (Table 1), we did not expect that including covariates that were not demonstrated confounders (i.e., associated with both the outcome and the exposure) in our models would substantially increase variance inflation and thereby reduce the statistical power; hence, we included all aforementioned covariates in our models except race. We omitted race from our main models because it was missing for 58.2% of the children in our study, but we investigated whether that choice influenced our results. Observations with missing data for other model covariates were excluded.

Study Area and Cohort
Omaha, the largest city in Douglas County, encompasses approximately 130 square miles of eastern Nebraska bordering the Missouri River. We defined the study area to include 27 sq miles and 14 postal codes in greater Omaha within Douglas County (Figure 1). The U.S. EPA sampled soils at residential properties and childcare facilities in the OLSS to define a “focus area” for cleanup operations; the final focus area (Figure 1) of approximately 13.8 sq miles was intended to delineate the area where soil concentrations for at least 1 in 20 homes exceeded 400 ppm; however, some residential properties that were outside the focus area boundary were also sampled and determined to be eligible for soil excavation and replacement (U.S. EPA 2009a). We constructed a cohort of children (0–7 y old) who resided within the study area and had one or more blood lead measurements between 1999 and 2016, comprising 165,124 blood samples from 76,537 children (Figure 2).

We created a remediation status variable using the date of the blood draw to indicate whether a blood lead measurement was collected before or after soil was excavated and replaced at the child’s residence. For a child who never moved [i.e., had

Figure 1. Map of the study area with ZIP codes. The focus area, which delineates the area where soil lead concentrations, at least one in 20 properties were above 400 ppm, is indicated as are the former smelter and the properties where soil measurements were available. Where the boundaries of the focus area and study area coincide, the figure shows the focus area boundary. Note that ZIP code 68101 is not shown on the map because it is encompassed by ZIP code 68102.
only one address recorded in the EPA database (79% of children), this variable would take two values: pre- vs. postremediation. If a child moved from a remediated to a nonremediated property, however, the dichotomous classification seemed problematic for measurements at the second residence. In such cases, the blood lead measurements at the second residence would nominally be classified as “preremediation” but could directly follow a measurement classified as postremediation at a previous residence. Whenever a BLL designated “preremediation” was dated after the first postremediation BLL, we opted to change its remediation status to “missing,” thus ensuring that children moving from a remediated property to an unremediated property would not contribute a “preremediation” BLL after a previous postremediation BLL. Such children could contribute postremediation BLLs at properties where they subsequently lived if those properties had recorded remediation dates. Because we lacked information on dates when children changed residences, we could not use the time residing at either residence to inform the classification.

Overall, we excluded 3,410 blood lead samples with “missing” remediation status and 10,877 with missing values for BLL, sample type (i.e., venous or capillary), and/or venous blood samples potentially measured using an instrument with a defective detector (Mason et al. 2019). The final analytic data set contained 150,837 BLLs from 74,537 children residing in the study area, among which 113,923 BLLs came from children residing within the focus area (totals determined from Figure 2). The 44,060 addresses for these children (Table 2) spanned 71 census tracts and 48 school catchment areas; correspondingly, the focus area (totals determined from Figure 2). The 44,060 addresses for these children (Table 2) spanned 71 census tracts and 32 catchment areas.

To accommodate our planned analyses, we considered venous and capillary BLLs together to classify children into three groups based on whether or not they had pre- and/or postremediation blood lead measurements (Figure 2). We defined the “remediation” group as children who had both pre- and postremediation BLLs [i.e., based on addresses reported at sample collection, they had samples taken at a property both before and after its remediation or at one property before its remediation and another property after its remediation (n = 3,279 children, 9,898 capillary samples, 1,385 venous samples)]. The “comparison” group was defined as children who had preremediation blood lead measurements only [i.e., based on the address reported at sample collection, they never had samples collected at any property after its remediation or only lived at properties with no recorded remediation dates (n = 65,144 children, 110,158 capillary samples, 18,369 venous samples)]. We defined the “postremediation-only” group as children who had postremediation blood lead measurements only [i.e., based on the address reported at sample collection, all their samples were collected at properties after their respective remediations (6,114 children, 10,054 capillary samples, 973 venous samples)].

Epidemiological Analyses

To visualize changes in SLL over time, we calculated the daily average SLL at the residences for each group and fitted locally weighted smoothing (LOESS) curves. Using a similar approach for the proportion of EBLL, we calculated children’s capillary EBLL status for each group by the month that the sample was taken and fitted LOESS curves.

For model fitting we used generalized estimating equation (GEE) with an exchangeable correlation structure to account sources of clustering among measurements (e.g., multiple measurements per child, multiple children in the same household, measurements taken at different clinics with different instruments, etc.). We substituted an independent correlation structure. Estimates of regression parameters from GEE models in large data sets are robust to possible misspecification of the correlation structure, though statistical efficiency improves with correct specification (Zeger and Liang 1986); the exchangeable structure was useful for addressing the complex clustering in our data, despite its not capturing every nuance of the underlying correlation structure.
Soil lead levels

Average yard SLL (ppm)

| Soil lead levels | 36,659 Residences | 7,401 Residences |
|------------------|-------------------|------------------|
| Not measured*    | 22,683            | 14               |
| 0–200            | 11,012            | 240              |
| >200–400         | 2,871             | 3,542            |
| >400–800         | 90                | 2,919            |
| >800–1,200       | 2                 | 469              |
| >1,200           | 1                 | 217              |
| Median (min, max) | 126 (15, 1,521)   | 395 (64, 5,802)  |
| Mean ± standard deviation (std) | 140 ± 80 | 481 ± 328 |
| Geomean ± geometric standard deviation (geostd) | 119 ± 2 | 421 ± 2 |

Maximum yard SLL (ppm)

| Soil lead levels | 36,659 Residences | 7,401 Residences |
|------------------|-------------------|------------------|
| Not measured     | 22,683            | 14               |
| 0–200            | 7,591             | 44               |
| >200–400         | 6,037             | 147              |
| >400–800         | 308               | 4,649            |
| >800–1,200       | 27                | 1,430            |
| >1,200           | 13                | 1,118            |
| Median (min, max) | 186 (15, 2,080)   | 652 (77, 16,499) |
| Mean ± std       | 204 ± 124         | 887 ± 873        |
| Geomean ± geostd | 170 ± 2           | 729 ± 2          |

Maximum SLL of yard and drip zone (ppm)

| Soil lead levels | 36,659 Residences | 7,401 Residences |
|------------------|-------------------|------------------|
| Not measured     | 23,262            | 223              |
| 0–200            | 6,697             | 544              |
| >200–400         | 2,592             | 841              |
| >400–800         | 2,162             | 1,814            |
| >800–1,200       | 929               | 1,160            |
| >1,200           | 1,017             | 2,819            |
| Median (min, max) | 201 (11, 54,800)  | 913 (19, 54,219) |
| Mean ± std       | 443 ± 909         | 1,417 ± 1,856    |
| Geomean ± geostd | 216 ± 3           | 880 ± 3          |

Table 2. Residential SLLs at properties included in the study area (N = 44,060), greater Omaha, Nebraska (1999–2016).

| Soil lead levels | 36,659 Residences | 7,401 Residences |
|------------------|-------------------|------------------|
| Not measured*    | 23,297            | 226              |
| 0–200            | 5,182             | 16               |
| >200–400         | 3,984             | 16               |
| >400–800         | 2,237             | 2,424            |
| >800–1,200       | 941               | 1,486            |
| >1,200           | 1,017             | 3,249            |
| Median (min, max) | 269 (20, 54,800)  | 1,100 (331, 54,219) |
| Mean ± std       | 477 ± 904         | 1,635 ± 1,900    |
| Geomean ± geostd | 277 ± 3           | 1,196 ± 2        |

Note: BLL, blood lead level; Geomean, geometric mean; Geostd, geometric standard deviation; max, maximum; min, minimum; ±, plus or minus; ppm, parts per million; SLL, soil lead level.

*U.S. EPA conducted soil sampling with the intent of delineating a “focus area” where 5% of properties had SLLs above 400 ppm. SLLs at many properties may not have been measured if they were outside the focus area (see Table S1), not targeted for SLL measurement in the absence of an immediate threat (or based on homeowner decision), or not matched to a BLL due to incomplete or inaccurate address.

Estimating the Association between SLL and Children’s EBLL

Study samples. To estimate associations between SLLs and children’s EBLL, we used capillary BLLs from all children in the study area (i.e., remediation, comparison, and postremediation-only groups; see Figures 1 and 2) because they were administered to most children regardless of their initial BLLs. Additionally, a large number of capillary measurements, including repeated measurements per child, were available. Our data set included 67,751 children contributing 130,110 capillary BLLs: 61,666 children contributed 115,405 preremediation BLLs, and 8,821 children contributed 14,705 postremediation BLLs. (Note that 3,218 children in the remediation group contributed both preremediation (n = 5,247) and postremediation capillary BLLs [n = 4,651]).

We derived several residential soil lead metrics for each property before and after soil remediation: a) average concentration of the yard quadrants (excluding the drip zone); b) maximum concentration of the yard quadrants (excluding the drip zone); c) drip zone concentration; and d) maximum concentration among yard quadrants and drip zone (Table 2; Table S1). If soil from a yard quadrant was excavated and replaced, we assigned that quadrant a postremediation SLL of 14 ppm, which was the average lead concentration in the backfill soil. The postremediation SLL for the yard was defined as the average of the SLLs across quadrants; quadrants assigned a postremediation SLL of 14 could be averaged with quadrants with measured SLLs that were below 400 ppm and never remediated. Among the children’s addresses recorded from 1999 to 2016 in the DCHD database, 21,363 addresses in the study area were also in the U.S. EPA database and thus could be assigned SLLs and soil remediation dates, whereas 22,697 could not be assigned SLLs and remediation dates (Table 2). Properties in the DCHD database but not in the U.S. EPA database were assumed to have no soil lead measurement or remediation. This situation could arise if an incorrect address has been reported with a child’s BLL or if the soil at a property had not been measured. For example, properties may not have been targeted for soil measurement if they were outside the focus area [as shown in Table S1, fewer properties within the focus area (n = 8,598) were without SLLs]. Properties missing
remediation dates were assumed never remediated. We had no information on the date that child moved into a house or how long they resided at that house. If a property’s SLL was not measured, the property and any BLLs measured on its residents were excluded from our analysis. If a residence had no recorded remediation date in the U.S. EPA database, we assumed that its SLL remained the same over time. We matched BLLs to SLLs based on the SLL of the child’s current residence on the date of blood sampling. For each blood lead observation, we also derived a neighborhood SLL, which was calculated as the mean of average yard SLL, excluding the drip zone, of all residences in an elementary school catchment area on the day when the blood lead sample was collected.

**Modeling strategy.** In our main analysis, we estimated the associations of residential (average of the quadrants in the yard excluding the drip zone) and neighborhood SLLs with EBLL5. We performed separate analyses of preremediation blood samples and postremediation blood samples because we think that the estimates based on preremediation BLLs provide a better estimate of the association between SLL and EBLL5, whereas the postremediation BLLs are more likely to be influenced by behavior and short-term kinetic factors that are dependent on the duration of exposure, which we could not derive from the available data. The preremediation analysis included preremediation samples from the remediation group plus samples from the comparison group (all of which were “preremediation”), whereas the postremediation analysis included postremediation samples from the remediation group plus samples from the postremediation-only group (Figure 2). We conducted sensitivity analyses in which we replaced the average SLL with the maximum SLL (including the drip zone concentration) and restricted the data to BLLs of children residing in the focus area.

We estimated the associations for residential and neighborhood SLLs separately in single-source models. We also included both SLL variables together in a two-source model to understand their relative contributions to EBLL5. We modeled SLL as a continuous variable (log2-transformed) and as a categorical variable (0–200, >200–400, >400–800, >800–1,200, and >1,200, using 0–200 ppm as the reference). The current U.S. EPA guidance recommends a SLL of 400 ppm as a residential screening level (see https://semspub.epa.gov/work/HQ/175347.pdf), which was used at the Omaha site to determine eligibility for soil removal and replacement. The SLL of 200 ppm limits the probability of children’s (age 1–5 y) BLLs exceeding 5 μg/dL to less than 5% based on the U.S. EPA’s Integrated Exposure Uptake Biokinetic (IEUBK) (version 2.0) model (Brown et al. 2021).

Our logistic GEE model for estimating the association between EBLL5 and residential SLL (one-source model) was as follows:

\[
\log \left( \frac{P(\text{EBLL}_{ij})}{1 - P(\text{EBLL}_{ij})} \right) = \beta_0 + \beta_1 \text{RSLL}_{ij} + \beta_2 \text{Year}_{ij} + \beta_3 \text{Season}_{ij} + \sum_{k=1}^{3} \beta_{4k} \text{I}(\text{Age}_k, ij) + \beta_5 \text{Sex}_{ij} + \beta_6 \text{Income}_{ij} + \beta_7 \text{House}_{40j},
\]

(1)

where \(i\) and \(j\) index the child and the repeated observations for each child, respectively; \(\text{RSLL}\) is residential soil lead level (ppm, log2-transformed continuous); \(\text{Year}\) is calendar year (continuous); \(\text{Season}\) is binary (1 for June–August, 0 for other months); \(\text{Age}\) is
categorical [0–1, 2–3, and 4–7 y old (the last as referent)], with \( k \) indexing the three levels respectively; \( \text{Sex} \) is binary (1 for male, 0 for female); \( \text{Income} \) is binary indicating whether the census tract level median household annual income was above $40,000 (= 1) or not (= 0); \( \text{House40} \) is binary indicating whether the census tract of children’s residence had more than half of the houses built before 1940 (= 1) or not (= 0); and \( I(\times) \) is the indicator function. The OR for \( \text{EBLL}_{5} \) per unit increase in \( \text{RSLL} \) is \( e^{b_{1}} \). We also fitted a one-source model using neighborhood \( \text{SLL} \) only and a two-source model that included both residential and neighborhood \( \text{SLL} \) with the same adjustments as in Equation 1.

**Estimating the Association of Soil Remediation with Children’s \( \text{EBLL} \)**

**Study samples.** We restricted our main analysis to children residing in the focus area because soil excavation and removal actions were generally targeted within the focus area. We conducted separate analyses for capillary and venous \( \text{BLLs} \). For our main analyses, we dichotomized capillary \( \text{BLLs} \) using a cut point of 5 \( \mu \text{g/dL} \) and dichotomized venous \( \text{BLLs} \) using a cut point of 10 \( \mu \text{g/dL} \). As noted previously, capillary tests were administered to most children, enabling us to include children regardless of their initial \( \text{BLLs} \) [i.e., 9,050 capillary \( \text{BLLs} \) from 3,135 children in the “remediation” group; 70,532 capillary \( \text{BLLs} \) from 38,667 children in the comparison group; and 9,910 capillary \( \text{BLLs} \) from 5,774 children in the postremediation-only group (Figure 2)]. Venous \( \text{BLL} \) measurements, however, were typically conducted in children with capillary \( \text{BLLs} \) greater than CDC reference levels; therefore, the pool of children with venous measurements tended to include the most highly exposed children, and confirmatory venous samples for capillary \( \text{BLLs} \) between 5 and 10 \( \mu \text{g/dL} \) were likely to be rare before 2012 when the CDC lowered the reference value to 5 \( \mu \text{g/dL} \). There were 1,255 venous \( \text{BLLs} \) from 551 children in the remediation group; 12,685 venous \( \text{BLLs} \) from 9,211 children in the comparison group; and 960 venous \( \text{BLLs} \) from 593 children in the postremediation-only group (Figure 2).

**Modeling strategy.** We used two approaches to investigate the effect of soil remediation on children’s blood lead. The first approach was directed primarily at comparing pre- vs. postremediation \( \text{EBLL} \) among children in the remediation group. In addition, we included comparisons involving the comparison and the postremediation groups. This analysis used a four-category exposure variable: comparison group (all measurements from comparison-group children), preremediation measurements from remediation-group children, postremediation measurements from remediation-group children, postremediation-only group (all measurements from postremediation-only group children). We hypothesize that odds of postremediation \( \text{EBLL} \) will be lower than the odds of preremediation \( \text{EBLL} \) for the remediation group children and that the odds of comparison-group \( \text{EBLL} \) and the odds of postremediation-only group \( \text{EBLL} \) will each be lower than the odds of postremediation \( \text{EBLL} \) in the remediation group because both comparison-group and postremediation-only group children generally lived at properties with residential \( \text{SLLs} \) below the threshold for remediation. In this approach, pre- vs. postremediation contrasts may confound a temporal trend toward lower \( \text{EBLLs} \) with any effect of soil remediation.

Our second approach was designed to separate the component of the association due to temporal trend from potential effects due to soil remediation by comparing the OR of \( \text{EBLL} \) between pre-
and postremediation measurements among children in the remediation group vs. OR of EBLL between early and late measurements among children in the comparison group. Our analysis has the spirit of, but differs in detail from, a typical difference-in-differences (DiD) analysis because our available data were incompatible with the usual analysis. In a typical DiD analysis, the intervention is applied to all members of the treated group during the same circumscribed calendar period; then, the difference in mean outcome in the untreated group before and after the same calendar period is estimated for various sources of correlation among samples and children. The single-source models were adjusted for child [sex (female or male), census tract level median income ($\geq $40,000 per year or not), and census tract level percent house built before 1940 ($\geq$50% or not) and characteristics that varied within child depending on the observation [year (continuous), season (June–August or other), age (0–1, 2–3, or 4–7 y)].

The two-source model included both the residential SLL and the neighborhood SLL plus the covariates included in the single-source models.

and three categories for remediated properties corresponding to the time periods when they became eligible for remediation, namely, 1999–2004, 2005–2009, and 2009 onward). Remediation phase was assigned to a BLL according to the house remediation phase (2004, 2005, and 2009 onward).

**Table 3.** Associations between categorical or continuous (log$_2$-transformed) average SLLs and elevated BLL (>5 µg/dL); associations were estimated separately using preremediation (n = 115,405) and postremediation (n = 14,701) capillary BLLs of children residing at properties within the study area where SLL was measured, greater Omaha, Nebraska (1999–2016).

| Exposure                          | Preremediation BLLs | Postremediation BLLs |
|-----------------------------------|---------------------|----------------------|
|                                   | n $\geq$ 5 µg/dL/n < 5 µg/dL | OR (95% CI)          | n $\geq$ 5 µg/dL/n < 5 µg/dL | OR (95% CI)          |
| Category                          | Referent            | —                    |Category | Referent | —         |
| Single-source models$^{b}$        |                      |                      |          |          |
| Residential SLL (ppm)             |                      |                      |          |          |
| 200–400 vs. 0–200                 | 2,701/13,635         | 3,433/34,629         | 1.60 (1.50, 1.70) | 202/1,583 | 1,430/11,486 | 1.03 (0.85, 1.24) |
| 400–800 vs. 0–200                 | 1,081/5,081          | 3,433/34,629         | 2.00 (1.83, 2.19) | NA      | NA         | NA         |
| 800–1,200 vs. 0–200               | 164/525              | 3,433/34,629         | 2.23 (1.80, 2.76) | NA      | NA         | NA         |
| Continuous (log$_2$)              | 52/127               | 3,433/34,629         | 1.89 (1.33, 2.70) | NA      | NA         | NA         |
| Continuous (log$_2$)              | NA                  | NA                   | 1.36 (1.32, 1.40) | NA      | NA         | 1.01 (0.96, 1.06) |
| Neighborhood SLL (ppm)            |                      |                      |          |          |
| 200–400 vs. 0–200                 | 5,361/21,640         | 5,906/80,379         | 1.59 (1.50, 1.68) | 626/1,758 | 999/11,302 | 1.70 (1.42, 2.05) |
| 400–800 vs. 0–200                 | 443/3,101            | 5,906/80,379         | 1.85 (1.62, 2.11) | 8/12    | 999/11,302 | 1.56 (0.58, 4.19) |
| Continuous (log$_2$)              | NA                  | NA                   | 1.41 (1.35, 1.48) | NA      | NA         | 2.20 (1.60, 3.03) |
| Two-source model$^{a}$             |                      |                      |          |          |
| Residential SLL (ppm)             |                      |                      |          |          |
| 200–400 vs. 0–200                 | 2,701/13,635         | 3,433/34,629         | 1.55 (1.46, 1.66) | 202/1,583 | 1,430/11,486 | 1.03 (0.86, 1.24) |
| 400–800 vs. 0–200                 | 1,081/5,081          | 3,433/34,629         | 1.91 (1.74, 2.10) | NA      | NA         | NA         |
| 800–1,200 vs. 0–200               | 164/525              | 3,433/34,629         | 2.11 (1.70, 2.62) | NA      | NA         | NA         |
| Continuous (log$_2$)              | 52/127               | 3,433/34,629         | 1.79 (1.25, 2.56) | NA      | NA         | NA         |
| Neighborhood SLL (ppm)            |                      |                      |          |          |
| 200–400 vs. 0–200                 | 4,091/15,474         | 3,032/35,734         | 1.25 (1.16, 1.35) | 625/1,757 | 999/11,300 | 1.70 (1.41, 2.04) |
| 400–800 vs. 0–200                 | 306/589              | 3,032/35,734         | 1.30 (1.09, 1.55) | 8/12    | 999/11,300 | 1.56 (0.58, 4.20) |
| Continuous (log$_2$)              | NA                  | NA                   | 1.35 (1.31, 1.39) | NA      | NA         | 1.02 (0.97, 1.08) |
| Residential yard SLL              |                      |                      |          |          |
| Neighborhood SLL                  |                      |                      |          |          |
| NA                                | NA                  | NA                   | 1.05 (0.97, 1.13) | NA      | NA         | 2.23 (1.61, 3.08) |

Note: Measured SLLs were used to determine the preremediation residential SLL by averaging across yard quadrants. Neighborhood SLL was estimated by averaging the average SLLs of residences within the elementary catchment area on the day of the BLL measurement. The total number of observations for each model are as follows: a) single-source residential SLL, n = 59,226 (preremediation BLLs) and n = 14,701 (postremediation BLLs); b) single-source neighborhood SLL, n = 144,739 (preremediation BLLs) and n = 14,705; c) Two-source residential SLL, n = 59,226 (preremediation) and n = 14,701 (postremediation BLLs). —, no data; BLL, blood lead level; CI, confidence interval; NA, not applicable (i.e., average residential yard soil concentrations are not above 400 ppm following remediation actions); OR, odds ratio; ppm, parts per million; SLL, soil lead level.

*Remediated yard quadrants were assigned a SLL of 14 ppm, and the residential SLL was determined by averaging across yard quadrants, including yard quadrants where soil was measured but never remediated because the quadrant had an average SLL $<400$ ppm.

A generalized estimating equation (GEE) was used to account for various sources of correlation among samples and children. The single-source models were adjusted for child [sex (female or male), census tract level median income ($\geq$40,000 per year or not), and census tract level percent house built before 1940 ($\geq$50% or not) and characteristics that varied within child depending on the observation [year (continuous), season (June–August or other), age (0–1, 2–3, or 4–7 y)].

The two-source model included both the residential SLL and the neighborhood SLL plus the covariates included in the single-source models.

The logistic GEE model for analyzing the association of remediation status with EBLL was as follows:

$$
\log \left( \frac{P(EBLL_{ij})}{1 - P(EBLL_{ij})} \right) = \beta_0 + \sum_{k=1}^{4} \beta_{1,k} I(E_{ik,ij}) + \beta_2 Year_{ij} + \beta_3 Sex_{ij} + \sum_{k=1}^{3} \beta_{4,k} I(Year_{ij}) + \beta_5 Age_{ij} + \beta_6 Income_{ij} + \beta_8 House_{ij,40},
$$

where k indexes the levels of any categorical predictor; E has four categories as described earlier; remediation phase as described earlier has four categories; and all other variables are defined following Equation 1. The ORs for comparisons of EBLL among exposure categories, conditioning on covariates, were calculated by exponentiating contrasts among the $\{\beta_{1,k}\}$. 

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Table 4. Percentage of capillary BLLs greater than 5 μg/dL by children’s characteristics for 9,050 BLLS among 3,135 children in the remediation group (i.e., children who had both pre- and postremediation blood lead measurements), 70,532 BLLS among 38,667 children in the comparison group (i.e., children who had only preremediation blood lead measurements), and 9,910 BLLS among 5,774 children in the post-only group. All children reside within the focus area, greater Omaha, Nebraska (1999–2016). The focus area boundary delineates the area where 1 in 20 properties are expected to have soil lead levels that exceed 400 ppm.

| Remediating group | EBLL preremediation | EBLL postremediation | Comparison group | Post-only group |
|-------------------|----------------------|--------------------|----------------|----------------|
| Overall           | EBLL (n) BLL (n)     | Percent            | EBLL (n) BLL (n) | Percent         |
| Overall           | 852 4,509 18.9       | 507 4,541 11.2     | 8,237 70,532 11.7 | 1,102 9,910 11.1 |
| By age (y)        |                      |                    |                |                 |
| 0–1               | 433 2,204 19.6       | 31 128 24.2        | 2,759 22,022 12.5 | 521 3,924 13.3 |
| 2–3               | 340 1,841 18.5       | 243 1,703 14.3     | 3,169 25,420 12.4 | 388 3,479 11.2 |
| 4–7               | 79 464 17.0          | 233 2,710 8.6      | 2,309 2,390 10.0  | 193 2,507 7.7  |
| By sex            |                      |                    |                |                 |
| Female            | 402 2,185 18.4       | 219 2,203 9.9      | 3,706 34,594 10.7 | 507 4,850 10.5 |
| Male              | 450 2,324 19.4       | 288 2,338 12.3     | 4,531 35,938 12.6 | 595 5,060 11.8 |
| By race           |                      |                    |                |                 |
| Black             | 161 538 29.9         | 94 525 17.9        | 1,647 9,743 16.9 | 198 733 27.0  |
| White             | 488 2,160 22.6       | 270 2,003 13.4     | 3,375 24,405 13.8 | 398 3,077 12.9 |
| Other             | 24 101 23.8          | 23 89 25.8         | 461 2,624 17.6   | 57 221 25.8   |
| Unknown           | 179 1,710 10.5       | 120 1,924 6.2      | 2,754 33,760 8.2 | 449 5,879 7.6  |
| By season         |                      |                    |                |                 |
| June–August       | 272 1,180 23.1       | 176 1,389 12.7     | 2,945 20,165 14.6 | 341 2,610 13.0 |
| Other months      | 580 3,329 17.4       | 331 3,152 10.5     | 5,292 50,367 10.5 | 761 7,300 10.4 |
| By remediation phase of the property where the blood lead sample was collected | | | | |
| 1999–2004 (≥1,200 ppm) | 102 158 64.6 | 132 521 25.3 | 234 482 48.5 | 281 1,423 19.7 |
| 2005–2009 (≥800 ppm) | 270 787 34.3 | 263 2,222 11.8 | 1,000 3,536 28.2 | 553 5,165 10.7 |
| 2010–2017 (≥400 ppm) | 128 1,019 12.6 | 112 798 6.2 | 826 5,169 16.0 | 268 3,322 8.1 |
| Never eligible (<400 ppm) | 352 2,545 13.8 | NA — — | 6,177 61,345 10.1 | NA — — |
| By census tract median income (SUSD) | | | | |
| 0–40,000 | 715 3,421 20.9 | 445 3,656 12.2 | 6,482 48,783 13.3 | 961 7,846 12.2 |
| ≥40,000 | 137 1,088 12.6 | 62 885 7.0 | 1,755 21,749 8.1 | 141 2064 6.8 |
| By census tract percent house built before 1940 | | | | |
| 0%–50% | 234 1,239 18.9 | 105 951 11.0 | 2,763 28,695 9.6 | 279 2,182 12.8 |
| ≥50% | 618 3,270 18.9 | 402 3,590 11.2 | 5,474 41,837 13.1 | 823 7,728 10.6 |

Note: —, no data; NA, not applicable; EBLL, blood lead level; EBLL, elevated blood lead level; % EBLL, percentage elevated blood lead level greater than 5 μg/dL; SLL, soil lead level.

*Remediation phase refers to time periods associated with a particular SLL required for a property to be eligible for remediation.

Interaction Analysis to Adjust Association with Remediation for Temporal Trend

For this analysis, we used essentially the same model structure as that of Equation 2, although the data and the meaning of some terms changed. We no longer included the postexposure-only group, and we split the comparison group into pre- and postremediation subgroups based on the median date of remediation among remediated properties. We used a different four-category exposure variable: preremediation measurements in the remediation group, postremediation measurements in the remediation group, comparison group measurements taken before the median date when remediations occurred, and comparison group measurements taken after that median date. Explicitly, the term \( \sum_{i=1}^{k} | 1_{x_i}I(E_{i,k}) \) involved a different set of exposure categories than it did in the previous evaluation. Estimates of interest were calculated by exponentiating contrasts among the \( \{b_{1,k}\} \); in particular, the interaction estimate, a ratio of ORs, involved exponentiating the prepost difference in the remediation group versus the pre-post difference in the comparison group.

All analyses were conducted using SAS (version 9.4; SAS Institute, Inc.).

Results

After excluding missing and potentially inaccurate venous blood lead data, BLLS for 74,537 children who lived in the study area from 1999 to 2016 were available for our analyses (Figure 2). The BLLS comprised 130,110 capillary and 20,727 venous measurements (n = 150,837 total). Most children (59%) were 0–1 y old at their first blood lead measurement (Table 1). The children were approximately balanced with regard to sex. Race was missing for most children (58.2%), whereas 25.8% of caregivers reported their child was White and 12.5% reported that their child was Black. Most children (62.3%) lived in census tracts where the median income was less than $40,000 per year, and more than half of the children (54.8%) lived in census tracts where less than half of the housing was built before 1940. A large proportion of children (44.3%) had multiple capillary BLL measurements, whereas a much smaller proportion of children (4.3%) had multiple venous BLL measurements (Table 1: Table S2). Although the proportions for most variables remained constant, the proportion of Black race reported by the caregiver and the number of venous measurements per child declined over time.

The study area contained 44,060 residences (Table 2). Among the properties that were not remediated, 22,683 (61.9%) lacked SLLS. Soil was remediated at 7,401 (16.8%) residences in the study area; among those, at most 226 (3.1%) were missing some SLL metric—primarily drip zone—but only 14 (0.2%) were missing average yard SLL (Table 2). Overall, SLLS were not measured at approximately half (51.5%) of the properties for which BLLS were available. SLLS at some of these properties were not measured because they were outside the focus area or because they were not targeted for sampling, whereas other properties may not have been matched to a BLL observation due to an incomplete or inaccurate address. Relatively few properties were remediated between 1999 and 2004 [n = 711 (9.6%)], whereas the number of remediations substantially increased between 2005 and 2009 [3,135 (42.4%)] and between 2010 and 2016 [n = 3,555 (48.0%)]. SLLS were relatively high before remediation and were substantially reduced afterward [Table 2 and Table S1 (focus area only)].

The proportion of elevated BLLS (defined as capillary BLL >5 μg/dL) for children, and SLLS within the focus area declined...
through the study period (Figures 3 and 4; Tables S3 and S4). A relatively large proportion of children in the remediation group had elevated BLLs at the beginning of the study period. This group experienced a steeper decline in the proportion of elevated BLLs in comparison with the comparison group residing in the focus area and the comparison group residing outside the focus area. Specifically, the proportion of elevated BLL declined from approximately 76% in 1999 to 6% in 2016 for the remediation group residing within the focus area, and it declined from 31% in 1999 to <5% in 2016 for the comparison group. We also observed a seasonal trend, where the proportion of elevated BLLs was higher during warm months (June–August) in comparison with cooler months in each of the groups (Figure S1).

**Estimated Associations between SLLs and Children’s EBLL**

In single-source models for preremediation BLLs, residential and neighborhood SLLs were each positively associated with children’s elevated BLL (Table 3; Tables S5 and S6). In two-source models with preremediation BLLs, ORs for the association of residential SLL with EBLL remained essentially unchanged from the single-source model, whereas ORs for neighborhood SLLs were closer to the null; in particular, the OR for continuous neighborhood SLL was essentially null.

Postremediation residential SLLs were not associated with EBLL, with ORs of approximately 1.0 before and after adjusting for neighborhood SLLs (Table 3). In contrast, postremediation neighborhood SLLs were positively associated with EBLL. We observed similar results when residential SLLs were based on the maximum of yard and drip zone SLLs (Table S5) and when the analysis was restricted to the focus area (Table S6).

In analyses to explore alternatives to the functional forms for the year and season adjustments, we found that our results were insensitive to the particular form (Table S7). Similarly, these results did not change substantially when race was included in the model (Table S8).

**Estimated Association of Soil Remediation with Children’s EBLLs**

Based on capillary measurements from the focus area, the observed proportion of EBLL\(_{10}\) for children in the remediation group was lower after remediation in comparison with the proportion before remediation (Table 4). The proportion of elevated BLLs was also lower in 70,532 samples from the comparison group (11.7% of EBLL\(_{10}\)) compared with 4,509 preremediation samples from the remediation group (18.9% of EBLL\(_{10}\)) (Table 4). The lower proportion of postremediation EBLL held overall and for each covariate level except the 0–1 y age category, possibly because children exited the age group before having a postremediation measurement (i.e., there are only 128 postremediation but 2,204 preremediation samples). We also found that the proportion of EBLL\(_{10}\) was higher among those blood samples collected from children living at properties that were remediated during earlier phases in comparison with those remediated more recently. This observation likely reflects the cleanup procedure that targeted children with an EBLL >10 µg/dL and the most contaminated properties first. We observed broadly similar patterns, though the observed proportions differed, when we raised the threshold for EBLL to 10 µg/dL for capillary samples (Table S9).

The percentage of venous EBLL\(_{10}\) was higher before remediation (42.8% of 725 BLLs) than after remediation considering the postremediation group (31.9% of 530 BLLs) and post-only group (24.6% of 960 BLLs) (Table 5). The lowest percentage of venous EBLL\(_{10}\) was found in the comparison group (12.25 of 1,548 BLLs). Similar to the pattern of capillary EBLL\(_{10}\), the percentage of venous EBLL\(_{10}\) changed with children’s characteristics and was generally lower after remediation in the remediation group (Table 5). The percentage of EBLL\(_{10}\) was higher among the 2- to 3-y-old children across all groups. Higher percentages of EBLL\(_{10}\) among males, Black children, and in the summer months that are expected based on the literature were observed for preremediation measurements in the remediation group but were not seen consistently across groups. We saw generally similar patterns with the lower threshold of 5 µg/dL applied to venous samples (Table S10).

In our regression analyses of the association between elevated BLL and remediation status, soil remediation was associated with reduced BLLs in children. The odds of EBLL in the remediation group were higher in samples collected before vs. after remediation, resulting in positive associations between EBLL and preremediation status for capillary samples (Table 6). The odds of EBLL were also higher in samples collected after remediation in the remediation group vs. samples collected in the comparison group. This finding held for ORs comparing samples from children in the post-only group to the samples from children in the comparison group. As expected, the odds of EBLL in the postremediation-only samples were approximately the same as the odds of EBLL in the postremediation group samples. For venous samples and a threshold of 10 µg/dL, we saw a similar pattern of associations, although the estimated ORs were larger in magnitude (Table 6). When we changed the thresholds for both sample types, patterns were again similar (Table S11).

In our interaction analyses, soil remediation was associated with lower BLLs, and the reduction was greater than would be expected based only on the general reduction in EBLL over time. When we partitioned comparison-group BLLs into those before and after the median date of remediation among properties that underwent remediation (i.e., 19 June 2009), the proportion of EBLLs before that date exceeded the proportion after that date both for capillary samples using the 5 µg/dL threshold and for venous samples using the 10 µg/dL threshold (Table 7). In our interaction models, for children residing within the focus area, using either capillary and or venous samples and the respective thresholds, the interaction OR, namely, the pre- vs. postremediation OR for EBLL in the remediation group divided by the comparable OR in the comparison group indicated a larger postremediation reduction in elevated BLL for the remediation group (Table 8). We had similar findings for the capillary samples with the threshold for EBLL increased to 10 µg/dL, although the ORs were somewhat larger (Tables S12 and S13). For venous samples with the lower threshold of 5 µg/dL, the results in the comparison group changed. The OR comparing the EBLL\(_{10}\) using pre-2009 venous samples in the comparison group to EBLL\(_{10}\) using post-2009 samples in the comparison group was less than one, indicating a lower odds of elevated BLL in the earlier years of the study (Table S13).

Results of our regression analyses of the association between elevated BLL and remediation status were not sensitive to alternative specification of year or season (Table S7). Similarly, the associations we report between remediation status and EBLL did not change substantially when race was included in the model (Tables S14 and S15).

**Discussion**

We examined the association between SLL and EBLL and the association between soil remediation and EBLL in children living near a former lead smelter. Consistent with prior studies (Egan 2021; Raymond and Brown 2016, 2017; U.S. EPA 2013), we found that proportion of EBLL was generally higher in males than in females and in June–August than in other months. The proportion of EBLL was higher in the lower income category in
the percentage of housing built before 1940. This trend reflects over the past decades due to various policies on lead reduction in the United States. Although lead-based paint has been a significant source of lead exposure, remediation on BLLs from the environment is ongoing. For example, in Omaha, Nebraska (1999–2016), the focus area boundary delineates the area where 1 in 20 properties are expected to have soil lead levels that exceed 400 ppm.

Table 5. Percentage of venous BLLs greater than 10 μg/dL by children’s characteristics for 1,255 BLLs among 551 children in the remediation group (i.e., children who had both pre- and postremediation blood lead measurements), 12,685 BLLs among 9,211 children in the comparison group (i.e., children who had only preremediation blood lead measurements), and 960 BLL among 593 children in the post-only group. All children reside within the focus area, greater Omaha, Nebraska (1999–2016). The focus area boundary delineates the area where 1 in 20 properties are expected to have soil lead levels that exceed 400 ppm.

Table 6. Estimated odds ratios (95% CI) for elevated BLL using capillary (EBLL5) and venous (EBLL10) measurements separately from children within the focus area, Omaha, Nebraska (1999–2016).

Note: BLL, blood lead level; CI, confidence interval; EBLL, elevated blood lead level greater than 10 μg/dL; SLL, soil lead level. *Remediation phase refers to time periods associated with a particular SLL required for a property to be eligible for remediation.

these data (Tables 4 and 5). Although this finding has been reported in previous studies (Pirkle et al. 1994), on a national level, the difference in BLLs reported between different income levels has been decreasing (U.S. EPA 2013). Although 2- to 3-year-old children typically have higher BLLs (Egan et al. 2021), we found a higher percentage of elevated capillary BLLs in the 0–1 year age group (Table 4).

Because BLLs of the U.S. population have been declining over the past decades due to various policies on lead reduction in the environment (Council on Environmental Health 2016), one of our key challenges was to differentiate the effect of soil lead and remediation on BLLs from the effects of other policies and interventions that occurred over time. A strength of our study was that we had information on the dates of the blood lead measurements and soil remediation that allowed us to employ two analytical strategies to control, at least in part, for temporal trends. Another strength of our study was its large sample size (n = 74,577 children aged 0–7 years) and information on the children’s addresses at the time of the blood draws, which we used to derive variables to indicate neighborhood-level SES and the presence of lead-based paint in the home.

We found that EBLL was associated with SLL, that the risk of EBLL generally increased with increasing SLL before remediation, and that the rate of increase decreased at higher concentrations (Table 3), though exposure misclassification of SLLs may have attenuated these observed associations. Our analyses...

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suggested important roles for both the residential SLL and neighborhood SLL in predicting EBLL, with neighborhood SLL becoming more influential following remediation. We hypothesize that the observed greater importance of neighborhood SLL after remediation was influenced by behavior, i.e., efforts to educate that accompanied remediation would improve parents’ ability to prevent exposure in their children. Our analysis of the association between EBLL and remediation status supported the conclusion that soil remediation is associated with reduced BLLs in children at the OLSS (Table 6; Table S11). Our interaction analysis further substantiated that the lower BLL that was associated with remediation was greater than what would be expected due to the general temporal decline in BLLs (Table 8; Table S13).

A small number of studies have employed similar methods to examine the association between SLL and children’s BLL (Lanphear et al. 1998; Lewin et al. 1999; von Lindern et al. 2003; Mielke et al. 2007; Zahran et al. 2011; Gulson et al. 2009; Mielke et al. 2019), including one study conducted in Omaha (Angle and McIntire 1979). Consistent with our findings, these studies generally report an increase in BLL with increasing soil concentrations. The quantitative results from the study of the SLL and BLL in Omaha (Angle and McIntire 1979) and other earlier studies may not inform the current relationship between soil lead concentration and BLL at the OLSS, however, because the relationship between lead concentrations in environmental media and BLLs has changed as lead concentrations have declined (U.S. EPA 2013; Richmond-Bryant et al. 2013; Richmond-Bryant et al. 2014). Nonetheless, observations from previous studies are useful to contextualize our findings. For example, Lanphear et al. (1998) reported that floor dust lead loading and soil lead concentration were the most significant predictors of BLLs in children 6 months to 3 y old. Child’s age, mouthing behaviors, and race were also significant predictors in that analysis. Lewin et al. (1999) and von Lindern et al. (2003) reported increases in BLL with increasing soil concentrations at Superfund sites. In a study of the decline in BLLs in New Orleans, Louisiana, following Hurricane Katrina and the blood lead reductions in children during the same period, Mielke et al. (2019) reported that the reductions in census tract–level BLLs from 99 ppm in 2001 to 54 ppm in 2017 influenced the concurrent decline in median BLL from 3.6 to 1.3 μg/dL. This finding is consistent with our analysis showing the importance of neighborhood SLL, calculated as the average of residential SLLs across the elementary school catchment area, on pre- and postremediation BLLs.
The association between living near a source of lead exposure such as a smelter and elevated BLLs is well documented (U.S. EPA 2013). We identified only a handful of studies examining the effectiveness of interventions to reduce exposure from contaminated soil on reducing BLLs, however. Yeoh et al. (2008) conducted a systematic review and meta-analysis of randomized controlled trials (RCTs) and quasi-RCTs, which was subsequently updated (Yeoh et al. 2014; Nussbaumer-Streit et al. 2016; Nussbaumer-Streit et al. 2020). The studies included in the review were conducted to evaluate the effectiveness interventions including dust control actions, such as soil excavation and replacement, that were intended reduce children’s BLLs. Overall, these reviews found no statistical evidence that these interventions were effective in reducing children’s BLL. The authors also noted that the evidence specifically pertaining to the effect of soil remediation was limited to two studies reporting contradictory findings (Weitzman et al. 1993; Farrell et al. 1998). The authors also found that the current evidence was insufficient to clarify whether a combination of interventions reduces BLLs.

The effectiveness of soil excavation and replacement actions likely depends on whether ongoing sources of contamination or recontamination are present (Bowers et al. 2014). In a cross-sectional analysis that was not included in the aforementioned systematic review, Lanphear et al. (2003) described a faster decline in BLL among children (6 months to 6 y old) who lived in residences where soil was removed and replaced in comparison with children who lived in housing where lead-contaminated soil was not remediated. The von Lindern et al. (2003) study, also observational, used mixed-effects models to assess the soil cleanup effort at the BHSS and reported a large reduction in a typical 2-y-old child’s mean BLL, i.e., 7.5 μg/dL over the course of the 10-y cleanup. Klemick et al. (2020) used a DiD model to compare the change in the risk of elevated BLL among children living closer vs. farther from lead-contaminated Superfund sites before, during, and after cleanup actions. These authors found that Superfund cleanups reduced the risk of elevated BLL by 13% to 26% among children in their study. In contrast, a study of children living in Philadelphia neighborhoods found that lead in floor dust was associated with children’s BLL, but proximity to lead-emitting industries was not (Dignam et al. 2019).

Some covariate information in our data set was lacking or incomplete. We opted to drop the race variable from our models because it was missing for more than half of the children in our study. We evaluated the impact of this decision by comparing our results with and without including race and found that the overall pattern of results, considering magnitude and direction, were similar across models (Tables S8, S14, and S15). Most housing in our study (98%) was built before 1978, when interior lead-based paint was widely used. We created a variable to indicate the proportion of housing built before 1940 within a census tract, which has been demonstrated to be a predictor of lead paint exposure (Klemick et al. 2020); based on a representative sample of U.S. housing units, a relatively large proportion (68%) of units built before 1940 have significant lead hazards from interior paint and dust (Jacobs et al. 2002). Despite the predictive ability of this variable, we recognize that it does not capture the behaviors, extent of interior lead paint damage, or lead paint abatement activities that together ultimately determine exposure in young children. Although the U.S. EPA database included some information on indoor dust lead loadings, on paint assessment and stabilization, and whether a high-efficiency particulate air (HEPA) vacuum was provided to the residents, the incompleteness of these data precluded analysis of the association between indoor dust lead and BLLs. Lead from soil can infiltrate indoors combining with house dust, which may be composed of lead from multiple sources, including paint and consumer products. Exposure to soil lead depends on activity patterns and the age of the child; i.e., very young children are exposed to relatively more indoor house dust, whereas older, more mobile children may be exposed to soil lead directly in their yards and neighborhoods (U.S. EPA 2013). In addition, children exhibiting pica behaviors may ingest more lead than others at a given BLL. The U.S. EPA (2009a), however, reported that, “the percent of lead from soil [contributing to indoor dust] is not a constant but may range from less than 50% when soil levels are low [≤60 ppm] to over 90% when soil levels are high [≥500 ppm].” This evidence generally indicates that soil was the dominant source of lead exposure at the OLSS before remediation. At low postremediation BLLs, the contribution of lead-based paint to indoor dust lead at the OLSS may equal or exceed the contribution of soil to dust lead. However, based on Figure F-11 of the U.S. EPA (2009b) report, just over 10% of homes with yard BLL of <500 ppm had indoor dust lead concentrations of ≥750 ppm. This statistic suggests that other sources such as lead-based paint were dominate sources of indoor dust lead even before in remediation some homes.

Another challenge in estimating the association between EBLL and BLL was that not all properties that were linked to a child’s BLL had a corresponding SLL. Because properties without SLLs were dropped from the analyses, our inferences about the association between EBLL and BLL are applicable only to properties that met criteria for receiving soil measurements. Nevertheless, the U.S. EPA’s faceted approach of working in collaboration with the DCHD, media sources, and even local physicians was developed to assure the successful identification of at-risk children; thus,

Table 8. Estimated interaction ORs (95% CIs) for elevated BLL using capillary (EBLL5) and venous (EBLL10) measurements separately for children within the focus area, Omaha, Nebraska (1999–2016).

| Sample type | Contrast | Pre | Post | OR (95% CI) |
|-------------|----------|-----|------|------------|
| Capillary<sup>a</sup> | Threshold = 5 μg/dL, n = 79,582 | Interaction<sup>b</sup> | Pre vs. post in the remediation group | 852/3,657 | 5074/034 | 1.69 (1.49, 1.92) |
| Capillary<sup>a</sup> | Threshold = 5 μg/dL, n = 79,582 | Interaction<sup>b</sup> | Pre vs. post in the comparison group | 6,171/29,524 | 1,666/32,771 | 1.44 (1.31, 1.57) |
| Venous<sup>b</sup> | Threshold = 10 μg/dL, n = 13,940 | Interaction<sup>b</sup> | Pre vs. post in the remediation group | 310/415 | 169/361 | 1.88 (1.24, 2.84) |
| Venous<sup>b</sup> | Threshold = 10 μg/dL, n = 13,940 | Interaction<sup>b</sup> | Pre vs. post in the comparison group | 1,149/2,499 | 169/888 | 1.04 (0.62, 1.76) |

Note: BLL, blood lead level; CI, confidence interval; EBLL, elevated blood lead level; EBLL<sup>≥5</sup>, BLL ≥ 5 μg/dL; EBLL<sup>≥10</sup>, BLL ≥ 10 μg/dL; GEE, generalized estimating equation; NA, not applicable; OR, odds ratio.

<sup>a</sup>GEE models used exchangeable correlation structure adjusted for year, season, age, sex, remediation phase, census tract level median income, census tract level percentage housing built before 1940.

<sup>b</sup>GEE models for venous samples used the independent correlation structure adjusted for year, season, age, sex, remediation phase, census tract level median income, census tract level percentage of housing built before 1940.

<sup>c</sup>Interaction OR may be regarded as assessing the association of EBLL with remediation after adjusting for temporal trend; interaction ORs >1 imply preremediation proportion of EBLL is greater than the postremediation proportion.
Inference based on our study population is relevant for informing policy decisions to assure protection of children at Superfund sites. A related issue stems from the fact that properties were not selected for soil excavation and replacement at random; instead, priority was given to properties with the highest SLLs and/or with resident children showing elevated BLL. Bias could be introduced because children compared with one another might be differentially selected based on preremediation soil lead and BLLs. To answer our primary research question (i.e., was remediation associated with lowered BLLs), we compared pre- and postremediation elevated BLLs on children in the remediation group; children in the comparison group tended to live farther from former smelter and likely differed from those in the remediation group. Accordingly, we also compared the odds of elevated BLL among postmediation samples in the remediation group to corresponding odds in the comparison group (Table 6). The OR for this contrast was positive for both venous and capillary samples, although the association using venous samples was larger in magnitude. This finding indicated that the odds of EBLL in postremediation samples among children in the remediation group may not decline to meet the odds among children in the comparison group and was consistent with our understanding that lead is stored in bone and may be released to the blood in the absence of ongoing exposure. The contrasts involving the post-only group indicated that children who lived only in remediated housing had odds of elevated BLL similar to those of children who lived in both unremediated and remediated housing after remediation but higher odds than those of children in the comparison group. We did not have data on duration of residence in the home (i.e., proxy for exposure duration) that would allow us to explore these findings in the context of the predicted decline in BLL after exposure ceases.

In an effort to better separate temporal trends unrelated to remediation from the influence of remediation itself, we proposed an analysis that, like a DiD analysis, examines an interaction contrast; but our analysis is not a true DiD and should not be interpreted as implying causal associations or as offering protection from unmeasured confounding. Unlike typical DiD data sets, the intervention was distributed over calendar time among subjects in the remediation group. Because we saw no obvious way to mimic that distribution closely among comparison group children, we opted to apply a single temporal cut point, set at the median date of remediation from the in-home (i.e., proxy for exposure duration) that would allow us to explore these findings in the context of the predicted decline in BLL after exposure ceases.

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