



Lead exposure in childhood and historical land use: a geostatistical analysis of soil lead concentrations in South Philadelphia parks

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Abstract Elevated soil lead (Pb) concentrations in public parks and outdoor spaces continue to have a significant impact on the public health of urban communities. This study evaluated the geospatial and statistical relationships between soil Pb concentrations, the urban environment, and child blood lead levels (BLLs) in the neighborhood of South Philadelphia, PA. Soil samples ($n=240$) were collected from forty (40) public parks and analyzed for Pb using a field portable X-ray fluorescence (XRF) analyzer. Geospatial mapping was used to investigate historical land use of each park, vehicular traffic on adjacent roadways, and density of residential/commercial development. Predicted child BLLs and BLL “high-risk areas” were identified using interpolation and biokinetic modeling. Childhood BLL data for South Philadelphia ($n=10,379$) was provided by the Philadelphia Department of Public Health (2013–2015). Of the two hundred forty (240) soil samples collected, Pb levels for 10.8% of samples were ≥ 400 ppm. Two hundred sixty-nine of 10,379 children screened were identified with BLLs ≥ 5 $\mu\text{g}/\text{dL}$. Historical land use of each park was shown to be significantly correlated ($p=0.01$)

with soil Pb concentrations and child BLLs ≥ 5 $\mu\text{g}/\text{dL}$. Approximately 13.3% of the variance in child BLLs ≥ 5 $\mu\text{g}/\text{dL}$ was attributed to historical site land use. Overall, undeveloped/greenspace historical land use exhibited the highest soil Pb concentrations in the study. Geospatial relationships were identified between census tracts with higher percentages of children with BLLs ≥ 5 $\mu\text{g}/\text{dL}$ and interpolated BLL “high-risk” areas (≥ 3.5 $\mu\text{g}/\text{dL}$). The results of this study suggest soil accumulation time and historical land use may influence soil Pb concentrations and child BLLs in urban communities. Measured soil Pb concentrations were determined to effectively model community-wide contamination and childhood Pb exposure.

Keywords Childhood lead exposure · Lead contamination · Land use · ArcGIS · Interpolation · Risk assessment · Urban environmental health

Introduction

Lead (Pb) is a cardiovascular, neurological, and immunological toxicant which is especially hazardous during the prenatal and infant stages of life (Abadin, 2020). Inhalation and/or ingestion of Pb-contaminated soils has been shown to be one of the most important exposure pathways in childhood (Mielke et al., 2016; Mielke & Reagan, 1998). When considering urban agriculture, Pb can also enter the human food chain

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through plant uptake (Roy & McDonald, 2015). Decrements in cognitive ability and neurological function (i.e., learning, memory, attention, dexterity, visual-motor integration) have been shown to be directly correlated with elevated blood lead levels (Abadin, 2020; Bandeen-Roche et al., 2009). The neurological effects of Pb exposure are particularly deleterious in children. Larger decrements in cognitive function are expected from child BLLs ranging from 1 to 10 $\mu\text{g}/\text{dL}$, than from child BLLs $>10 \mu\text{g}/\text{dL}$ (Abadin, 2020). In addition, current evidence suggests a “safe” threshold has not been identified for childhood Pb exposure (Abadin, 2020; Vorvolakos et al., 2016). The Centers for Disease Control and Prevention (CDC) adopted the blood lead reference value in 2012, a statistically derived Pb concentration that can be used to characterize BLLs as “elevated” or “non-elevated” (Paulson & Brown, 2019). The current CDC blood lead reference value of 3.5 μg per deciliter of blood ($\mu\text{g}/\text{dL}$) was adopted in 2021 (CDC, 2021).

The urban environment consists of various outdoor areas where children can be exposed to elevated soil Pb concentrations including public parks (Han et al., 2017; Pavidonis et al., 2021), playgrounds (Takaoka et al., 2006), and residential soils (Bradham et al., 2017; Thompson et al., 2014). Inhalation and/or ingestion of Pb-contaminated soils has been shown to be one of the most important exposure pathways in childhood (Mielke et al., 2016; Mielke & Reagan, 1998). Pb soil contamination can be considered a function of legacy sources of Pb (i.e., lead-based paint, leaded gasoline, industrial operations) and their accumulation in urban soils (Mielke & Reagan, 1998; Han et al., 2017; Pavidonis et al., 2021). Numerous studies have identified public parks and residential soils as primary urban sources and reservoirs for accumulated lead dust (Sun et al., 2021; Thompson et al., 2014; Pavidonis et al., 2021; Mielke & Reagan, 1998; Duzgoren-Aydin et al., 2006). According to data provided by the 2007–2010 US Geological Survey Background Soil Lead Survey, the 95th and 99th percentiles for background soil Pb concentrations in the state of Pennsylvania were identified as 153 ppm and 261 ppm respectively (USEPA, 2022). Urban soils have been shown to exhibit much higher soil Pb concentrations, ranging from 150 to 10,000 ppm (Bradham et al., 2017).

The adoption of leaded gasoline in the early 1920s resulted in a period of significant Pb emissions from the early twentieth century until the phase-out of

leaded gasoline in the 1970s–1980s (Eichler et al., 2015). Consequently, global Pb emissions were estimated to be roughly 248,000 tons in 1983 and decreased by over 60% to approximately 90,000 tons in the mid-1990s (Nriagu & Pacyna, 1988; Pacyna & Pacyna, 2001). Pb-contaminated particulates generated by modern vehicular traffic and former use of leaded gasoline play a vital role in urban soil Pb concentrations (Mielke et al., 1997, 2010). A 2015 study demonstrated low and moderate volumes of vehicular traffic can result in measurable concentrations of particulate Pb in urban environments (Wiseman et al., 2015). Lead-based paint (LBP) also continues to be a common source of exposure in urban communities, despite the US banning of residential LBP in 1978 (Jacobs et al., 2002). Sixty-four million homes in the USA were estimated to contain LBP in 1990 and 38 million housing units were estimated to contain LBP in the early 2000s (Jacobs et al., 2002). Various studies have established contaminated household and street dust as common sources of Pb exposure in cities (Bradham et al., 2017; Jacobs et al., 2002; Mielke et al., 2016).

In addition to LBP and leaded gasoline use, soil Pb concentrations are also influenced by land use. Industrial operations such as metalworking, textile manufacturing (i.e., dye houses and tanneries), and lead smelters serve as potential sources of Pb soil contamination associated with historical land use in the city of Philadelphia (O’Shea et al., 2021b; Simon, 2017). Mining, fossil fuel operations, and agricultural operations can also contribute to the accumulation of heavy metals in soils (Duzgoren-Aydin et al., 2006; Roy & McDonald, 2015). Fueling operations, such as gas stations, can significantly impact soil Pb concentrations in large cities. A 2017 study in Xi’an, China, reported surface dust associated with urban gas stations exhibited over four (4) times the background soil Pb concentration (Li et al., 2017). When compared to rural and suburban residential communities, concentrations of Pb and other anthropogenic contaminants have been shown to increase from rural and suburban areas to the urbanized core of large cities (Datko-Williams et al., 2014; Mao et al., 2014).

The US and Canadian governments have established Pb soil screening levels that can be used to identify elevated risk of soil Pb exposure and provide guidance on soil remediation. Currently, the US EPA has adopted a Pb soil screening level (SSL)

of 400 ppm for residential/recreational land uses (USEPA, 2001) and the Canadian Soil Quality Guidelines for Pb (SQGs) have been established at 140 ppm for residential/parkland areas (CCME, 2022). In 2007, the California Environmental Protection Agency adopted a Pb soil screening level that was estimated to result in a BLL increase of 1 $\mu\text{g}/\text{dL}$ for individuals exposed to the specified concentration (Carlisle, 2009). Based on the 1 $\mu\text{g}/\text{dL}$ site-specific benchmark dose, the Revised California Soil Screening Level for Pb (RSSL) was established at 80 ppm for residential soils (Carlisle, 2009). According to the California Department of Toxic Substances Control, soils which contain a Pb concentration of ≤ 80 ppm are considered generally acceptable for residential land use and/or reuse without restriction (CADTSC, 2022).

Recent studies in Philadelphia, PA, have identified significant Pb soil contamination throughout several neighborhoods in the city (Bradham et al., 2017; O'Shea et al., 2021a, 2021b). Soil Pb concentrations ranged from "Non-Detect" to 4443 ppm, and significant exceedances of the EPA SSL were observed in the Center City, River Wards (Northeast), and Southwest Philadelphia communities (Bradham et al., 2017; O'Shea et al., 2021a, b). According to the 2018 Philadelphia Childhood Lead Poisoning Surveillance Report, approximately 4.9% ($n=1867$) of the 37,584 children < 6 years old that were screened possessed a $\text{BLL} \geq 5 \mu\text{g}/\text{dL}$ (Philadelphia Department of Public Health, 2018). Previous investigations have not significantly evaluated soil Pb concentrations in the South Philadelphia zip codes of 19145, 19146, 19147, and 19148.

Rapid industrial development and disorganized urbanization have been shown to significantly contribute to the accumulation of heavy metals in urban soils (Zwolak et al., 2019). In addition, studies have established a positive correlation between the age of housing and child blood Pb levels in urban communities (O'Shea et al., 2021a; Pavilonis et al., 2021; Philadelphia Department of Public Health, 2018). Considering the influence of aging housing stock on childhood Pb exposure and the deposition of heavy metals in soils due to urbanization, the demolition of structures constructed prior to 1978 is likely to increase the risk of elevated soil Pb concentrations in the City of Philadelphia. Starting in the 1970s, significant losses in housing stock resulted in (1) an increase in demand for the development of new

higher quality/higher cost housing and (2) a growth of abandoned and/or vacant buildings in lower-income communities (Adams, 1991). Changes in population and outmigration also played vital roles in structuring the urban landscape of the city. Philadelphia's population dropped from 2.1 to 1.7 million from 1960 to 1980, and communities in North Philadelphia lost nearly 40% of their 1960 population by the early 1980s (Adams, 1991). As a result of this mass outmigration, the estimated quantity of abandoned and/or vacant properties in Philadelphia remained at 22,000 throughout the 1980s (Adams, 1991). Approximately 10,000 additional buildings were demolished during the same time period (Adams, 1991). In South Philadelphia, $> 57\%$ of the residential properties in the 19148, 19147, and 19146 zip codes and 48–57% of the residential properties in the 19145 zip code were built before 1940 (Philadelphia Department of Public Health, 2018). With 48–57% of residential structures developed prior to 1940, the potential for lead exposure in childhood increases as older structures are demolished and anthropogenic Pb accumulates in urban soils.

The City of Philadelphia has become a desirable location for residential and commercial development in recent years (Rinde, 2020; Williams, 2021). Despite the prevalence of the global coronavirus pandemic, the Philadelphia Zoning Board of Appeals received zoning variance requests by August 2020 that totaled 2,436 residential units (Rinde, 2020). In addition, the city approved the construction of 3,239 residential units in 2018 and 4,556 residential units in 2019 (Rinde, 2020). According to US census data, Philadelphia reported 726,797 housing units in 2020 and 670,171 housing units in 2010 (U.S. Census, 2010 & 2020). Housing in the city increased by 56,626 units over the 10-year reporting period; however, 68,722 housing units were reported as vacant in 2020 (U.S. Census, 2020). The City of Philadelphia and/or the Pennsylvania Department of Environmental Protection (PADEP) has not proposed any regulation requiring the sampling of urban soils for metals and other pollutants prior to development. By comparison, regulatory standards requiring the sampling and delineation of urban soil contamination (e.g., historic fill material) prior to soil disturbance have been adopted in neighboring states, including New Jersey (NJDEP, 2018) and New York (NYSDEC, 2010). The objective of this study is to investigate the geospatial and

statistical association between the urban environment (i.e., historical land use, vehicular traffic, density of residential/commercial development), soil Pb concentrations, and child BLLs in South Philadelphia, PA.

Methods and materials

Soil sampling and elemental analysis

Soil sampling for this study consisted of collecting two hundred forty (240) soil samples from forty (40) public parks within the Philadelphia Parks & Recreation system throughout the 19145, 19146, 19147, and 19148 Zip Code Tabulation Areas (ZCTAs) in Philadelphia, PA. Soil samples were collected in accessible areas containing soil within four to six (4–6) inches below the ground surface. Fifty to one hundred (50–100) gram bulk soil samples were collected from each sampling location in polypropylene bags for ex situ soil screening. The effect of sample location on soil Pb concentration was investigated by collecting three (3) roadside soil samples within 50 ft of a roadway for each public park. In addition, three (3) soil samples were collected near recreational areas (i.e., park benches, playgrounds, open lawns) and within the dripline (i.e., 3 ft of the building perimeter) of any structures observed in the park.

The analytical methods used in this study were adapted from EPA Method 6200: *Field Portable X-Ray Fluorescence (XRF) Spectrometry for the Determination of Elemental Concentrations in Soil and Sediment* and the EPA Region 4 Operating Procedure for Field XRF Measurement (EPA, 2007; EPA, 2017). Ex situ soil analysis was performed using a Thermo Scientific™ Niton™ model XL3t field portable XRF analyzer. Following the collection of soil samples, each sample bag was opened and allowed to air-dry for at least 72 hours. According to EPA Method 6200 and the EPA Region 4 Operating Procedure, excessive soil moisture (i.e., moisture content > 20%) can result in lower reported concentrations relative to the soil Pb concentration reported by laboratory analytical methods (EPA, 2007; EPA, 2017). Samples were visually inspected for excessive moisture content prior to analysis and additional drying time was used as applicable. The accuracy of XRF soil analysis can also be impacted by sample homogeneity and uniformity of the soil surface. Greater soil

homogeneity results in increased XRF measurement accuracy (EPA, 2017). Additionally, EPA Method 6200 indicates the XRF detector window should be in direct contact with a consistently flat and smooth surface to minimize measurement error (EPA, 2007). After the drying process, the homogenization process consisted of crushing soil into a fine mixture with hand pressure and flattening the soil into a 1-cm-thick, relatively uniform surface. XRF readings were collected directly from the surface of the sample bag using a reading count time of 30.1 seconds. The analytical work surface and sampling bag were observed to be free of metals and elements detectable via XRF, such as manufacturer's printing or labeling surfaces on bags. XRF analyzer calibration was performed at the start and completion of each soil sampling session using soil reference standards produced by the United States Geological Survey (USGS) and the National Institute of Standards and Technology (NIST). Reference standards and certified values used in this study included: SiO₂ Blank (Pb=0 ppm), NIST 2709a (Pb=17.3±0.1 ppm), and USGS SdAR-M2 (Pb=808±14 ppm). In addition, a system check was performed of the XRF analyzer prior to each calibration event. In order to account for variance, readings < LOD were calculated using the LOD divided by the square root of two (2). The limit of detection varied per reading and ranged from 9.9 to 10.2 ppm.

Historical land use

Historical land use prior to the widespread adoption of leaded gasoline in the early 1920s (Eichler et al., 2015) was identified using the Atlas of the City of Philadelphia, 1910, created by Geo. W. & Walter S. Bromley, Civil Engineers. Historical maps were accessed through the Greater Philadelphia GeoHistory Network (Philadelphia GeoHistory, 2021). The historical land use of each public park and corresponding adjacent properties was categorized and ranked in the following order: Rank 1-undeveloped/greenspace; Rank 2-commercial/residential/unreported; and Rank 3-industrial/manufacturing. "Adjacent properties" were considered any property or structure adjoining the depicted site boundary of the park. Undeveloped/greenspace land use consisted of properties identified as parks, open land, or primarily undeveloped land with minor wood-framed improvements. Commercial/residential/unreported land use consisted of properties reported as

dwellings, commercial buildings such as schools and stores, and buildings with unreported land use. Industrial/manufacturing land use consisted of properties identified as chemical manufacturing facilities, railroad operations, coal yards, worsted mills, and factories. For adjacent properties, the presence of one (1) industrial/manufacturing facility determined the overall adjacent historical land use. Hydrologic gradient and topography were not evaluated in this study.

Geospatial mapping

Geospatial analysis was performed using Environmental Systems Research Institute's (ESRI's) ArcGIS ArcMap software (version 10.7.1). Sample location coordinates in decimal degrees were obtained in the field using Google Earth. Soil sample coordinates were converted to the State Plane Coordinate System in US Survey Feet for geocoding purposes. Average annual daily traffic (AADT) for each road segment in the study was identified and mapped using 2021 *Pennsylvania Traffic Counts* metadata provided by the Pennsylvania Department of Transportation (PennDOT, 2021). An overlay of the road segments mapped as line features, and soil Pb concentrations aggregated by ZCTA was produced. The nearest road segment and corresponding AADT for each soil sample location were identified using basic ArcMap functions. The final layout was assessed for any spatial correlations between AADT and soil Pb concentrations.

The density of development in the study area was identified using completed building and demolition permits reported by the Philadelphia Department of Licenses & Inspections from 2007 to 2021. Completed permits were mapped using metadata accessed through the OpenDataPhilly online catalog (OpenDataPhilly, 2021). The locations of completed permits were mapped as dot features and a kernel density map was generated. An overlay was created using the kernel density estimation and soil Pb concentrations aggregated by ZCTA. Lastly, the completed permits quartile range associated with each soil sample was identified (for maps of AADT and completed permits used in the study, refer to Supplement 1).

In previous studies, geospatial interpolation has been shown to be an effective means of identifying the spatial distribution of soil contaminants and clusters of elevated soil Pb concentrations (Jadoon et al.,

2020; O'Shea et al., 2021a, b; Tepanosyan et al., 2019). For the purposes of identifying clusters, or "high-risk areas" with >400 ppm soil Pb concentrations, natural neighbor interpolation was used to create a continuous gradient of soil Pb concentrations across the study area. The interpolated Pb values were derived from measured soil Pb concentrations, which were also mapped in the soil Pb interpolation. In order to identify the spatial distribution of on-site historical land use in relation to soil Pb concentrations, a separate map was produced depicting the historical land use of parks in the study area and interpolated soil Pb concentrations.

Risk evaluation and predicted BLLs

North American Pb soil screening levels in residential settings were used to evaluate the risk of exposure to soil Pb concentrations in the study area. Regulatory soil screening levels used included the California RSSL, Canadian SQGs, and the US EPA SSL. The US EPA Integrated Exposure Uptake Biokinetic (IEUBK) Model for Lead in Children Version 2.0 was used to estimate child blood lead levels (BLLs) in the study area (SRC, 2019). The IEUBK model approximates a longitudinal exposure pattern during the years of interest (up to 84 months) based on Pb exposure measurements for different environmental media (i.e., soil, drinking water, dust, and air), diet, and alternate sources. Pb exposure and uptake rates are estimated for a hypothetical child or population of children exposed to similar conditions. The absorption algorithm used in the IEUBK model was derived using human data from Pb balance studies in infants and children, and exact values for each model parameter were based on cross-sectional human data (SRC, 2019). Soil ingestion rates in outdoor settings were derived from fieldwork associated with the development of the model and the expected amount of time spent outdoors was generated from survey data (SRC, 2019). The mean soil Pb concentration for each park was used in the IEUBK model to adjust for site-specific soil conditions. Based on the 2020 Philadelphia Drinking Water Quality Report, 3 parts per billion (ppb) was chosen as a conservative model parameter for drinking water. In 2020, the City of Philadelphia reported 90% of tested homes had drinking water Pb concentrations below 3 ppb (PWD, 2021). According to the 2021 Philadelphia Air Quality Report, total

suspended particulate Pb monitoring was discontinued in 2017 due to a lack of industrial sources emitting ≥ 0.5 tons of Pb per year (Philadelphia Department of Public Health, 2021). During the previous sampling period in Philadelphia from 2009 to 2016, the highest concentration of Pb in ambient air was identified as 0.05 ppb (Philadelphia Department of Public Health, 2021). Based on the previous ambient air sampling period, 0.05 ppb was selected as a moderate IEUBK model parameter for Pb inhalation exposure. Default values were used for the remaining model parameters including time spent outdoors, dietary uptake, gastrointestinal absorption, and relative bioavailability.

The mean soil Pb uptake rate and BLL for each park were computed for children from 6 months to 6 years. The CDC reference value of 3.5 $\mu\text{g}/\text{dL}$ was used as a screening level for areas with a high risk of BLLs ≥ 5 $\mu\text{g}/\text{dL}$. The predicted average BLLs for each park were utilized to develop an interpolation map which identified high-risk areas with BLLs ≥ 3.5 $\mu\text{g}/\text{dL}$. Lastly, the historical use of each park was mapped with the BLL interpolation to evaluate the spatial distribution of historical land use in relation to predicted BLLs.

Child blood lead levels in South Philadelphia

Child BLL data from 2013 to 2015 was provided by the Philadelphia Department of Public Health and accessed via the OpenDataPhilly online catalog (OpenDataPhilly, 2016). Available data was aggregated by census tract; census tracts located within the study area were identified in ArcMap. A choropleth map was produced depicting the percentage of recently identified children from 2013 to 2015 with BLL ≥ 5 $\mu\text{g}/\text{dL}$ per number of children screened in the study area. In addition, measured soil Pb concentrations were mapped as part of the 2013–2015 BLL choropleth to identify potential spatial relationships.

The number of children within 1500 ft or approximately six (6) city blocks was identified for each park using buffer analysis. Physical location and other sensitive information were redacted from available data. Therefore, BLL data associated with the nearest census tract was used to delineate the number of children with BLLs ≥ 5 $\mu\text{g}/\text{dL}$ within 1500 ft of each park. Based on information reported by the American Planning Association regarding walkable distances

to public parks for children and families, 1500 ft or roughly six city blocks were chosen as the buffer radius (Harnik & Simms, 2004) for the study.

Statistical analysis

The Kolmogorov–Smirnov test was used to identify normality and account for variance in the measured soil Pb data. Based on the obtained significance factor, soil Pb concentrations in the study were identified as lognormally distributed. Sample mean and background soil Pb concentrations in the study area were identified using 95% confidence intervals, 95th percentiles, and upper tolerance limits (UTLs). Non-parametric statistics were calculated using Microsoft Excel, and were based on Land's "exact" method for calculating confidence intervals of lognormally distributed data proposed by Hewett and Ganser (1997). This method expands upon Land's "exact" procedure (Land, 1974) by providing a series of supplemental equations to allow for an accurate estimation of the sample mean and background concentrations (Hewett & Ganser, 1997).

Categorical data including historical land use, soil sample location, AADT of the nearest roadway, and completed permits were assigned ordinal or nominal numerical ranks. Kruskal–Wallis (KW) tests were performed of soil Pb concentration and ranked independent variables to determine significant differences between group mean rank, and the presence of stochastic homogeneity in at least one ranked group (Vargha & Delaney, 1998). Spearman's rank-order correlations were calculated to evaluate the strength of association between the variables of interest, soil Pb concentrations, and the number of children possessing BLLs ≥ 5 $\mu\text{g}/\text{dL}$ within 1500 ft of each park. Measured soil Pb data was log-transformed to identify Spearman's correlation coefficients and confidence intervals. Simple and multiple regression was performed using independent variables with statistically significant correlation coefficients to identify the overall contribution to the variation in child BLLs and soil Pb concentrations. KW tests, Spearman's correlations, and multiple regression were calculated using IBM SPSS Version 28.0. The author confirms that the data supporting the findings of this study are included in this published article and its supplementary information files. Raw data that support the findings of this study are available from the author, upon reasonable request.

Results

Soil Pb concentrations in South Philadelphia parks

Land’s “exact” confidence intervals for soil Pb concentrations identified throughout the study area are shown in Table 1. The standard deviation within each park ranged from 28.17 to 692.06 ppm. Approximately 22.5% of parks exhibited greater variability in soil Pb concentrations than their respective ZCTA. ZCTA 95th percentiles ranged between 546.6 and 685.2 ppm and upper tolerance limits (UTLs) ranged between 648.8 and 824.1 ppm. The observed 95th percentiles and UTLs indicate background soil Pb concentrations are expected to be in exceedance of the previously specified regulatory thresholds. Based on the 95% confidence intervals calculated, the mean soil Pb concentration throughout the study area lies between 181 and 232.3 ppm (for statistical data, refer to Supplement 2).

Measured and interpolated soil Pb concentrations throughout the study area (Fig. 1) demonstrated an increasing trend from the center city areas in the north-central portions of the 19146 and 19147 ZCTAs to the outlying areas of the 19145 and 19148 ZCTAs. A cluster of samples on the southwest portion of the 19146 ZCTA and the northwest portion of the 19145 ZCTA exhibited higher than average concentrations, ranging from 495 to 1948 ppm. In addition, a cluster of above-average soil Pb concentrations ranging from 400 to 1170 ppm was identified in the central portion of the 19148 ZCTA. Interpolated soil Pb concentrations exhibited four distinct areas with Pb concentrations above 400 ppm, or “high-risk areas.” Areas with the highest interpolated soil Pb concentrations were located near the central portion of the 19148 ZCTA, and between the 19146 and 19145 ZCTAs. The interpolation of average soil

Pb concentration per park exhibited similar geospatial trends, and high-risk areas were identified in the center of the 19148 ZCTA and at the boundary between the 19146 and 19145 ZCTAs (for XRF analytical results and soil sample coordinates, refer to Supplement 3).

Influence of historical land use

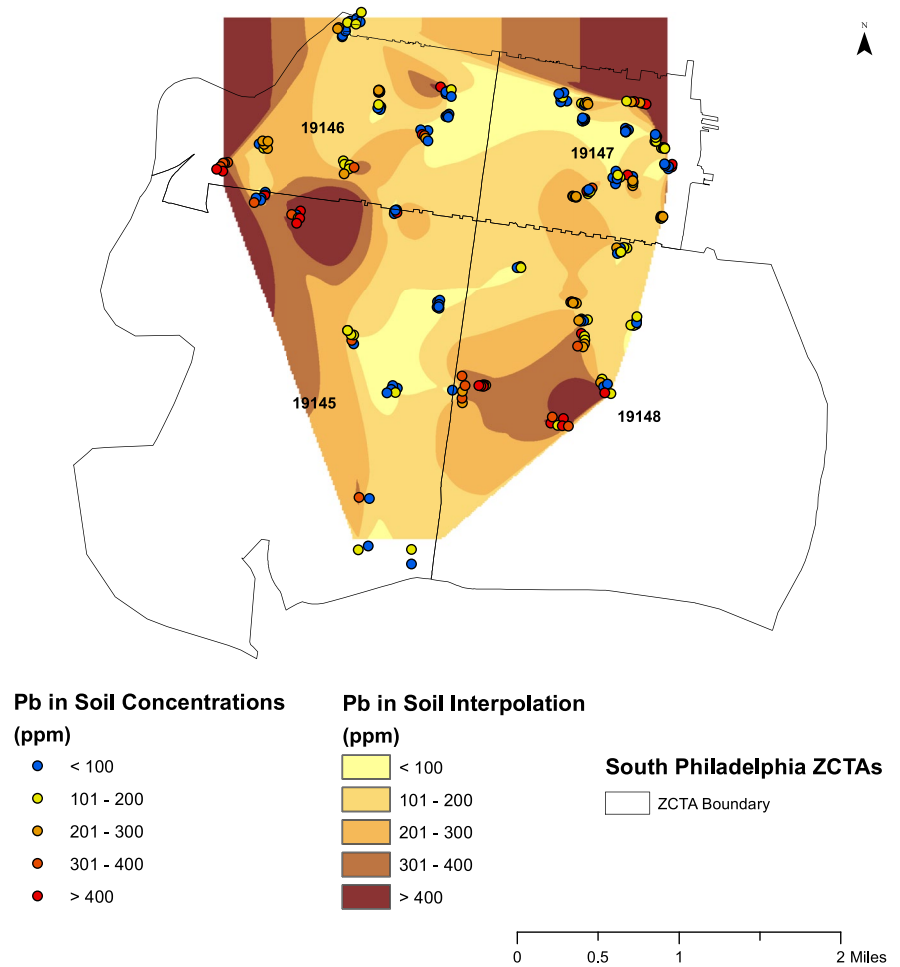
Percentages of samples exceeding a specified soil screening level were calculated for each sample type (Table 2). Overall, 167 of 240 (69.5%) samples were ≥ 80 ppm, 112 of 240 (46.6%) samples collected ranged between 140 and 400 ppm, and 26 of 240 (10.8%) samples collected were ≥ 400 ppm. Samples collected in the 19148 ZCTA displayed the highest overall percentage (18.5%) above the EPA SSL. Among the specified land use types, parks with undeveloped/greenspace historical land use exhibited the greatest percentage (18.7%) of EPA SSL exceedances. When considering sample location (e.g., roadside, recreational area, roadside/recreational area, and building dripline), roadside samples exhibited the highest overall percentage (16.5%) above the EPA SSL (for relevant data, refer to Supplement 2).

Kruskal–Wallis tests performed of soil Pb concentrations ($n=240$) and ranked independent variables are listed in Table 3. Statistically significant differences between groups of variables are depicted in Fig. 2. Statistically significant differences ($p=0.05$) among ranked groups were identified for historical site land use, historical adjacent land use, sample location, and completed building and demolition permits. Historical site land use exhibited the highest degree of statistically significant difference ($p<0.001$). Stochastic homogeneity was determined to be present for groups ranked by average annual daily traffic of the nearest roadway.

Table 1 Descriptive statistics and Land’s “exact” confidence intervals for soil Pb concentrations

ZCTA	<i>n</i>	Median (ppm)	Standard deviation (ppm)	Geometric mean	Geometric standard deviation	95 th percentile (ppm)	Upper tolerance limit (ppm)
19145	48	92.6	312.2	114.8	2.9	670.5	824.1
19146	60	127.0	137.4	126.1	2.4	546.6	648.8
19147	78	123.9	145.6	114.6	2.7	581.5	703.0
19148	54	176.5	236.2	170.9	2.3	685.2	805.9
Total	240	125.4	209.6	128.5	2.6	622.3	748.3

Fig. 1 Soil Pb concentrations and interpolated Pb concentrations throughout the study area



Interpolated soil Pb concentrations and historical land use of public parks are shown in Fig. 3. Pb concentrations demonstrated a decreasing trend

from areas with undeveloped/greenspace land use to areas with residential/commercial/unreported and industrial/manufacturing land use (Fig. 4). Overall,

Table 2 Regulatory threshold exceedances by Pb soil sample type

Sample type	<i>n</i>	California RSSL (%)	Canada SQGs (%)	EPA SSL (%)
Total	240	69.5	46.6	10.8
ZCTA 19145	48	58.3	37.5	10.4
ZCTA 19146	60	71.7	45.0	8.3
ZCTA 19147	78	66.7	44.9	7.7
ZCTA 19148	54	81.4	59.2	18.5
Undeveloped/greenspace	96	75.9	64.5	18.7
Residential/commercial/unreported	84	73.8	47.6	3.6
Industrial/manufacturing	60	53.2	16.6	8.3
Roadside	127	72.4	54.3	16.5
Recreational area	81	61.7	39.5	3.7
Roadside/recreational area	21	71.5	19.1	4.8
Building dripline	11	90.9	63.6	9.1

Table 3 Kruskal–Wallis analysis of ranked variables

Variable of interest	Test statistic	<i>p</i> -value
Historical site land use	24.896	<0.001
Historical adjacent land use	12.951	0.002
Sample location	11.254	0.010
Permits	9.069	0.028
AADT	5.477	0.140

the 19145 and 19147 ZCTAs exhibited the highest amount of undeveloped/greenspace land use. In addition, high-risk areas were exclusively located

near public parks that were reported as undeveloped/greenspace. Conversely, the majority of public parks previously identified as industrial/manufacturing properties exhibited overall lower soil Pb concentrations than the other land use types.

Potential risk of Pb exposure in childhood

Based on the IEUBK model output, the average Pb soil and dust uptake rate in the study ranged between 1.05 and 9.46 µg/day for children aged six (6) months to six (6) years old. The predicted mean child BLLs resulting from 2 to 4 hours of daily recreational activity in each park

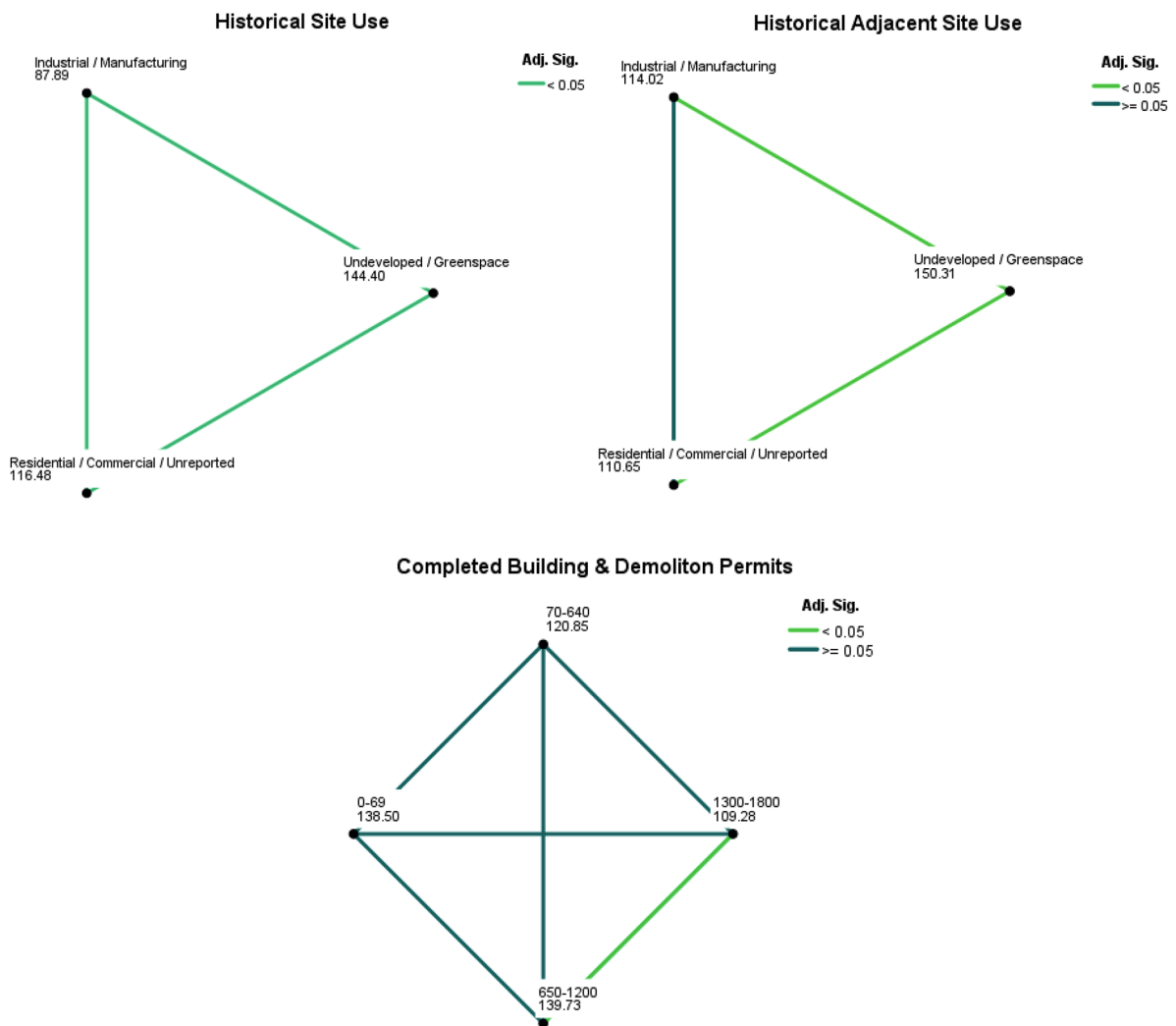
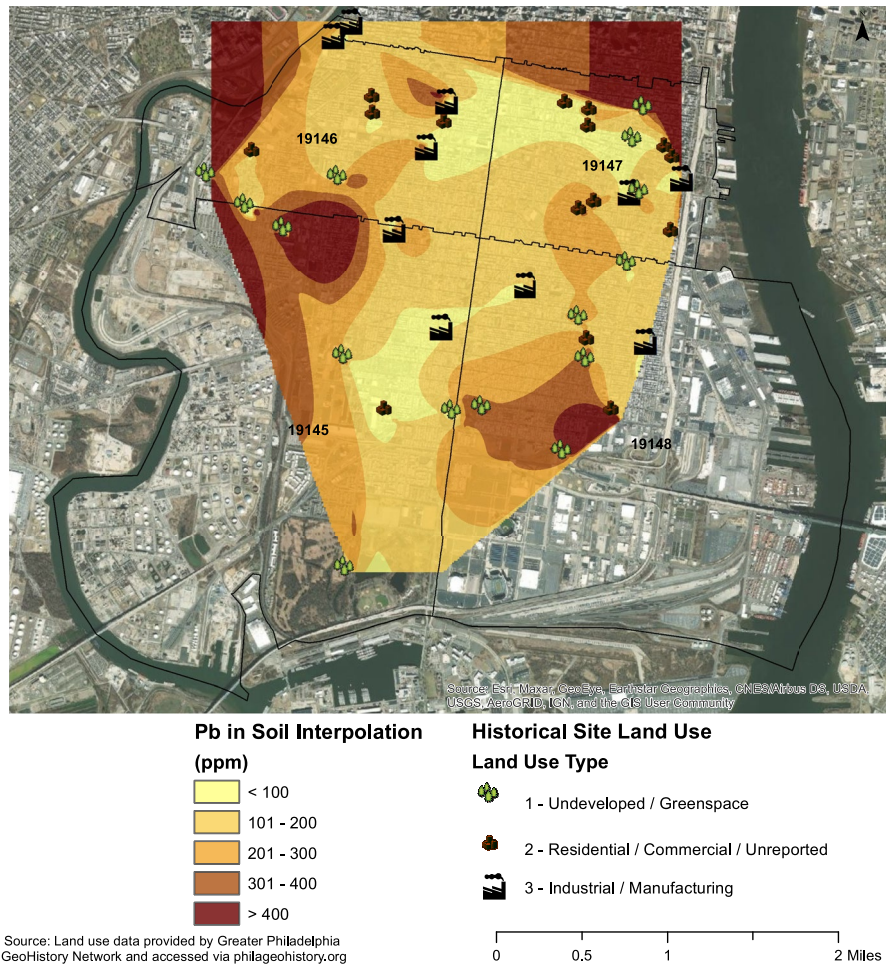


Fig. 2 Statistically significant differences between groups of variables are shown. Each node depicts the average rank of the variable of interest

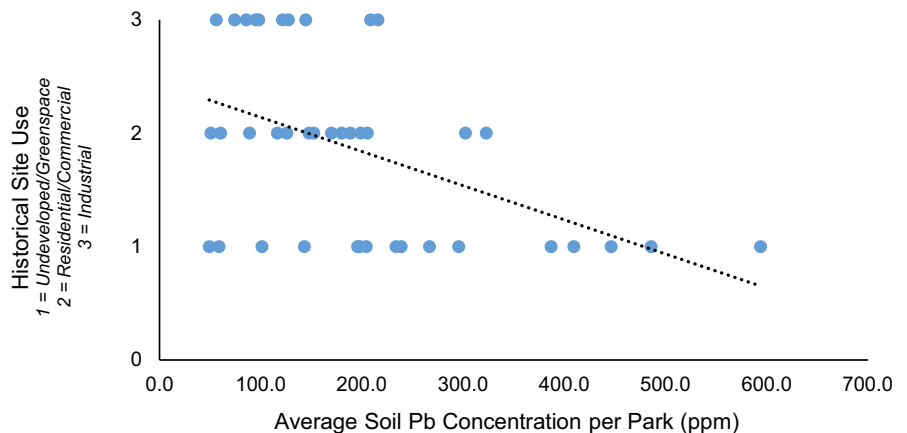
Fig. 3 Historical land use of parks and interpolated soil Pb concentrations throughout the study area. Values were not available for areas beyond the extent of parks at the outer edge of the study area



are depicted in Fig. 5. Using the CDC reference value as a screening level, two (2) distinct high-risk areas were identified with expected blood lead levels of 2.6–4.8 $\mu\text{g}/\text{dL}$

When examining historical site land use, many of the areas with greater risk for a $\text{BLL} \geq 5 \mu\text{g}/\text{dL}$ were identified near parks reported as undeveloped/greenspace.

Fig. 4 The relationship between historical site use and average soil Pb concentration is shown



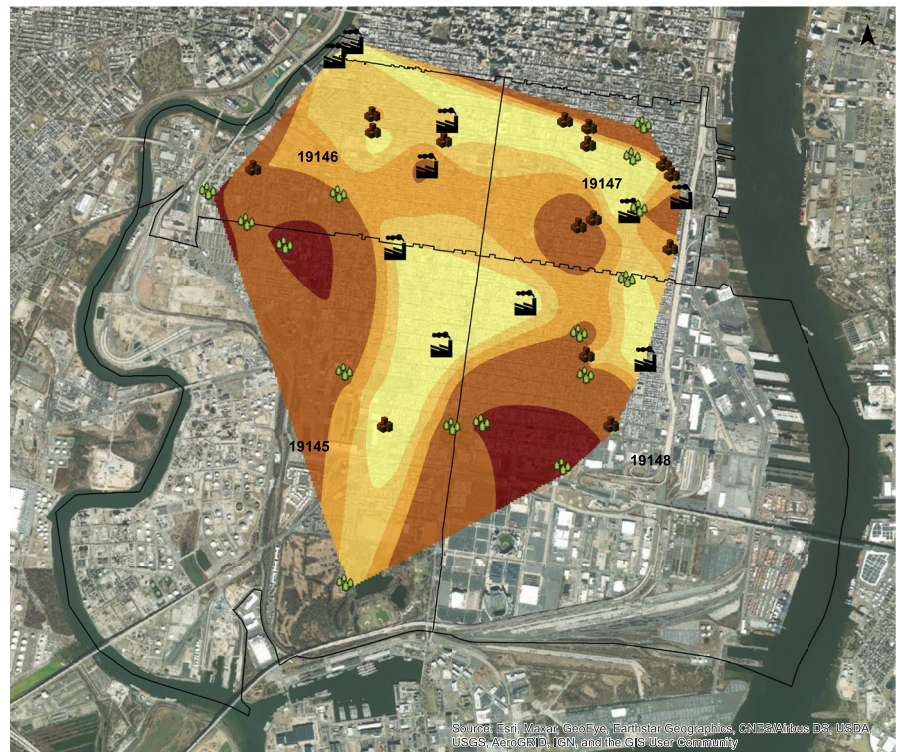
Overall, 10,379 children were screened within the study area from 2013 to 2015 and 269 children were reported with a BLL $\geq 5 \mu\text{g/dL}$. As shown in Fig. 6, geospatial relationships were identified between the percentage of newly identified children with a BLL $\geq 5 \mu\text{g/dL}$ and soil Pb concentrations measured in the study. Three (3) parks in the 19148 ZCTA with confirmed soil Pb concentrations above 400 ppm were located within 1500 ft (six city blocks) of census tracts that reported 4.6–6.7% of children screened with a BLL $\geq 5 \mu\text{g/dL}$. Three (3) parks with significantly elevated soil Pb concentrations (495–1948 ppm) were located adjacent to census tracts in the 19146 and 19147 ZCTAs which reported the highest child BLL percentages (4.1–8.9%) in the study area. Spatial correlations become evident when comparing predicted BLL high-risk areas (Fig. 5) to neighborhoods with

high percentages of child BLLs $\geq 5 \mu\text{g/dL}$ (Fig. 6). Census tracts with higher percentages of child BLL $\geq 5 \mu\text{g/dL}$ were located within 1500 ft or directly within high-risk areas identified in the predicted BLL interpolation.

Spearman’s rank correlations and regression modeling

Variables with statistically significant Spearman’s rank correlations ($p=0.01$) and $\rho \geq \pm 0.3$ are shown in Table 4. Moderate, positive correlations were exhibited among historical site land use and historical adjacent land use (CI: $0.35 < \rho < 0.55$), log soil Pb concentration – number of children with BLL (CI: $0.19 < \rho < 0.43$), and historical adjacent land use – completed building and demolition permits (CI: $0.17 < \rho < 0.41$). Moderate, negative

Fig. 5 Expected average BLL in $\mu\text{g/dL}$ for children aged 6 months–6 years throughout the study area. The CDC blood lead reference value of $3.5 \mu\text{g/dL}$ was used to establish the fifth range of values



Average BLL Interpolation ($\mu\text{g/dL}$)

1.6 - 2.1
2.2 - 2.2
2.3 - 2.5
2.6 - 3.4
3.5 - 4.8

Historical Land Use Land Use Type

- 1 - Undeveloped / Greenspace
- 2 - Residential / Commercial / Unreported
- 3 - Industrial / Manufacturing

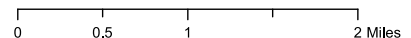
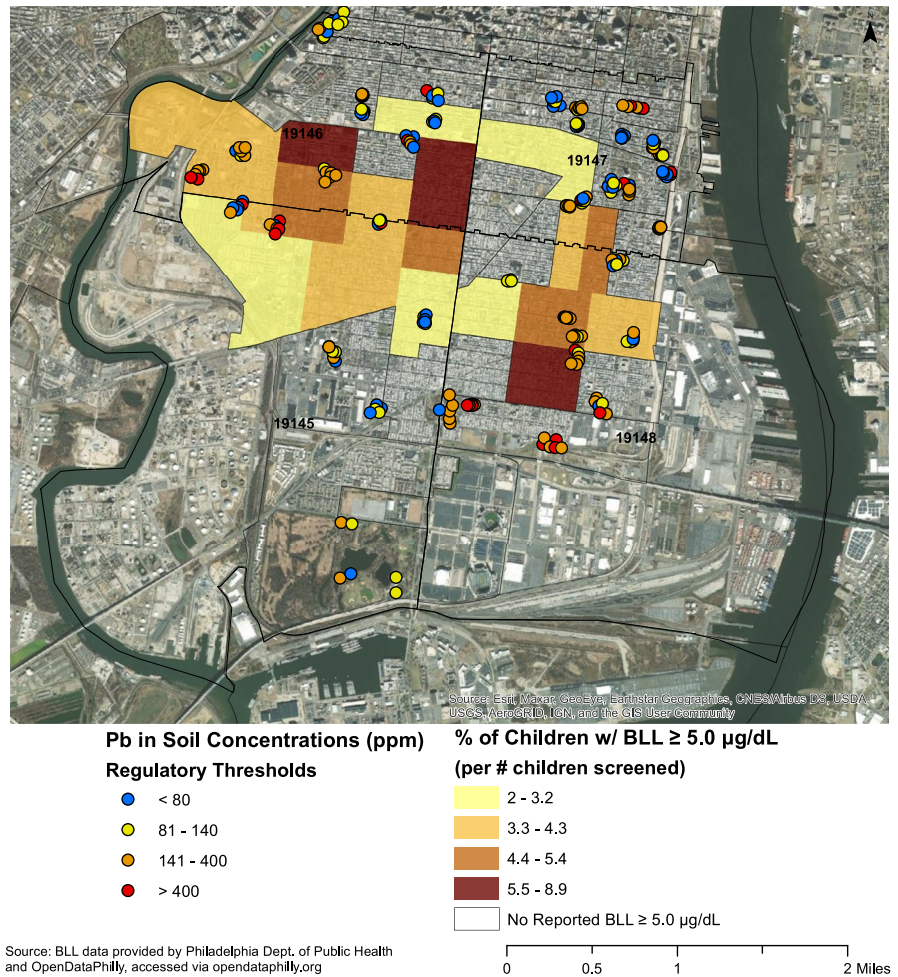


Fig. 6 The percentage of newly identified children in 2013 with a blood lead level $\geq 5.0 \mu\text{g/dL}$ per number of children screened within the study area



correlations were identified among historical site use – log soil Pb concentration (CI: $-0.43 < \rho < -0.20$) and number of children with BLL – historical site land use (CI: $-0.43 < \rho < -0.20$). The observed negative correlations indicate measured Pb concentrations and the quantity of children with a $\text{BLL} \geq 5.0 \text{ ug/dL}$ decreased

as historical land use “increased” from undeveloped/greenspace (rank 1) to industrial/manufacturing (rank 3). Significant correlations were not identified for AADT.

Based on the observed correlations, the following variables were selected as predictor variables: historical site use, adjacent land use, and log Pb soil

Table 4 Spearman’s rank correlation confidence intervals

Variables of interest	R	p-value	95% CI
Historical site land use–historical adjacent land use	0.46	<0.001	0.35 to 0.55
Log soil Pb concentration–number of children with BLL	0.31	<0.001	0.19 to 0.43
Historical adjacent land use–completed building and demolition permits	0.29	<0.001	0.17 to 0.41
Historical site use–log soil Pb concentration	-0.32	<0.001	-0.43 to -0.20
Number of children w/ BLL–historical site land use	-0.32	<0.001	-0.43 to -0.20

*Correlation is significant at the 0.01 level (2-tailed)

Table 5 Child BLL simple and multiple regression

Independent variables	Dependent variable	R ²	Adjusted R ²	p-value
Log Pb concentration, historical adjacent use, historical site use	Child BLL	0.24	0.23	<0.001
Log Pb concentration	Child BLL	0.12	0.12	<0.001
Historical adjacent use	Child BLL	0.12	0.11	<0.001
Historical site use	Child BLL	0.13	0.13	<0.001

*Correlation is significant at the 0.01 level (2-tailed)

concentration. Results of the child BLL simple and multiple regression are shown in Table 5. When considering children with BLLs ≥ 5 $\mu\text{g}/\text{dL}$ as the dependent variable, 23.6% of the variance in the elevated BLL population could be attributed to the specified predictors. The variance in BLLs attributed to the individual explanatory variables ranged from 11.8 to 13.3%. Overall, historical site use exhibited the most significant contribution (13.3%) to child BLLs. Based on the results of the regression model, historical land use of public parks (on-site and adjacent properties) and soil Pb concentrations appear to have a significant association with the number of children with a BLL ≥ 5 $\mu\text{g}/\text{dL}$.

Discussion

The purpose of this study was to determine if geospatial and statistical associations exist between soil Pb concentrations, the urban environment, and children with a BLL ≥ 5 $\mu\text{g}/\text{dL}$. Two hundred forty (240) soil samples were collected from forty (40) parks in the 19145, 19146, 19147, and 19148 ZCTAs of South Philadelphia, PA. Variables associated with the urban environment were investigated, including historical land use, AADT, and completed building and demolition permits. North American soil screening levels for Pb were used to identify the elevated risk of Pb exposure. Soil Pb concentrations in the current study were determined to be lognormally distributed, which was consistent with previous studies of contamination in urban soils (Liu et al., 2010; McClintock, 2012; Saby et al., 2006). Measured soil Pb concentrations, 95th percentiles, and UTLs identified in the current study were within the range of previous studies in Philadelphia, PA, conducted by O’Shea et al. (2021a, b); and Bradham et al. (2017). The elevated soil Pb concentrations identified in this study were also consistent with the 2014 CDC child BLL assessment in Philadelphia,

PA, which reported 71% of residential soil samples in the study exceeded the EPA SSL (Dignam et al., 2019). Overall, the soil Pb concentrations identified in the study area can be attributed to a combination of legacy Pb sources, including industrial activity, lead-based paint use, and leaded gasoline use (Bradham et al., 2017; O’Shea et al., 2021a, b).

The 19148 ZCTA exhibited the largest percentage of regulatory threshold exceedances across all ZCTAs and some of the highest soil Pb concentrations in the study. In 2021, O’Shea et al. (2021a) reported in the current study area soil Pb concentrations ranging from “Non-Detect” to 2000 ppm ($n=83$). Using metadata provided in the O’Shea et al. (2021a) study, a mean soil Pb concentration of 262 ppm was calculated for the study area. Concentrations identified in the current study were within comparable ranges; however, soil samples were collected exclusively within public parks for this study. When accounting for sample location, roadside samples exhibited the highest percentage of EPA SSL exceedances. The high percentage of EPA SSL exceedances in roadside samples can likely be attributed to legacy-leaded gasoline use typical of large cities (O’Shea 2021b; Bradham et al., 2017; Mielke et al., 2010; Takaoka et al., 2006), and the re-suspension of Pb soil particles found in roadways by vehicular traffic (Laidlaw et al., 2012). In addition, soil Pb concentrations in urban settings have been shown to decrease relative to distance from roadways (Laidlaw et al., 2017).

Based on the results of the study, the historical land use of each park was determined to be strongly correlated with soil Pb concentrations and the number of children with BLLs ≥ 5 $\mu\text{g}/\text{dL}$ within 1500 ft of each park. Approximately 13.3% of the variation in child BLLs was attributed to historical site land use. As shown in Fig. 4, a decreasing trend was observed in these variables as the historical land use of each park changed from undeveloped/greenspace to industrial/manufacturing. Parks with undeveloped/greenspace

historical land use exhibited the highest percentage of regulatory exceedances across all historical land uses. The results of the current study do not appear to be typical of previous investigations concerning the influence of land use on heavy metal contamination in soils. Soil Pb concentrations and other anthropogenic contaminants have previously been shown to increase from suburban areas to the urban core of major cities (Datko-Williams et al., 2014; Liu et al., 2010; Mao et al., 2014; Saby et al., 2006). In the current study, it was found that soil Pb concentrations decreased from the densely urbanized center city areas to the relatively less urbanized areas at the periphery of the 19145 and 19148 ZCTAs. The exception to this trend was an area of elevated soil Pb concentrations in the northeast corner of the 19147 ZCTA.

The presence of industrial and agricultural historical land use has been shown to have a significant influence on soil Pb concentrations. Childcare centers in Yakima County, WA, with historical agricultural land use, and neighborhoods in Oakland, CA, with historical industrial activity, exhibited soil Pb concentrations above applicable regulatory thresholds (Durkee et al., 2017; McClintock, 2012). Industrial/manufacturing historical land use exhibited the least amount of EPA SSL exceedances in the current study; however, a positive association was identified between historical adjacent land use and reported building and demolition permits. In effect, the number of reported building and demolition permits increased as historical adjacent land use changed from undeveloped/greenspace to industrial/manufacturing. Previous studies have shown lower soil Pb concentrations in urban settings resulting from soil restoration and importing clean fill during development activities (Mao et al., 2014; McClintock, 2012; Nielsen et al., 2005). In 2021, O'Shea et al. (2021b) reported that soil Pb concentrations in Philadelphia did not have a significant correlation to the locations of former lead smelting facilities. Based on the concentrations observed, public parks in the study area with historical industrial/manufacturing land use likely underwent some form of soil restoration during development.

The results of a 2011 investigation in Beijing, China, revealed that soil Pb concentrations were higher in urban parks than in other land uses such as industrial and agricultural (Wang et al., 2011). Consistent with previous investigations, soil Pb concentrations in the

2011 Beijing study were shown to increase toward the more urbanized areas of the city (Wang et al., 2011). A 2005 investigation in Seville, Spain, reported elevated soil Pb concentrations in urban ornamental gardens can be attributed to organic gardening amendments (Ruiz-Cortés et al., 2005). In the current study, bare soil, recreational areas, building driplines, and roadside soil were prioritized for sampling purposes over soil found in flowerbeds and planted settings. In 2010, Lui et al. (2010) reported soil polycyclic aromatic hydrocarbon (PAH) concentrations in Beijing, China, were positively associated with heavily urbanized areas, "urban age" of the soil, and accumulation time. Consistent with the Lui et al. (2010) study, elevated soil Pb concentrations in the current study were significantly correlated with the age of the corresponding public park. When assessing the relationship between historical land use and soil Pb concentrations, it is proposed that longer duration of land use as an urban greenspace allows for greater accumulation of anthropogenic Pb in soils. Consequently, public parks with undeveloped/greenspace historical land use serve as a primary sink and source in urban environments for legacy anthropogenic Pb.

Significant associations were identified between the spatial distribution of predicted BLL high-risk areas in the current study (Fig. 5) and areas with high percentages of children with BLLs ≥ 5 $\mu\text{g}/\text{dL}$ in 2013–2015 (Fig. 6). Areas with higher percentages of child BLLs ≥ 5 $\mu\text{g}/\text{dL}$ were found to be located within 1500 ft or directly within high-risk areas identified in the BLL interpolation. A significant, positive correlation was identified between soil Pb concentrations, historical land use, and the number of children with BLL ≥ 5 $\mu\text{g}/\text{dL}$ located within 1500 ft of each park. The results of the current study were consistent with previous investigations which have established significant associations between soil Pb concentrations and elevated BLLs in children (Bradham et al., 2017; Pavilonis et al., 2021; von Lindern et al., 2016; Zahran et al., 2013). Soil found in neighborhood recreational areas, such as public parks, can migrate indoors via footwear track-in and can contribute significantly to levels of indoor dust (Hunt et al., 2006; Layton & Beamer, 2009). Studies have established a temporal dimension to elevated BLLs, and the summer months have been shown to result in increased child BLLs (Zahran et al., 2013; Fileppi et al., 2005; Haley & Talbot, 2004). The observed increase in child BLLs may be attributed to increased outdoor recreational activity during the summer months, which

results in greater exposure to Pb-contaminated soil. In addition, hand-to-mouth or “mouthing” behaviors in childhood have been shown to result in increased exposure to Pb-contaminated soil and dust (Nielsen et al., 2005). Pb atmospheric dispersion studies by Le Roux et al. (2008) and Stille et al. (2011) have demonstrated that Pb-contaminated soil and dust can travel significant distances, and Pb dispersion is influenced by factors such as wind direction, rainfall, and vegetative cover. Based on these parameters, drier atmospheric conditions and the presence of bare soil in public parks is likely to result in increased Pb soil and dust dispersion.

The geospatial and statistical relationships observed in the study between elevated soil Pb concentrations and child BLLs from 2013 to 2015 suggest measured soil Pb concentrations can effectively model community-wide contamination and childhood Pb exposure. Approximately 23.6% of the variance in child BLLs ≥ 5 $\mu\text{g}/\text{dL}$ was attributed to soil Pb concentration, historical adjacent land use, and historical site land use, and 13.3% was attributed solely to historical site use. Other factors which are likely to have a significant correlation with the elevated BLLs identified in the study area include age of housing, variance in outdoor activity times or soil ingestion rates, and indoor sources of Pb exposure. According to the 2014 CDC child BLL assessment in Philadelphia, entryway Pb floor dust concentrations were strongly correlated with participant BLLs (Dignam et al., 2019). Overall, two (2) distinct areas were identified where elevated risk of exposure to Pb-contaminated soil and significant potential for child BLLs ≥ 5 $\mu\text{g}/\text{dL}$ exist. In addition, geospatial interpolation and the EPA IEUBK model were used successfully as a multi-disciplinary approach for mapping soil Pb contamination and predicted BLLs throughout the study area. The results obtained regarding soil Pb concentrations and historical land use clearly demonstrate that accumulation time and the age of soils in the urban environment play significant roles in heavy metal contamination. Based on these findings, the assessment of historical land use can be used to identify high-risk recreational areas in urban communities with greater potential for accumulation of anthropogenic Pb in soils.

The current study has some limitations regarding the collection of soil samples and analytical methods. Soil samples for this study were collected from accessible areas within public parks. Residential

soil samples were not included in the study; however, residential sampling conducted during previous studies is discussed in “Discussion.” Laboratory analytical methods were not used in this study. Soil Pb concentrations were determined using a XRF direct-reading instrument. For the purposes of this study, “Historical land use” was determined based on land use prior to the widespread adoption of leaded gasoline in the early 1920s. Historical land use was identified using atlas maps of Philadelphia, PA, from 1910; additional historical documents were not included in this investigation. The predicted mean child BLLs in the study are based on the assumption that children are likely to contact Pb through several exposure routes including outdoor recreational activity on grass or exposed dirt, consumption of drinking water, ambient air exposure, and fugitive dust ingestion. The proximity to each public park of children with BLLs ≥ 5 $\mu\text{g}/\text{dL}$ was determined using the corresponding census tract boundaries containing the child’s primary address and not physical location/address. Physical location, primary address, and other sensitive information were redacted from available data.

Conclusion

Public park soils are a primary reservoir for anthropogenic Pb in the urban environment. The current study has identified strong correlations between undeveloped/greenspace historical land use, soil Pb concentrations above the EPA SSL, and elevated child BLLs. Based on these findings, future investigations of soil Pb concentrations in urban public parks may focus on historical land use and accumulation time as meaningful explanatory variables. This study has expanded on the available analytical tools for investigating childhood BLLs by integrating XRF soil sampling, geospatial mapping, statistical analysis, and biokinetic modeling. Using the CDC reference value for BLL screening purposes, predicted BLL high-risk areas in this study have the potential to guide future community screening efforts in South Philadelphia, PA. Considering the soil samples in this study were collected within public recreational areas, childhood Pb exposure should be of greater public health concern in the City of Philadelphia. Soil restoration and routine maintenance activities throughout South

Philadelphia public parks should include the removal of contaminated topsoil, importing clean fill, and decreasing areas with bare soil. In addition, state and municipal governments can choose to adopt regulations requiring the sampling of urban soils prior to disturbance.

Declarations

Conflict of interest The author declares no competing interests.

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