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Social and spatial distribution of soil lead concentrations in the City of Santa Ana, California: Implications for health inequities

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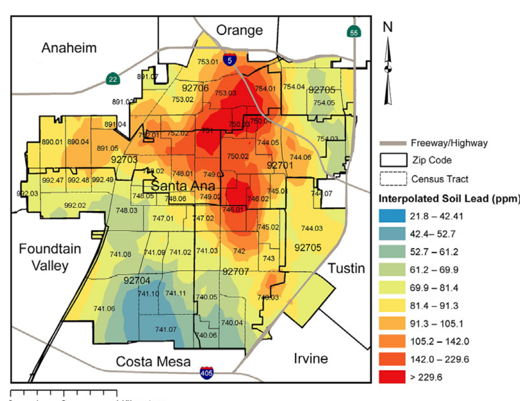
HIGHLIGHTS

- Lead exposure is a problem that disproportionately impacts communities of color and low income.
- Assessed the distribution of soil Pb levels and related social vulnerabilities in Santa Ana, CA.
- Soil Pb varied by landuse, with residential and roadway areas showing the highest concentrations.
- Soil Pb concentrations were higher in socioeconomically disadvantaged Census tracts.
- Over 50% of residential samples had Pb levels above California EPA recommendations.

GRAPHICAL ABSTRACT



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ABSTRACT

Background: Lead (Pb) exposure is a problem that disproportionately impacts low-income communities and communities of color. We applied a community-based participatory research approach to assess the distribution of soil Pb concentrations and related social vulnerabilities across Census tracts in Santa Ana, CA.
Methods: Soil Pb samples (n = 1528) were collected by the *¡Plo-NO! Santa Ana! Lead-Free Santa Ana!* partnership in 2018 across Santa Ana, CA, at a high spatial resolution and measured using XRF analysis. Pb concentrations were mapped and spatial interpolation was conducted to generate a continuous smoothed map of soil Pb concentrations across the city. American Community Survey data was used to examine Pb across Census tracts based on social and economic factors, and to allow for the development of a Cumulative Risk Index to identify areas at high risk of health impacts.
Results: Soil Pb concentrations varied by landuse type and socioeconomic factors. Census tracts with a median household income below $50,000 had over five times higher soil Pb concentrations than high-income Census tracts. Soil samples collected in tertiles with the highest percent children, residents without health insurance,

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Risk assessment

renter-occupied housing units, and lowest percent college educated residents had 90.0%, 96.1%, 75.2%, and 87.0% higher Pb concentrations on average, respectively, compared to their counterparts. Overall, 52.7% of residential samples had Pb concentrations in excess of the 80 ppm California EPA recommendation, and 11 Census tracts were characterized as high risk according to our Cumulative Risk Index.

Discussion: This study underscores the need for precautionary measures relating to disturbances of the soil, particularly for areas where children play outside, given children's higher absorption of lead. It also informs environmental justice initiatives and identifies vulnerable subpopulations at greater risk of Pb exposure, thus warranting community-driven recommendations for policies and initiatives to remediate soil Pb and protect public health and health equity.

1. Introduction

Exposure to lead (Pb), a neurotoxicant, is associated with an array of adverse educational, health, and socioeconomic outcomes (LeBrón et al., 2019a, 2019b; Markowitz and Rosner, 2013). Moreover, communities of color, low-income communities, and residents of urban areas are disproportionately affected by Pb exposures (Jones et al., 2009; Mielke et al., 1983; Rothenberg et al., 1996).

The health and health equity implications of Pb exposure are many. For example, evidence links exposure to Pb during childhood with adverse neurological and cognitive outcomes, including smaller brain volume, lower working memory and processing speed, and more limited perceptual reasoning (Canfield et al., 2003; Grandjean and Landrigan, 2014; Lanphear et al., 2005; Reuben et al., 2017); poor school attendance and academic performance (Aizer et al., 2018; Zhang et al., 2013); asthma (Boskabady et al., 2018; Pugh Smith and Nriagu, 2011; Wang et al., 2017; Wu et al., 2018); and engagement with carceral systems (Needleman et al., 2002; Nevin, 2007). Furthermore, previous studies have found positive associations between lead and pregnancy complications including gestational hypertension and pre-eclampsia (Kennedy et al., 2012; Poropat et al., 2018). Maternal eclampsia risk was found to increase dose-responsively to neighborhood soil Pb levels, with women being four times more likely to develop eclampsia in areas with high levels of soil Pb relative to areas with low levels of soil Pb (Zahran et al., 2014). Even relatively low prenatal Pb exposures as assessed by maternal blood or cord blood are also associated with adverse birth outcomes including low birthweight, preterm birth, smaller head circumference, and smaller crown-heel length (Taylor et al., 2015; Xie et al., 2013). Pb exposures throughout the life course – including, for example, during childhood and adulthood – also affects the health of older adults, with implications for cardiovascular risk (Navas-Acien et al., 2007; Vig and Hu, 2000), renal problems (Vig and Hu, 2000), osteoporosis (Alswat, 2017), and reduced cognitive functioning later in life (Reuben et al., 2017; Shih et al., 2006; Weuve et al., 2009).

Pb exposures are unequally distributed in the US population. Blood Pb levels are a common indicator of recent Pb exposures in children (Centers for Disease Control and Prevention, n.d.). The percent of children one to five years of age with blood lead levels above 5 μg/dL has declined in the early 21st century (Centers for Disease Control and Prevention, n.d.; Wheeler and Brown, 2013). Yet, Black (Jones et al., 2009) and Latina/o/x (Jones et al., 2009; Rothenberg et al., 1996) children and children of low-income households (Jones et al., 2009) consistently have elevated blood lead levels relative to their counterparts that are non-Latino white and are from higher income households.

This evidence has led to policies to prevent the sales of lead-based paint and leaded gasoline in the U.S. (Hanna-Attisha, 2018; Markowitz and Rosner, 2013) and to the development of national, state, and local Childhood Lead Poisoning Prevention programs (Centers for Disease Control and Prevention, n.d.). Despite these policies, individuals, households, and communities continue to be exposed to lead, including through the legacies of past lead-based products as well as contemporary Pb exposures (Hanna-Attisha, 2018; Markowitz and Rosner, 2013). Pathways of Pb exposure include lead paint in older homes and other buildings through lead chips in building and house dust (Jacobs et al., 2002; Rabinowitz et al., 1985), lead-contaminated water systems (Hanna-Attisha et al., 2016), lead in other consumer products (e.g., food systems), Pb exposures in workplace settings (e.g., metal smelting) (Grigoryan et al., 2016), and lead in soil (Laidlaw et al., 2016; Mielke et al., 2016; Wu et al., 2010), which may have originated from lead-based paint, historical gasoline, or other sources. However, environmental assessments indicate ongoing environmental Pb exposures despite the removal of lead from many consumer products (Hanna-Attisha et al., 2016; LeBrón et al., 2019a, 2019b). Importantly, numerous studies show Pb and the resuspension of soil Pb to be strongly associated with blood Pb levels in children (Maisonet et al., 1997; Mielke et al., 2007; Weitzman et al., 1993; Zahran et al., 2013).

In community settings, lead in the soil is a persistent exposure source due in part to limited disturbances of soil and limited degradation of lead. While a robust evidence base indicates that no level of Pb exposure is safe for young children (LeBrón et al., 2019a, 2019b), the Environmental Protection Agency (EPA) indicates a limit of soil Pb levels of 400 ppm (ppm) in areas where children play, and 1200 ppm in other uncovered areas (U.S. Environmental Protection Agency, 2001). However, in an effort to minimize Pb exposure for children, the California EPA's Office of Environmental Health Hazard Assessment advises that areas where children play have soil Pb levels at or below 80 ppm (Carlisle, 2009).

The study described below builds upon a robust history of community-academic partnerships in environmental health research (Israel et al., 2012). Our community-academic partnership, *¡Plo-NO! Santa Ana! Lead-Free Santa Ana!,* formed in response to community concerns about soil Pb identified by an investigative report (Cabrera, 2017). The research questions that guided these analyses extend the body of research regarding the spatial distribution of soil Pb by examining cumulative social and environmental exposures. Extending studies of cumulative social vulnerabilities and risk of exposure to air pollution (Morello-Frosch et al., 2011; Sadd et al., 2011; Schulz et al., 2017) to the study of risk of exposure to soil Pb, this study focuses on the following questions: (1) given susceptibility to long-term health effects of lead exposure for children, is a younger age composition at the Census tract level associated with higher soil Pb levels? (2) is residential socioeconomic status at the Census tract level associated with soil Pb concentrations? (3) are residential racial/ethnic characteristics at the Census tract level associated with soil Pb concentrations? and (4) do multiple social and economic vulnerabilities at the Census tract level cumulate to render communities particularly vulnerable to soil Pb? Based on community knowledge elicited through ongoing discussions among our community-academic partnership and review of the literature, we hypothesized that Census tracts with a higher fraction of children, households of lower SES and those with a higher proportion of residents who identify as Latina/o/x/Hispanic, immigrant, or limited English proficiency will have higher soil Pb concentrations; and that social and economic vulnerabilities to soil Pb exposure will be correlated with one another and with soil Pb concentrations.

2. Materials and methods

This study was conducted as part of the *¡Plo-NO! Santa Ana! Lead-Free Santa Ana!* community-academic partnership that has been working together since 2017 to equitably bring together community and academic partners to understand and address environmental injustices and their implications for health equity and social, economic, and political well-being in Santa Ana, CA (LeBrón et al., 2019a, 2019b). Partners include Orange County Environmental Justice; Jóvenes Cultivando Cambios, a youth-led cooperative; and a subset of faculty and staff at the University of California, Irvine. Our partnership emerged following an investigative report by Cabrera (2017), which indicated that several areas in Santa Ana – a predominantly Latina/o/x, immigrant, and low-income community (American Community Survey, 2016a, 2016b) – had soil Pb levels three to ten times higher than the EPA's cut-point for lead toxicity (400 ppm) (U.S. Environmental Protection Agency, 2001). Santa Ana children are 64% more likely to have elevated blood lead levels relative to children across California (California Department of Public Health, 2012a, 2012b). This investigative report activated community-driven questions about the prevalence of Pb and other toxicants in Santa Ana, the distribution of these toxicants, and connections between Pb exposures and adverse social, economic, and health outcomes for residents of Santa Ana, CA. These discussions catalyzed the formation of our community-academic partnership, and the study described below. The University of California, Irvine Institutional Review Board classified this study as exempt. Data for the analyses described below are drawn from soil samples collected by our trained personnel and from the U.S. Census Bureau's American Community Survey.

2.1. Study region

Santa Ana is a densely populated city located in southern California in the southwestern region of the United States. It is the administrative center of Orange County, which is the sixth most populated county in the U.S. With a total population of approximately 337,716 residents, Santa Ana spans an area of 70.6 km^2 and includes 61 Census tracts (The City of Santa Ana, 2020). In terms of population, Santa Ana ranks the second largest city in Orange County, and is the eleventh largest city in the state (The City of Santa Ana, 2020). The majority of Santa Ana residents identify as Latina/o/x (77.3%), followed by Asian (11.4%) and white (9.4%), with a relatively high proportion (45.2%) of residents being immigrants (U.S. Census Bureau, 2020). As of 2019, the city includes 78,563 housing units and has a median household income of $65,313 (2018 dollars) (The City of Santa Ana, 2020).

Potential sources of soil Pb contamination in Santa Ana include both historic and present-day emissions. Prior to its incremental phaseout beginning in 1986, and its subsequent ban from on-road use by EPA in 1996, leaded gasoline and therefore vehicle traffic represented a major source of lead emissions in the United States (Newell and Rogers, 2003). While leaded gasoline has not been entirely eliminated in the U.S., it's use is limited to small piston engine aircraft, marine vessels, farm equipment, and other off-road vehicles (Kessler, 2013). Since Santa Ana is bordered by three major freeways, including the interstate 5 and 405 freeways and state routes 22 and 55, as well as the John Wayne Airport, the city is particularly vulnerable to legacy contamination from on- and off-road vehicle-related lead emissions. Santa Ana is also an industrial center with over 26,432 companies, including many metal-related industries (i.e. metal fabrication, metal cutting, metal processing) (U.S. Census Bureau, 2018). Thus, historic and present-day point-source emissions represent potential contributors. In the U.S., lead paint was historically used on many houses and other buildings. Disturbances of these painted surfaces through building renovations, demolitions, and weathering over time is therefore another likely contributor to soil Pb in the city (Rabinowitz et al., 1985). In Santa Ana an estimated 81% of housing units were constructed before 1980, whereas the U.S. federal government did not ban the sale of lead paint until just two years prior (1978) (U.S. Census Bureau, 2017). Lastly, given the city's history of agriculture, prior applications of lead arsenate pesticides represent another avenue through which lead may have entered the soil.

2.2. Field sampling

Soil samples were collected in Summer-Fall 2018 across seven landuse types: arterial roads, schools, parks, gardens, industrial areas, business areas, and residential units. Because most schools, businesses, and industrial sites were not directly accessible for this study, samples were collected immediately adjacent to their boundaries (e.g. roadside near school). When feasible, at least six residential units across each Census tract in Santa Ana, CA, were sampled. Landuse type and the location of each sample point using global positioning system (GPS) coordinate was recorded by on-site field teams who were trained by the field coordinator.

Following methods by Wu et al. (2010), at each sampling location field teams selected an area that was unobstructed by physical barriers. When possible, a three-foot radius area was then marked, and soil samples from five points (central point and 4 separate points that were three feet from the center of the square) were obtained after removing 1 cm of soil (including vegetation cover). If it was not possible to achieve a three-foot radius, at residential units, samples were drawn from near the dripline of the home, and at least two locations in the yard (e.g., front, back, side). Four to five samples were drawn from each garden. Samples were then air dried and sieved with brass screen (#50 mesh, twice; #100 mesh once), yielding fine soil dust samples to characterize Pb exposures for which young children are most vulnerable (Stalcup, 2016). Soil samples were collected from 560 locations throughout Santa Ana, CA with 1528 soil samples to yield a high spatial resolution. Additionally, in order to establish a baseline soil Pb level, eight soil samples were collected outside of Santa Ana in nearby state and regional parks in Orange County that could be considered relatively pristine and unaffected by major local anthropogenic lead sources (i.e. traffic, industry, buildings).

2.3. Soil analysis

Samples were analyzed via XRF instrumentation (SPECTRO XEPOS HE Benchtop XRF Spectrometer), a well-established and recognized method for identifying the total lead levels, as well as the levels of other commonly measured metals in soil samples (Maliki et al., 2017). The machine used in this study operates under optimal temperature conditions of 20–25 °C and undergoes routine multi-channel analysis calibration using standard reference materials at the start of each week, with global calibration taking place every six months. Each soil sample in this study was scanned five times by the XRF machine to ensure reproducibility and stability of measurements, showing a low average absolute measurement error of 1.0% across all Pb samples. To further confirm quality laboratory analysis, a subgroup of samples ($n = 18$) was subjected to XRF analysis a second time (five more scans), yielding an excellent correlation ($r = 1.0$).

2.4. Landuse

For this analysis, park and garden samples were treated as a single landuse type called "park," while industrial area and business area samples were treated as a single landuse type called "industrial." This was done because these landuse types were considered similar enough in nature to consolidate, and because their consolidation resulted in more meaningful sample sizes. Thus, there were five landuse types in total used for this analysis including: arterial roadways, schools, parks, industrial areas, and residential units. In three cases, samples were described to be a mix of two landuse types. Categorizing these samples into a single landuse type therefore required further discretion. In only one of these cases would a different classification have meaningfully impacted the average lead concentration for a landuse type. This was the case for a mixed school-roadway sample, where a high lead concentration of 314.0 ppm would have resulted in a significant increase in the average lead concentration for school samples due to the small school sample size (n = 10) and low concentration of school samples. Instead, the categorization of this sample within the roadway category (n = 76) had a negligible impact (±1%) on the average.

2.5. Demographics

We used 2010 Census data to obtain population counts for all Census tracts (n = 61) in Santa Ana, CA. The American Community Survey (ACS), conducted every year, was also used to obtain information about household income, race/ethnicity, education, insurance coverage, spoken languages, nativity, and age at the Census tract level. For the ACS, five-year averaged data from 2012 to 2016 (henceforth, 2016) was used since averages provide a more stable representation of community-level factors, and because 2016 was the most recent year for which geo-coded shapefiles were available in ArcGIS.

2.6. Analysis

Summary statistics for soil Pb samples were calculated across all samples, by landuse type, and for one group of samples collected outside of Santa Ana that represent baseline soil Pb. In order to visualize soil Pb concentrations spatially and estimate concentrations between sampling sites, we conducted simple kriging in ArcGIS.

To assess differences in soil Pb concentrations and demographic factors within Census tracts, demographic factors were first converted to percentages of the population in each Census tract for each indicator before constructing the vulnerability index described below. These indicators included: percent of residents who identified as Latina/o/x or Hispanic, immigrant non-native residents (henceforth, *immigrants*), residents who reported speaking no or limited English, residents who did not have health insurance coverage, residents under five years of age, renter-occupied housing units, and residents with a college education or higher.

Once a percentage for a given demographic variable was calculated across each Census tract, that percentage could be assigned to all lead samples collected within that Census tract. Using these assigned percentages, we then determine the 33th and 66th percentiles for that specific demographic factor across all samples. This allowed us to separate soil Pb samples into tertiles depending on the demographic characteristic of the Census tracts within which each sample was collected. Using the prior example of percent Latina/o/x/Hispanic population, this would mean that we divided soil Pb samples into three approximately equal sized groups depending on whether those samples were collected in Census tracts with a percent Latina/o/x/Hispanic population that was relatively low (1st tertile), high (3th tertile), or in between (2nd tertile). Therefore, percentiles did not reflect citywide statistics, but rather sample-wide statistics. With a total soil sample size of n = 1528, samples sizes for each tertile were approximately n = 510 ± 20. Statistical significance between sample means was assessed at the $p = 0.05$ cutoff. In addition to tertile analyses, we also conducted quartile analyses, the results of which are presented in the supplementary materials section.

2.6.1. Hazard Index

To characterize the potential for Pb exposure via the soil, each Census tract was assigned a score ranging from 1 (low) to 4 (high) based on the quartile distribution of soil Pb concentration (4 = high lead). This score was then scaled to be equally weighted with the vulnerability index described below.

2.6.2. Vulnerability Index

To characterize social and economic vulnerability of communities within each Census tract to Pb exposure and heightened or more adverse responses to these exposures, we developed a vulnerability index (Schulz et al., 2017). This index took into account six social and economic factors that could place a community at an increased health risk due to Pb exposure, including: median household income, percent of housing units occupied by renters, percent of population under age five, percent of residents reporting speaking limited or no English, percent of residents without health insurance coverage, and percent of residents with a college education or higher. Values for each factor were calculated based on quartile distribution rankings, ranging from 1 (low risk) to 4 (high risk). Due to our interest in assessing whether cumulative risk was disproportionately elevated among Census tracts with higher proportions of people of color, our vulnerability index did not include "percent Latina/o/x/Hispanic population" as a factor in our ranking system. Since each Census tract was assigned a vulnerability score ranging from 1 to 4 across six different factors, each Census tract had a potential cumulative vulnerability score (sum of individual scores) that ranged from 6 to 24. This methodology is similar to that developed elsewhere (Morello-Frosch et al., 2011; Sadd et al., 2011; Schulz et al., 2017).

2.6.3. Cumulative Risk Index

To assess cumulative risk, a single aggregated index was derived as the sum of the equally-weighted Hazard Index and Vulnerability Index, and then scaled to range from 0 (low risk) to 1 (high risk). Risk scores were then projected onto a map at the Census tract level.

3. Results

3.1. Descriptive statistics

Fig. I presents boxplots, whiskers, and outliers for soil Pb samples categorized by landuse type. The lower and upper boundaries of each box indicate the interquartile range (IQR) of the sample, while the centerline and "X" symbol indicate the sample median and mean, respectively. The lower and upper whiskers indicate the minimum and maximum data points after excluding outliers as defined as Q_1 or $Q_3 \pm 1.5*IQR$. Such outliers are depicted as individual points. As shown in the figure, the sample means for each landuse type were all higher than their medians, suggesting that the distribution of lead soil samples was consistently skewed in the positive direction. This is also made apparent by the abundance of outliers above the mean. Residential landuse had the most outliers and areas proximal to schools had the fewest outliers. Residential and school landuse types also had the largest (n = 1173) and smallest (n = 10) sample sizes, respectively.

Table I presents summary statistics for all soil Pb samples and groups of samples categorized by landuse type, as well as the extent to which soil Pb standards were exceeded. The average Pb concentration (standard deviation) across all soil samples (n = 1528) was 123.1 ppm (181.3 ppm), with a median concentration of 77.8 ppm and range from 11.4 to 2687.0 ppm. The high standard deviation suggests a wide amount of variability, which is also reflected by the boxplots in Fig. I. By comparison, the average and standard deviation of Pb concentrations across our baseline soil samples (n = 8) was 30.3 ppm and 7.9 ppm, respectively (min: 21.8 ppm; max 42.5 ppm). In terms of landuse type, roadway samples had the highest mean lead concentration (172.9 ppm), followed in order by residential (128.4 ppm), industrial (122.6 ppm), park (72.5 ppm), and school (37.9 ppm) samples. For the industrial landuse type, further distinguishing these samples into business (n = 4) and industrial (n = 85) landuse types did not have a meaningful impact on results (data not shown). The sum of samples

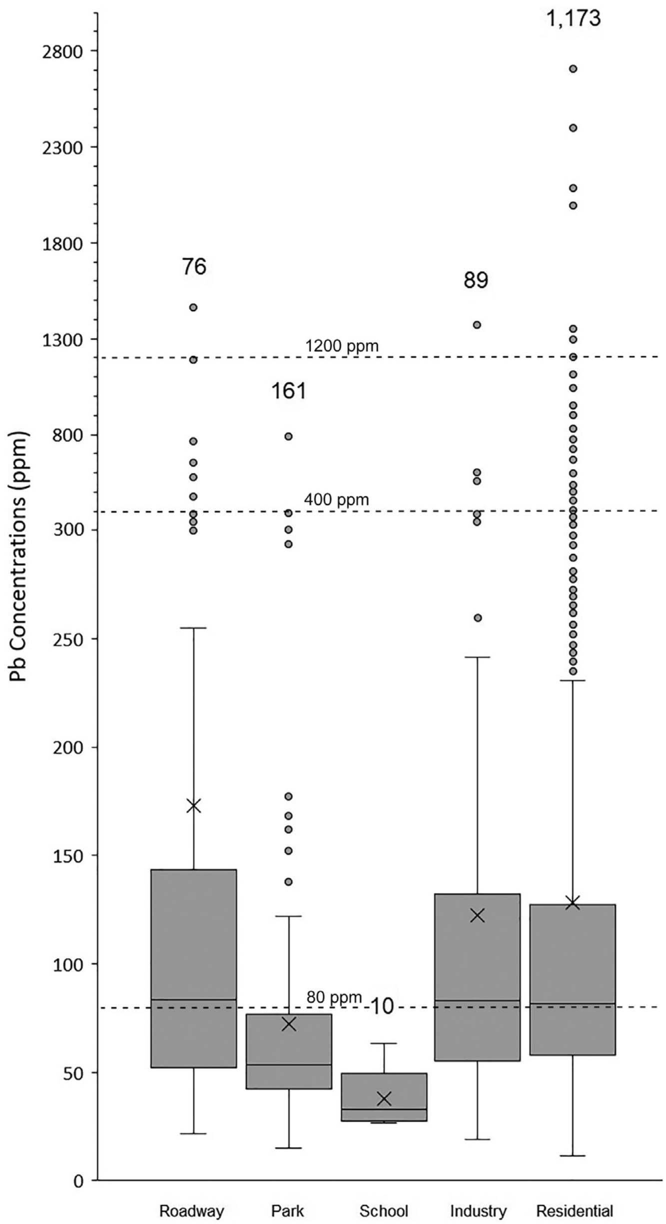

Fig. I. Boxplots describing lead soil concentrations across samples collected by landuse types. The symbols "X" denote sample means while the overlying values indicate sample sizes. The California recommendation for play areas with children (80 ppm), and U.S. EPA standards for areas where children play (400 pmm) and other uncovered areas (1200 ppm) for soil Pb are presented as dotted lines.

across all landuse types (n = 1509) does not add up to our total sample size (n = 1528) because there were 19 samples that were excluded from landuse analysis because their landuse information was not available.

Concentrations exceeding 80 ppm and 400 ppm, which represent the California EPA recommended safety level for soil Pb in areas where children play and the U.S. EPA standard for Pb in soil for play areas, respectively, were found across all landuse types except for samples collected near schools. The California recommendation was exceeded by 751 soil samples, and the EPA standard by 60 samples, accounting for approximately 48% and 4% of samples, respectively. The EPA standard for non-play area soil (1200 ppm) was exceeded by 10 soil samples, eight of which were found in residential areas that could serve as play areas for children. As a fraction of samples collected within a single landuse type, roadway and residential samples exceeded the 400 ppm EPA standard at the highest frequency (11.8% and 4% of samples, respectively), whereas the 1200 ppm standard was exceeded most frequently by samples collected in the roadway (1.3%) and industry (1.0%) landuse areas.

3.2. Social and spatial distribution of soil Pb

Fig. IIa–h presents average Pb concentrations across soil samples grouped into tertiles based on Census tract data for eight separate demographic characteristics. Fig. IIa presents average Pb concentrations (95% CI) of soil samples categorized according to the median household income of each sample's Census tract. Statistically significant differences ($p < 0.05$) in average Pb concentrations were observable across each income category, with Pb concentrations tending to decrease with increasing income bracket. On average, soil samples collected in Census tracts with median household incomes below \$50,000 had 440% higher and 70% higher Pb concentrations compared to samples collected in Census tracts where the median household income was greater than \$100,000, and between \$50,000 and \$100,000, respectively.

As shown in Fig. IIb, average Pb concentrations decreased as the proportion of college educated residents increased. In Fig. IIc–g, there was a consistent pattern of increasing Pb concentrations within Census tracts that had a higher proportion of: children under five years of age, residents without health insurance coverage, renter occupied housing units, Latina/o/x/Hispanic residents, immigrant residents, and residents speaking limited or no English. In nearly all cases, each tertile exhibited statistically higher ($p < 0.05$) average Pb concentrations than the previous. One exception was for Fig. IIe (percent renter-occupied), where differences were only statistically significant for the upper tertile ($p < 0.05$) relative to the low and middle tertiles. Additionally, for Fig. IIh (percent limited or non-English speaking), differences between the lowest two tertiles were not statistically significant. However, there was a statistically significant increase in average Pb concentrations for the upper tertile ($p < 0.05$) compared to the low and middle tertiles.

Table I
Summary statistics for soil Pb concentrations (ppb) in Santa Ana, CA, according landuse type and the extent of regulatory threshold exceedances.

Landuse	N	50th	Mean	S.D.	Min	Max	>80 ppm[a]		>400 ppm[b]		>1200 ppm[c]	
							N	%	N	%	N	%
Industry	89	82.8	122.6	164.8	19.2	1371.0	46	51.7	3	3.4	1	1.1
Park	161	53.4	72.5	75.3	15.1	790.2	37	23.0	1	0.6	0	0.0
Residential	1173	81.7	128.4	187.9	11.4	2687.0	608	51.8	47	4.0	8	0.7
Roadway	76	83.6	172.9	251.1	21.8	1461.0	40	52.6	9	11.8	1	1.3
School	10	32.8	37.9	12.9	26.4	63.1	0	0	0	0	0	0
Baseline	8	28.9	30.3	7.9	21.8	42.5	0	0	0	0	0	0
All[d]	1528	77.8	123.1	181.3	11.4	2687.0	737	48.2	60	3.9	10	0.7

[a] California EPA safety recommendation for soil Pb in play areas.
[b] U.S. EPA standard for soil Pb in play areas.
[c] U.S. EPA standard for soil Pb in non-play areas.
[d] Does not include baseline samples.

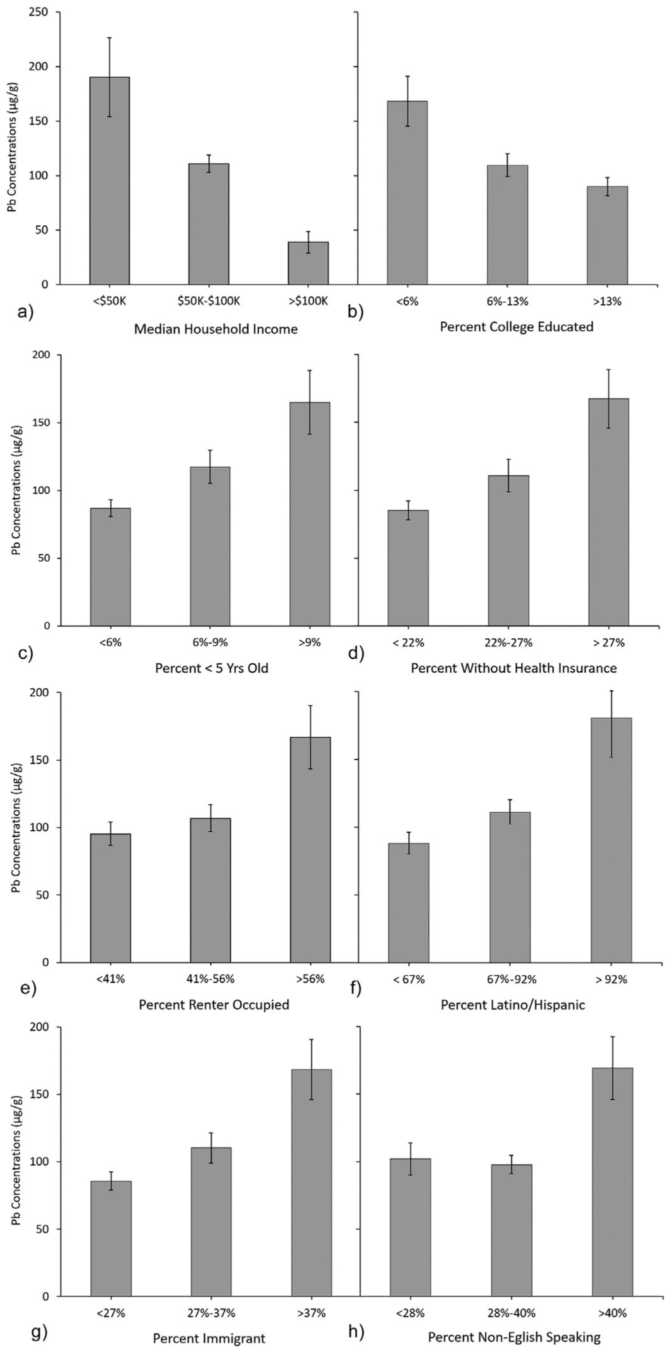

Fig. II. Average Pb concentrations (95% CI) of soil samples by social and economic characteristics of Census tracts.

More specifically, soil samples collected in tertiles with the highest percent children, highest percent of people without health insurance coverage, highest percent of renter occupied housing units, and lowest percent of college educated residents had 90.0%, 96.1%, 75.2%, and 87.0% higher Pb concentrations on average relative to those from the lowest tertile, respectively.

Soil samples collected in tertiles with the highest percent Latina/o/x/Hispanic residents, immigrant residents, and residents speaking limited or no English had 105.1%, 96.4%, and 66.1% higher Pb concentrations, on average relative to the lowest tertile, respectively. This latter pattern was not observed across all groups of residents speaking limited or no English. Census tracts with higher fractions of Asian limited or non-English speakers, for instance, had relatively lower average Pb concentrations, as shown in Fig. SIV of the supplemental materials section.

Fig. III presents the number of Census tracts depicted according to their average Pb concentrations, as well as the total number of residents under five years of age who resided in those Census tracts. Of the 61 Census tracts in Santa Ana, the majority (78.7%) had average leads concentrations between 50 and 150 ppm, with 21 tracts (34.4%) between 150 and 400 ppm and three (4.9%) with concentrations less than 50 ppm. Importantly, there was one Census tract (18 samples) where average Pb concentrations were in excess of the 400 ppm EPA standard for play areas. Although this was only a single Census tract, there were over 650 children under five years of age who resided in that Census tract. What is more, an analysis of maximum Pb concentrations showed that 56 different Census tracts housing over 28,000 children had maximum Pb concentrations that exceeded the 80 ppm California safety recommendation, while 20 Census tracts housing over 12,000 children had maximum concentrations in excess the 400 ppm EPA standard.

Presented in Fig. IV is a map of interpolated soil Pb concentrations based on kriging. Results show the highest lead levels in the central region and northeast quadrant of Santa Ana, just southwest of the I-5 freeway. This area also corresponds with the downtown area of Santa Ana, and the 92,701, 92,706, and 92,703 zip codes. In contrast, the southwest quadrant and northeast corner of the map show the lowest estimated Pb concentrations. These areas correspond with zip codes 92,704 and 92,707.

Fig. V is a map depicting Santa Ana Census tracts according to their Cumulative Risk Index scores. As shown, the cluster of Census tracts in the central region of the city, just south of the I-5 freeway, had the highest cumulative risk scores. A map presenting the Vulnerability Index scores by Census tract is presented in Fig. SIII of the supplemental materials section. As shown in Fig. SV, we found a positive correlation ($r = 0.41$) between the Cumulative Risk Score of each Census tract and its percent Latina/o/x/Hispanic population.

4. Discussion

This study sought to examine the spatial distribution of soil Pb in an urban area in the Southwest region of the U.S. and to identify social and economic vulnerabilities to soil Pb exposure. Pb concentrations were found to vary widely, with approximately 4% and <1% exceeding U.S. EPA standards for play and non-play areas, respectively. Moreover, nearly half of Pb concentrations exceeded the California safety recommendation of 80 ppm for soil Pb in play areas. Soil Pb concentrations varied by landuse type, with samples collected near major roadways and residential areas having the highest concentrations.

There are three key findings from this study. First, within residential areas, 51.8% of samples had soil Pb concentrations in excess of the California EPA safety guideline for soil Pb in play areas, and 4% had concentrations in excess of the 400 ppm U.S. EPA standard for play areas. This finding is of importance for early life exposure given that residential areas frequently serve as play areas for children. One Census tract that housed over 650 children under age five had average Pb concentrations in excess of the 400 ppm U.S. EPA standard. In general, Census tracts with a higher fraction of children had higher average Pb concentrations. These findings highlight an important public health issue since children are an especially vulnerable subpopulation to the adverse neurological and social impacts of Pb exposure (Canfield et al., 2003; Lanphear et al., 2005; Reuben et al., 2017). Additionally, soil Pb and the resuspension of soil Pb have been demonstrated to be significant contributors to the blood Pb burden in children (Maisonet et al., 1997; Mielke et al., 2007; Weitzman et al., 1993; Zahran et al., 2013).

The mean (median) soil Pb concentration of 123.1 ppm (77.8 ppm) from this analysis was similar to recent findings from another community-based participatory study by Johnston et al. (2019), which showed median soil Pb concentrations in nearby Los Angeles County, CA, to be 190 ppm, with nearly 14% of samples exceeding the 400 ppm U.S.

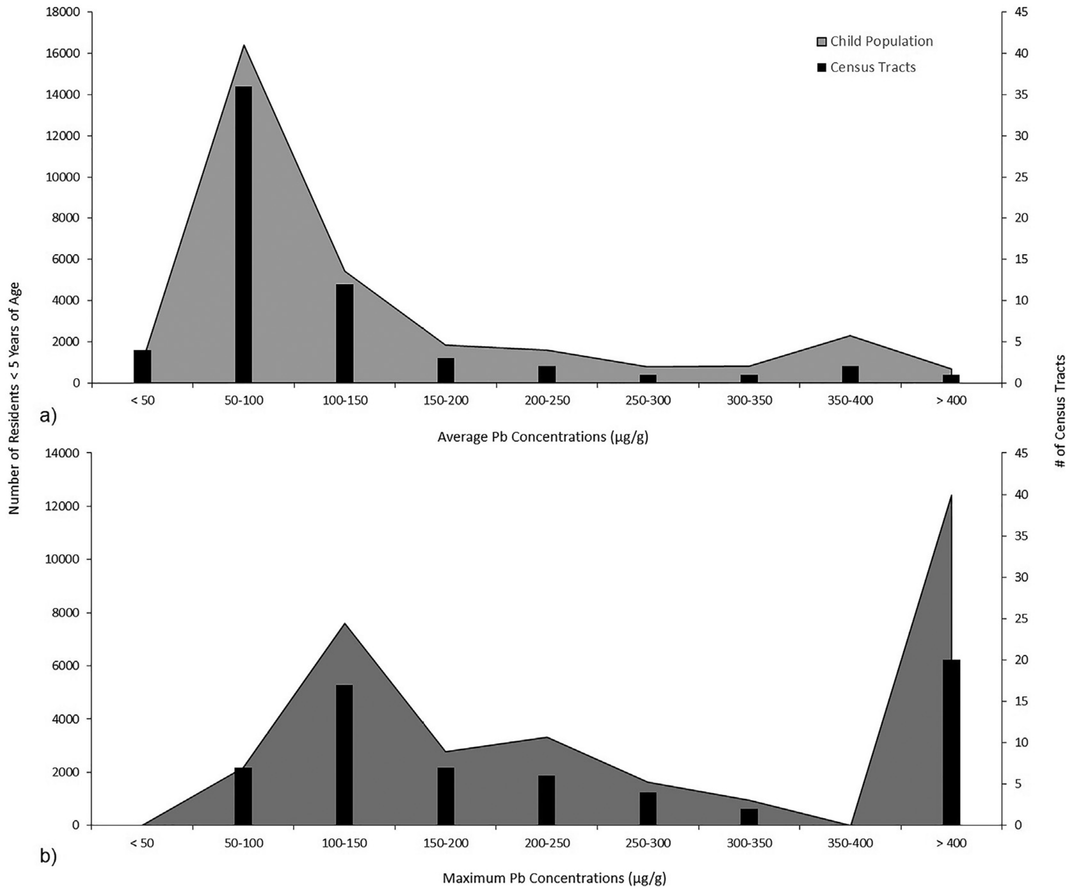

Fig. III. The number of Census tracts where a) average and b) maximum Pb concentration fell within specified ranges, and the total number of residents under age five who resided in such Census tracts.

EPA standard. Higher concentrations in that study appear attributable in part to the proximity of measurement sites to a lead-acid battery smelter. An important finding from the Los Angeles study was an association between soil Pb levels with both in utero and early life exposure to Pb (based on teeth Pb levels) even where neighborhood-averaged soil Pb concentrations were below 400 ppm. In another soil sampling study of central Los Angeles County, results showed a mean (median) soil Pb concentration of 181 ppm (81 ppm), with a total of 8% of samples exceeding 400 ppm (Wu et al., 2010). As with the present study, higher concentrations were reported near freeways and arterial roads.

Second, results suggest a robust pattern of greater vulnerability to soil Pb exposure for residents of lower socioeconomic statuses. For example, Census tracts with a lower median household income had considerably higher average soil Pb concentrations compared to higher income Census tracts. Similarly, Census tracts with a lower fraction of college educated residents had much higher Pb concentrations on average. Lastly, we observed higher soil Pb concentrations within Census tracts that had higher fractions of renter-occupied housing units and residents without health insurance coverage. Across nearly all of the socioeconomic factors examined, soil Pb concentrations either increased or decreased in a stepwise fashion across all three tertiles, reinforcing the existence of a meaningful socioeconomic gradient in vulnerability to exposure to soil Pb. These results showcase environmental and socioeconomic inequities in the city of Santa Ana and underscore the need for increased public outreach, awareness, and intervention to protect children and families and minimize Pb exposure. These results may also serve to aid in the deployment of municipal resources towards areas and residents of lower socioeconomic status.

Third, when examining important social characteristics, Census tracts with a higher fraction of immigrant, limited or non-English speaking, and Latina/o/x/Hispanic residents exhibited considerably higher average Pb concentrations. However, this pattern was reversed for Census tracts with higher fractions of limited or non-English speaking Asian residents. This could reflect differences in the socioeconomic statuses of these two populations, as indicated in post-hoc analyses of Census estimates of median household income included as Fig. SIV of the supplemental materials section.

Collectively, these results are consistent with a body of geospatial literature that reveal the disproportionate impact of Pb contamination in low-income communities and communities of color (McClintock, 2015; Mielke et al., 2007; Zhuo et al., 2012) and that theorize race and class as social constructs that are fundamental causes of health inequities (Phelan et al., 2010). Importantly, the presence of multiple social and economic disadvantages can foreseeably be synergistic so as to render a particular subgroup or Census tract at considerably higher vulnerability to Pb exposure. For example, neighborhoods where residents may be concerned about immigrant policing and have limited English fluency may be less inclined to inquire with authorities about Pb exposures in their community or engage with public health officials or initiatives relevant to their individual, household, or neighborhood experiences (Nichols et al., 2018). Additionally, having lower income and lacking health insurance may limit a household's or neighborhood's ability to individually or collectively obtain either public health advice for exposure prevention or medical attention following exposures, which are over-concentrated in these areas. It is also common that families who rent their homes have less flexibility to manipulate the property or landscape compared to families who own their homes. This lack of flexibility may render a household less able to take precautionary

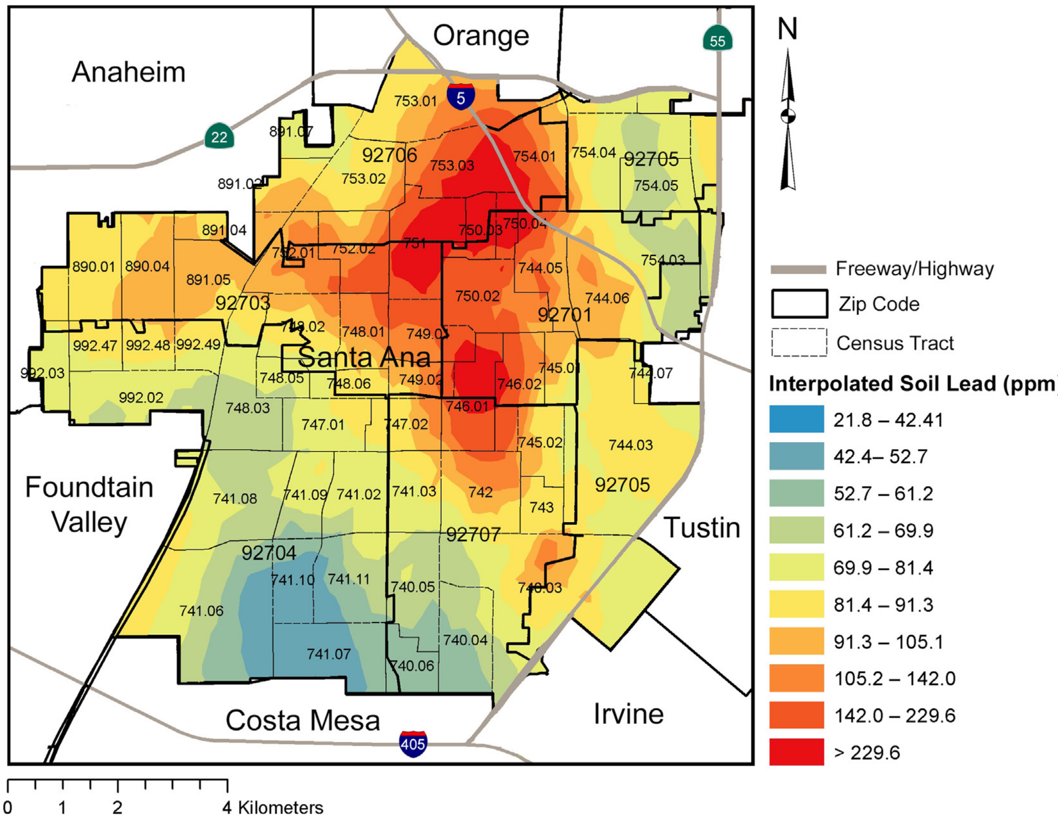

Fig. IV. Interpolated soil Pb concentrations based on 1528 samples collected in Santa Ana, CA.

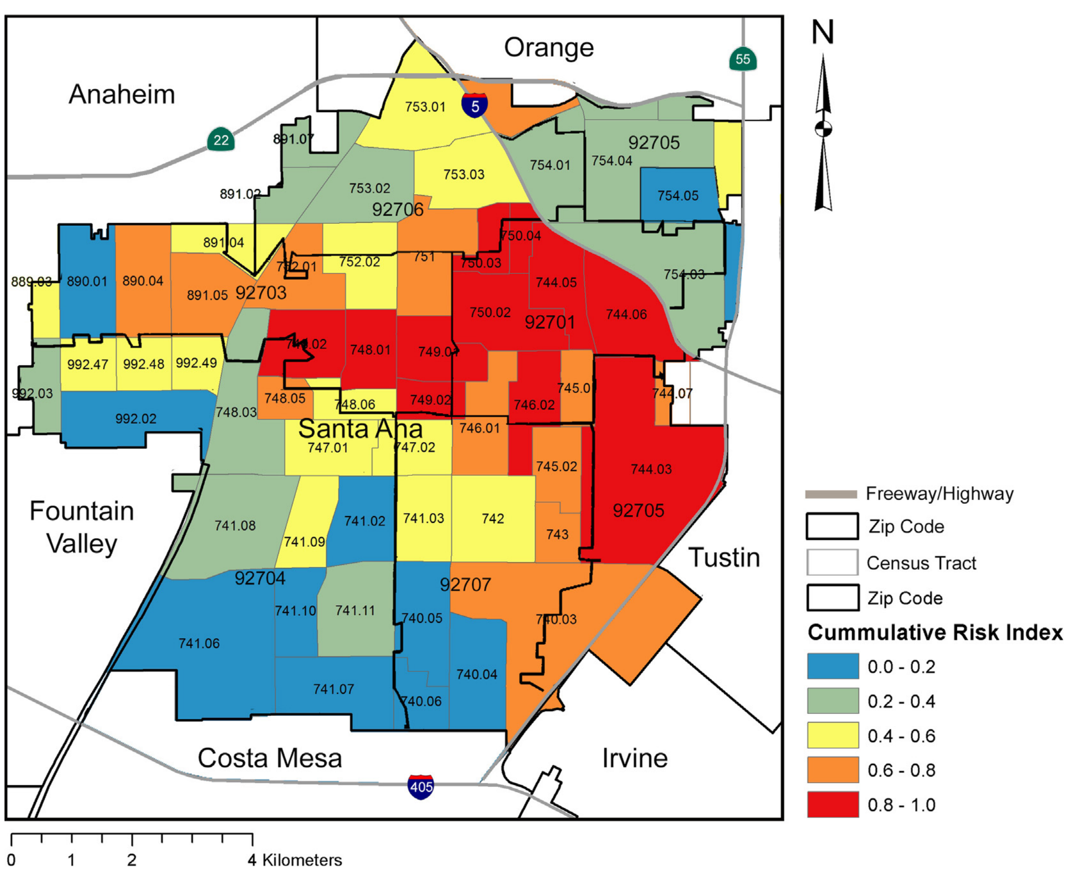

Fig. V. Map of Santa Ana and the Cumulative Risk Index scores for each Census tract, where 1 = greater and 0 = less risk related to Pb exposure.

measures to minimize Pb exposure, such as lead paint remediation, replacing topsoil, or covering topsoil with grass or gravel. These findings suggest that neighborhoods with a greater proportion of renters are important spaces for governmental action to support lead remediation.

We considered six social and economic factors in conjunction with average soil Pb concentrations for each Census tract in order to calculate Cumulative Risk scores across Santa Ana. Approximately eleven Census tracts were considered high risk (CR 0.8–1.0) and were primarily located in the central region of the city. We found a positive correlation between the Cumulative Risk score of each Census tract and its percent Latina/o/x/Hispanic population, which highlights the interconnections of racial-, age-, and socioeconomic-related vulnerabilities to soil Pb exposure. Such results are not only important for members of affected neighborhoods, but also for public health officials, city managers, and elected representatives charged with protecting public health and allocating resources for disease prevention and health promotion across the life course.

Additionally, results showing increased Pb concentrations near roadways and residential areas were reasonable and were consistent with prior studies (Wu et al., 2010). Higher concentrations near roadways may be explained by historic use of leaded gasoline in vehicles, making traffic emissions an important historic source of lead in the atmosphere and surrounding environment. Similarly, increased Pb concentrations in residential areas may be explained by the historic use of lead-based paint. As painted surfaces erode over time, lead-containing paint particles deposit on nearby soils. Moreover, in community discussions residents highlighted concern about several metal processing plants located in Santa Ana. While the U.S. EPA Toxic Release Inventory identifies five industrial sources of atmospheric lead in Santa Ana, with total lead emissions of 19.1 kg (42.0 lbs) reported between 1987 and 2017, these reported emissions likely represent an underestimate of true emissions. For instance, auto-repair shops, body shops, and auto-battery recycling centers are usually small-scale businesses that do not report to EPA. Importantly, however, these sources are more dispersed and often closer to residents, rendering them of high importance to exposure. Future studies should disentangle contemporary sources of lead to soil and the contribution from historical lead in gasoline, paint, and industrial emissions.

4.1. Community-driven recommendations

Our partnership is developing several community-driven recommendations for policies and community-based initiatives to remediate soil Pb and prevent and mitigate exposures to lead. These recommendations are informed by our process of leveraging a community organizing strategy to discuss with residents who participated in the study: emerging findings, their interpretations of these findings, and recommendations for how our partnership moves forward to promote a healthier environment. Emerging recommendations fall into two interconnected multi-sectoral approaches: remediating soil with high Pb concentrations and addressing the effects of Pb exposures for affected community members. Recommendations that are currently still in development include eliciting support from governmental agencies with jurisdiction over soil Pb in Santa Ana to remediate soil, continuing to engage popular education strategies to enhance community consciousness of exposures to soil Pb, investing in early childhood education, making improving access to healthy and affordable foods, and ensuring that residents have regular access to quality health care. Additionally, our partnership is engaging in a visioning process to imagine new systems to promote community health, such as augmenting the vibrant local food sovereignty movement, developing a cooperative focused on soil remediation, and developing new channels of communication across generations and social identities in Santa Ana. As we continue to discuss these findings with affected community members, we will translate recommendations into a public health equity action plan.

4.2. Strengths and limitations

An important strength of this study is that it is grounded in community priorities and principles of community-driven community-academic partnerships (González, 2019; Israel et al., 1998; LeBrón et al., 2019a, 2019b; Wolff et al., 2016). The research questions, study design, study implementation, interpretation of findings, and ongoing development of a vision for a healthier community were each guided by our partnership process. Community-academic partnerships characterized by ownership of action research agendas by community and academic partners have greater potential for informing the translation of research into action to promote community health and health equity (González, 2019; Wolff et al., 2016). Another strength of this study is the random sampling of a large number of soil samples ($n = 1528$), thus allowing for a more spatially resolved understanding of the distribution of lead in the soil. This helps to reduce exposure misclassification. High density spatial sampling also enabled an assessment of average Pb concentrations at each Census tract, which is an improvement from prior studies which only examined the zip code level. An additional strength is the characterization of soil Pb across landuse types, which is useful to allow for targeted interventions to minimize exposure and to enable a better understanding of potential contributing sources of Pb.

This study had several limitations. First, despite a high number of sampling sites, a limitation of this study nonetheless was the inherent uncertainty of Pb concentrations between sampling sites. Such uncertainty can potentially lead to exposure misclassification, particularly where samples are sparser. Second, examining correlations between lead and social and economic characteristics at the Census tract level, as opposed to individual level, comes with limitations in the ability to draw conclusions. For example, while low-income Census tracts had the highest Pb concentrations, we do not know how Pb concentrations varied according to income level within a given Census tract. Third, our Cumulative Risk index can only be used as a general guideline of risk since risk assessment inherently involves a number of assumptions. Fourth, the vulnerability index was informed by U.S. Census estimates, which may systematically underestimate the population in subregions (e.g., Census tracts, zip codes) of Santa Ana, potentially contributing to an underestimate of the cumulative burden of exposure to lead. For example, Santa Ana is characterized by high levels of engagement of youth and adults of color with the criminal justice system who may not be represented in Census estimates of the population (Avila et al., 2019; Lai and Ashar, 2013). Additionally, as with many urban areas, Santa Ana is undergoing gentrification processes that escalate housing instability, housing quality concerns, and homelessness in the community. Accordingly, recent Census estimates may offer a conservative assessment of place-based risk of soil Pb exposure. Future studies are warranted that examine the source(s) of soil Pb, associations of soil Pb levels with health outcomes, and that test the effectiveness of health equity interventions designed to mitigate soil Pb exposures and remediate the environment.

5. Conclusions

This spatial analysis of soil Pb concentrations across Census tracts found that Census tracts with a higher fraction of children, lower median household income, lower percent of college educated residents, higher proportion of renters, and higher fraction of residents lacking health insurance coverage had higher average Pb concentrations compared to other Census tracts. Similarly, Census tracts with a higher fraction of immigrant, limited English proficiency, and Latina/o/x/Hispanic residents exhibited much higher Pb concentrations than other Census tracts. These findings illuminate environmental inequities and areas of vulnerability as it relates to Pb exposure, and underscore the need for public outreach and intervention to reduce and eventually eliminate inequities in exposure to soil Pb.

CRediT authorship contribution statement

Shahir Masri: Conceptualization, Methodology, Software, Data curation, Formal analysis, Writing - original draft, Writing - review & editing, Visualization. **Alana LeBrón:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Michael Logue:** Data curation, Writing - review & editing. **Enrique Valencia:** Conceptualization, Investigation, Supervision, Project administration, Funding acquisition, Writing - review & editing. **Abel Ruiz:** Conceptualization, Supervision, Project administration, Funding acquisition, Writing - review & editing. **Abigail Reyes:** Conceptualization, Funding acquisition, Writing - review & editing. **Jean M. Lawrence:** Writing - review & editing, Funding acquisition. **Jun Wu:** Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.140764.

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