Title

Use of historical mapping to understand sources of soil-lead contamination: Case study of Santa Ana, CA

Permalink
https://escholarship.org/uc/item/6398k31g

Journal
Environmental Research, 212(Pt D)

ISSN
0013-9351

Authors
Rubio, Juan Manuel
Masri, Shahir
Torres, Ivy R
et al.

Publication Date
2022-09-01

DOI
10.1016/j.envres.2022.113478

Peer reviewed

Environmental Research 212 (2022) 113478

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Use of historical mapping to understand sources of soil-lead contamination: Case study of Santa Ana, CA

Juan Manuel Rubio [a,1,*], Shahir Masri [b,1,**], Ivy R. Torres [c], Yi Sun [b], Keila Villegas [d], Patricia Flores [d], Michael D. Logue [b], Abigail Reyes [e], Alana M.W. LeBrón [c,f], Jun Wu [b]

[a] *School of Humanities, University of California, Irvine, CA, 92697, USA*
[b] *Department of Environmental and Occupational Health, Program in Public Health, University of California, Irvine, CA, 92697, USA*
[c] *Department of Health, Society, and Behavior, University of California, Irvine, CA, 92697, USA*
[d] *Orange County Environmental Justice, Santa Ana, CA, 92705, USA*
[e] *Community Resilience Projects, Office of Sustainability, University of California, Irvine, CA, 92697, USA*
[f] *Department of Chicano/Latino Studies, University of California, Irvine, CA, 92697, USA*

ARTICLE INFO

Keywords:
Lead
History
Environmental justice
Soil contamination
Traffic emissions
Heavy metal
Leaded gasoline

ABSTRACT

This paper investigates the historical sources of soil-lead contamination in Santa Ana, California. Even though dangerous levels of soil-lead have been found in a wide variety of communities across the United States, public health institutions lack clarity on the historical origins of these crises. This study uses geo-spatial data collected through archival research to estimate the impact of two potential sources of lead contamination in the past – lead-paint and leaded gasoline. It examines, through a combination of statistical and historical methods, the association between lead concentrations in contemporary soil samples and patterns in the evolution of the city's physical features, such as the growth of urbanized areas and the historical flow of traffic. We emphasize the value of historical data collected through archival research for understanding the sources of environmental lead, particularly leaded gasoline, which our study found to be the most likely and most prominent contributor to soil-lead in Santa Ana's environment. This research contributes to environmental-justice advocacy efforts to reframe lead poisoning as a systemic environmental issue and outlines the path forward to community-level remediation strategies.

1. Introduction

Lead poisoning is a pressing environmental justice issue worldwide. To date, however, lead-related public health literature has primarily focused on the effects of lead on the human body, demonstrating that severe cases of lead poisoning (30 μg/dl or above) result in the deterioration of the gastrointestinal, hematological, and neurological systems (potentially leading to death), with less severe cases still impacting health and developmental outcomes (ATSDR, 2002). Studies have shown that children, given their greater lead exposure (e.g., greater hand-to-mouth activity, lead in play areas, etc.), can suffer from attention-deficit/hyperactive disorder (ADHD), decrements in IQ, behavior problems, lowered test scores, and other developmental issues when exposed to blood-lead levels of 10 μg/dl or lower (Geier et al., 2018; Aizer et al., 2018; Lanphear et al., 2000; Jusko et al., 2008; Wang et al., 2008; ATSDR, 2002). To date, there is no safe level of lead in children's blood that has been identified.

Despite extensive research on lead-related health effects, few studies attempt to characterize the environmental causes behind lead poisoning and elevated blood lead levels. What is more, the dominant understanding of lead contamination rests on problematic assumptions about the sources of lead in living environments. In some cases, direct industrial emissions are known to be responsible for affecting local communities, as demonstrated in smelter towns such as South Bend, Indiana and El Paso, Texas (Pell and Schneyer, 2016; Díaz-Barriga et al., 1997). In most cases, however, lead poisoning is attributed to the presence of lead-paint in old buildings. The IEUBK (Integrated Exposure, Uptake, and Biokinetic) model used by the Environmental Protection Agency

---

* Corresponding author.
** Corresponding author.
E-mail addresses: rubiojm1@uci.edu (J.M. Rubio), masris@uci.edu (S. Masri).
[1] First authors with equal contribution.

https://doi.org/10.1016/j.envres.2022.113478
Received 15 December 2021; Received in revised form 10 May 2022; Accepted 11 May 2022

(EPA), for example, uses "age of buildings" and "poverty" as proxy variables for estimating the risk of lead exposure in any given census tract. This assumption, however, does not account for important environmental sources of lead contamination (Levin et al., 2008). More specifically, the conventional approach to estimating lead contamination does not adequately address historical emissions of leaded gasoline within urban environments. Between the 1920s and 1990s, automobiles using leaded gasoline exhausted lead into the air through tailpipe emissions. The deposited lead, then, accumulated in the soil near roadways, given that lead does not appreciably dissolve, biodegrade, or decay and is not rapidly absorbed by plants (Mielke et al., 2011; Sciences, National Academy, 1993).

Research describing lead-based paint as the primary cause of lead poisoning, particularly among children, points out that deteriorating lead paint in homes contains between 1 and 5 mg/cm^3 of lead (Meyer et al., 2008; ATSDR, 2002). In 1974, however, Sayer et al., 1974 identified dust and hand-to-mouth contact as a potential primary contributor to lead ingestion among children. Subsequently, in 1998, Mielke and Reagan examined blood-lead samples and presented epidemiological evidence that lead particles deposited to the soil and house dust posed a greater threat to children than intact lead-paint. Other studies have similarly suggested that the "soil-to-dust-to-blood" pathway to lead poisoning, rather than direct ingestion of paint chips, is the main pathway behind child lead poisoning (Mielke and Reagan, 1998; Lanphear et al., 1996, 2002).

Although it is possible that urban lead contamination is primarily a consequence of natural building wear (e.g., improper lead-paint removal and/or home-remodeling activities that pulverized lead-paint and release lead particles) (Mielke et al., 2001), significant evidence has shown leaded gasoline to be an important historical source of lead emissions (accounting for 66–86% of emissions worldwide) (Sciences, 1993; U.S. Environmental Protection Agency (USEPA, 1986; Kovarik, 2005). One study estimated that 4.6 million metric tons of lead were used in gasoline nationwide between 1950 and 1980 (Mielke et al., 2011). Importantly, southern California (including Santa Ana) consumed the largest share of total lead additives (0.4 M metric tons) used over that time period in the state (Mielke et al., 2010, 2011). As it relates to exposure, soil-lead can become resuspended into the air, especially during the summer and fall months, even decades after initially being emitted by vehicles (Harris and Davidson, 2005; Laidlaw and Filippelli, 2008).

In contrast to drawing blood, which identifies lead exposure once it has already occurred and is therefore only a means of secondary prevention, understanding the nature of soil-lead contamination in urban spaces allows for primary prevention and is paramount in the fight against lead poisoning. What is more, understanding the sources of lead contamination has important implications for groups advocating for environmental justice. Specifically, in the U.S., race-based residential segregation and other discriminatory practices have resulted in lead poisoning disproportionately affecting communities of color (Markowitz and Rosner, 2014). Despite important reductions in the number of lead-poisoning cases since the 1980s, environmental injustice around lead exposure remains a major issue today, particularly among children. Following the 2015 lead-poisoning crisis in Flint, Michigan, an investigative report counted at least 3000 communities across the U.S. where the share of lead poisoning cases among children was 5% or higher (Pell and Schneyer, 2016). Worldwide, the United Nations has estimated that one in three children are currently poisoned with lead (i.e., blood lead ≥5 μg/dl), primarily in developing countries (Rees and Fuller, 2020). In the predominantly Latina/o/x city of Santa Ana, California, children are 64% more likely to have elevated blood lead levels relative to other children across the state (CDPH, 2012a, 2012b). In Santa Ana, soil lead concentrations are also disproportionately prevalent among lower-income and Latina/o/x communities, as previous studies from our research group have shown (Masri et al., 2020, 2021), causing community members in the city to advocate for remediation strategies and lead-prevention measures that are effective, equitable, and community-based.

This study presents an innovative methodological approach to estimate the relative contribution of leaded gasoline to contemporary soil-lead levels in Santa Ana, California. We used archival material, such as historical road maps and historical aerial images, to generate GIS data that were then analyzed against soil-lead measurements. These data were also examined in relation to other variables, such as zoning maps and the age of buildings, to evaluate the relative impact of other potential sources of lead contamination. We hypothesized that historical urban features (e.g., older roadway networks) would be better correlated with soil-lead concentrations than its newer counterparts. Using Santa Ana as a case study, this study enables a better understanding of the role that leaded gasoline and other sources have played in contributing to soil-lead contamination in urban environments. What is more, this study emphasizes the importance of incorporating historical variables, such as historical roadways and traffic flows, when attempting to understand the sources of lead contamination and lead poisoning in a community.

2. Materials and methods

2.1. Community-based science

This study is the result of a multi-year community-academic collaboration that was catalyzed following the publication of a report documenting lead contamination within the city of Santa Ana, California (Cabrera, 2017). Orange County Environmental Justice (OCEJ) partnered with the youth collective Jóvenes Cultivando Cambios (JCC; Youth Cultivating Changes) and scholars and staff at the University of California, Irvine (UCI) to launch a campaign (*¡Plo-NO Santa Ana! or Lead-Free Santa Ana!)* dedicated to investigating the lead crisis in this city and advocating for its remediation, which culminated in a comprehensive soil contamination study involving the collection of soil samples across Santa Ana, CA (Lebrón et al., 2019). The analysis of social and spatial distributions of soil-lead in Santa Ana, and the health risk they present, were subsequently published (Masri et al., 2020, 2021). An important question that was not answered by these earlier publications, yet which was frequently raised by residents in Santa Ana and members of OCEJ, was "where did all this lead come from?" The present study stems from this unanswered question and the critical concern among community members about the sources of lead contamination in their city.

This research is connected with collaborative efforts to remediate the lead crisis in Santa Ana and address environmental injustices in both Orange County and elsewhere. It contributes to strengthening community-science organizing models, which seek to: leverage peer-reviewed studies for mobilizing residents, conduct community science (in which members of affected communities drive the research agenda and actively participate in the research process), and support public advocacy efforts related to outreach, education, policy, and remediation (Israel, Eng, and Schulz, 2005; Wallerstein et al., 2017). It also informs conversations with local authorities and elected officials regarding strategies for remediating the soil, protecting tenant rights when remediating soil and other sources of lead, and offering public blood testing for city residents. In this sense, this research directly informs policy debates, policy recommendations, and resident-driven discussions regarding community-based solutions to fostering a healthier environment. Data for the analyses described below are drawn from archival sources and soil samples collected by our trained personnel and from the U.S. Census Bureau's American Community Survey. The UCI Institutional Review Board classified this study as exempt.

2.2. Study region

Santa Ana is a densely populated city located in southern California in the southwestern region of the United States, ranking as the second largest city in Orange County and the eleventh largest in the state (The City of Santa Ana, 2020). It is the administrative center of Orange County, which is the sixth most populated county in the U.S. with a population of approximately 3 million. 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). As one of the oldest established towns in Orange County, CA, Santa Ana is home to predominantly working class Latina/o/x, Asian, and immigrant residents and is also a community with a vibrant community organizing history (González, 2017). 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). The city also consists of a relatively young population, with approximately 7% of residents under five years of age and a median age of 33.2 years (U.S. Census Bureau, 2019; City of Santa Ana, 2020). Within the city is a mix of residential, commercial, and industrial areas, with the so-called industrial corridor being an area of particular importance to residents who are concerned about potential sources of environmental pollution. As of 2019, the city included 78,563 housing units and had a median household income of $65,313 (2018 dollars) (City of Santa Ana, 2020).

2.3. Field sampling & laboratory analysis

In the summer and fall of 2018, trained community members collected soil samples across seven landuse types in Santa Ana: arterial roads, parks and gardens, schools, industrial regions, business areas, and residential zones. Field teams responsible for soil sampling and the recording of landuse types consisted of local community members, including numerous members of the youth community, who were first trained by a field coordinator.

Building upon methodologies by Wu et al. (2010), field teams selected sampling locations at each sampling site that were not obstructed by physical barriers. Where possible, field teams marked a three-foot radius and obtained soil samples from five distinct points (one central point and four other points that were three feet away from the central point). Soil samples were collected at a depth of 2–6 cm after first removing 1 cm of soil (including vegetative matter). At residential units, field teams drew samples from dripline areas around the home and from a minimum of two locations throughout the yard (e.g., front yard, back yard). Field teams also made note of whether or not a visible irrigation system existed near each residential sampling location. Four to five samples were drawn from each residence. Samples were then air dried and sieved with brass screen (#50 mesh, twice; #100 mesh once), yielding fine soil dust samples to characterize lead exposures for which young children are most vulnerable (Stalcup, 2016). In total, 1528 samples across 560 different locations were obtained throughout Santa Ana, resulting in a highly spatially resolved characterization of soil heavy metals. Soil samples examined in this study were not composite samples (samples combined together), but rather were reported and analyzed separately from each distinct sampling point across residential and other areas.

Soil samples were measured using XRF technology (SPECTRO XEPOS HE Benchtop XRF Spectrometer), a well-established procedure for identifying the concentrations of commonly measured heavy metals in different sampling media (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. XRF methods have been used extensively in scientific research (Masri et al., 2015; Griffith et al., 2009; Carr et al., 2008) and have been shown to give results that are comparable to ICP-MS methods (Maliki et al., 2017). Each soil sample was analyzed five times to ensure reproducibility and stability of measurements, with an absolute measurement error and limit of detection of 1% and 0.2 ppm, respectively, across all soil-lead samples.(Instruments, Spetcro Analytical,). 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). Further details about the soil sampling protocol, including the collection of baseline samples, as well as laboratory analyses can be found elsewhere (Shahir Masri et al., 2021, 2020).

2.4. Historical research

This study leverages historical analyses for the purpose of understanding the sources of soil-lead contamination in urban environments, using the city of Santa Ana as a case study. It draws from the work of historians of the United States and Orange County to better understand the association between lead in urban environments and histories of industry, housing, and science. It also draws from original archival research to generate data for scientific analysis. The authors conducted archival research at the Orange County Archives in Santa Ana and examined digital archival collections, such as the David Rumsey Map Collection and the Online Archive of California. They also processed historical material from Orange County Public Works.

At the core of this methodological approach was the examination of historical maps and aerial photographs produced between 1906 and 1980. These maps and photographs were first digitized and georeferenced. They were then imported into ArcGIS software and several shapefiles (or layers) were created based on the information provided by these historical maps. Examples of these layers included points, polygons, and polylines drawn to reflect key features of the city (e.g., surface streets, vehicle counts, etc.). These shapefiles were then overlaid with the contemporary city map containing the locations of sampling points (n = 1528) where soil-lead measurements were collected. Fig. 1 presents an example of historical features, in this case 1931 roadways, that were reconstructed using historical maps, juxtaposed with a map of contemporary (2020) roadways. The association between such historical and contemporary layers and the contemporary soil-lead concentrations was then examined using ArcGIS and SAS Analytics software, as described below.

2.5. Historical landuse & statistical analysis

An important goal of this study was to understand the extent to which roadway traffic and other historical landuse variables may have contributed to contemporary soil-lead contamination. To achieve this aim, we examined correlations between the proximity of roadways at various timepoints in history (1906, 1931, 1938, 1953, 1960, and 2020) and soil-lead concentrations as measured in 2018 (henceforth, “contemporary” soil contamination). To conduct this analysis, we manually digitized historical roadway maps using ArcGIS software (except for the 2020 roadway map for which a digitized version was already publicly available in ArcGIS) and then calculated the geodesic distance of each soil sampling site to the nearest historical roadway. Scatter plots relating these distances and the concentrations of lead at their corresponding sampling points (n = 1528) were then generated, along with Pearson correlation coefficients, for each historical map. We compared correlation coefficients in order to identify the period in history during which roadways, and thus roadway traffic, best correlated with contemporary soil-lead contamination.

A similar approach was employed to assess the correlation between historical traffic counts and contemporary lead concentrations. In this case, vehicles visible through the 1931 and 1960 aerial photographs were converted into points in ArcGIS. These points were then summed within different radius buffer sizes (100, 250, 500, and 750 m) to generate continuous traffic count variables that were then used to generate correlation coefficients when plotted against contemporary lead concentrations. Since only one image was available per year, it was not possible to average several images per year to reduce potential count

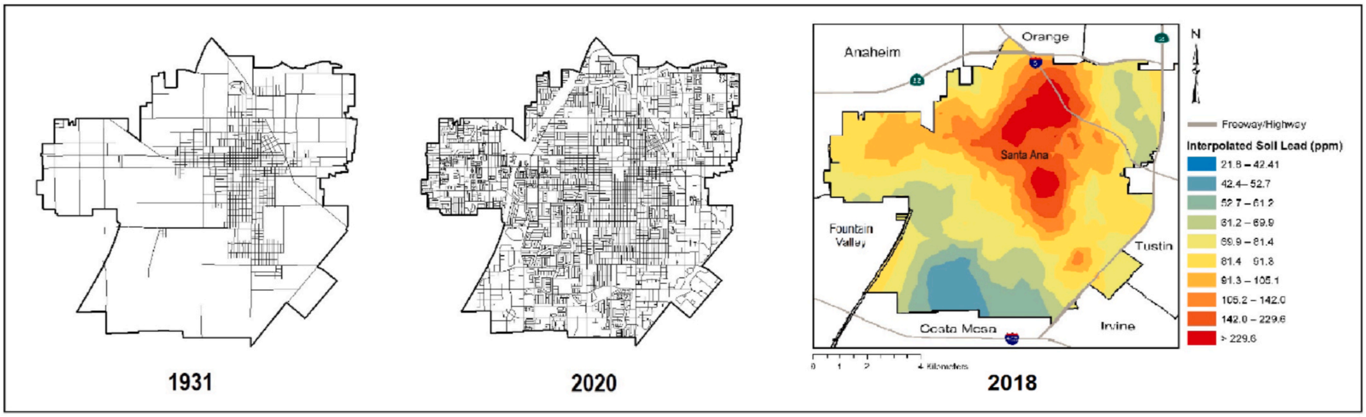

Fig. 1. Spatial distribution of historical and contemporary roadway networks in relation to soil-lead concentrations in Santa Ana, CA.

bias.

Additionally, we examined the urban footprint of Santa Ana at different periods in time. Although not source-specific, this approach enabled us to consider a multitude of human-related sources that included, but was not limited to, paint- and vehicle-related sources, and therefore to identify the extent to which lead contamination could be considered anthropogenic as opposed to natural. To conduct this analysis in ArcGIS, a polygon was drawn to represent the perimeter of the urbanized portion (henceforth "urban footprint") of Santa Ana during each point in history for which we were able to obtain historical maps. Circular buffer areas of various radii (100, 250, 500, and 750 m) were then drawn around each soil sampling site, and the overlapping area (expressed a percent of buffer overlap) between each buffer and the urban footprint was calculated. This enabled us to produce Pearson correlation coefficients relating lead concentrations to urban footprints over time and, in turn, to understand the potential association between lead contamination and anthropogenic sources.

Lastly, lead-paint is a commonly cited source of lead exposure. To investigate the hypothesis that paint on the exterior of buildings contributed to lead in Santa Ana's soil, we analyzed the association between soil-lead concentrations and both the total number of nearby buildings as well as the average age of buildings within various radius buffer sizes (10, 20, 30, 40, 50, 75, 100, 250, 500, 750 m) using parcel data obtained via the City of Santa Ana's GeoSpatial Open Data platform (City of Santa Ana, 2021).

2.6. *Quantile mixture analysis*

We analyzed the joint effects of gasoline, paint, and industrial sources using the "qgcomp" package in R (https://CRAN.R-project.org/package=qgcomp). Quantile g-computation is a causal inference method that combines the inferential simplicity of weighted quantile sum (WQS) regression with the flexibility of g-computation, a method of causal effect estimation. It can be seen as a generalization of standardization that computes estimates of the expected outcome distribution (i.e., soil-lead levels) under specific patterns of influencers or sources (e.g., house age as an indicator of paint emissions and traffic count as an indicator of traffic emissions) (Keil et al., 2020). Unlike inferential approaches that evaluate the effects of individual variables while holding other covariates constant, quantile g-computation can estimate the effect of a mixture of variables (or "exposures"), making it a very useful tool for public health research and understanding the effects of environmental exposures.

Quantile g-computation yields estimates of the effect of increasing all sources by one quantile simultaneously, which is useful to estimate a causal dose-response parameter of the source mixtures. Quantile g-computation can handle sources that are not associated with the outcome in the same direction (both negative and positive) and allows for non-linear and non-additive effects of individual sources and the mixture. In the multi-source model, we simultaneously included: 1) average building age within a 100 m buffer; 2) on-road vehicle count within multiple buffer sizes (100, 250, 500 m); and 3) distance to Santa Ana's industrial corridor (area between South Standard Ave. and South Grand Ave., and between East 1st Street and East Warner Ave.). The first two variables were chosen because they were the variables with the highest Pearson correlation, compared to other variables examined in this study, when plotted against contemporary soil-lead concentrations. In the case of the industrial corridor, this variable was included because it represented a distinct source relative to either traffic or paint sources and is a source for which local residents have expressed particular concern. Importantly, the industrial corridor in Santa Ana has remained stable in its location, primarily in the periphery of the city.

In multi-source models, β coefficients >0 indicate positive weights of individual source components while β coefficients <0 indicate negative weights of individual source components. The g-computation estimator ψ is the sum of all regression β coefficients of the exposures of interest, corresponding to the change in soil-lead concentrations expected for a one-quantile change in all sources simultaneously. In g-computation, the weight of an individual source is output as a scaled effect size based on which sources are included in the current analysis. Since the effect sizes are scaled to total to 100%, each variable's effect estimate corresponds to a percent contribution to the outcome variable of interest. In our case, this enabled the identification of the relative contribution of each unique lead source. Since modeling outputs can vary depending on slight changes in the input variable (e.g., buffer sizes), we ran the g-computation model five separate times using alternative buffer sizes (100–500 m) and map periods (years 1931 & 1960) so as to enable the calculation of average percent contributions.

3. Results

Fig. 2 depicts the association between present-day soil-lead concentrations and their proximity to historical roadway networks. Pearson correlation coefficients were used to characterize the association between lead measurements and the distance to the nearest roadway at several time points in history. The strongest Pearson correlation coefficients corresponded to the roadway networks as they existed in 1906, 1931 and 1938 ($r = -0.20$ for each) and the weakest correlation ($r = -0.06$) corresponded to the contemporary (2020) roadway network. A scatter plot shows that the association between lead and the distance to the nearest road decreases linearly as more recent roadway networks are considered ($r = 0.95$). As shown, older roadway networks (built prior to 1960) were over three times more correlated with lead contamination than the contemporary (2020) roadway network.

Fig. 3 presents average soil-lead concentrations at various distances from the roadway network, using 1931 as an example. The histogram

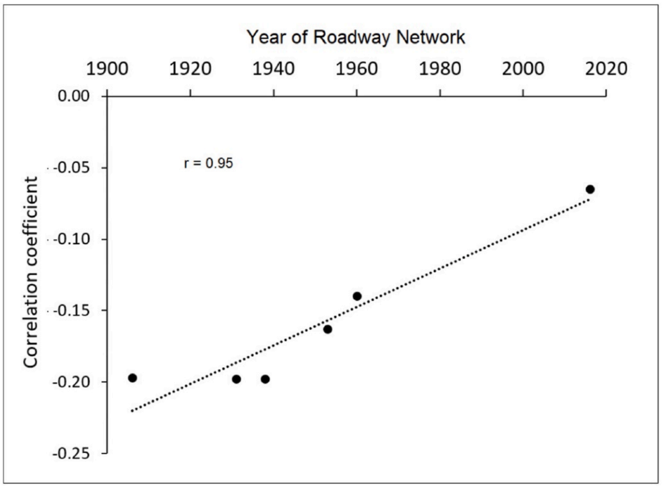

Fig. 2. Pearson correlation coefficients between present-day soil-lead concentrations (2018) and the distance to the nearest roadway at various time points in history in Santa Ana, CA (1900–2020).

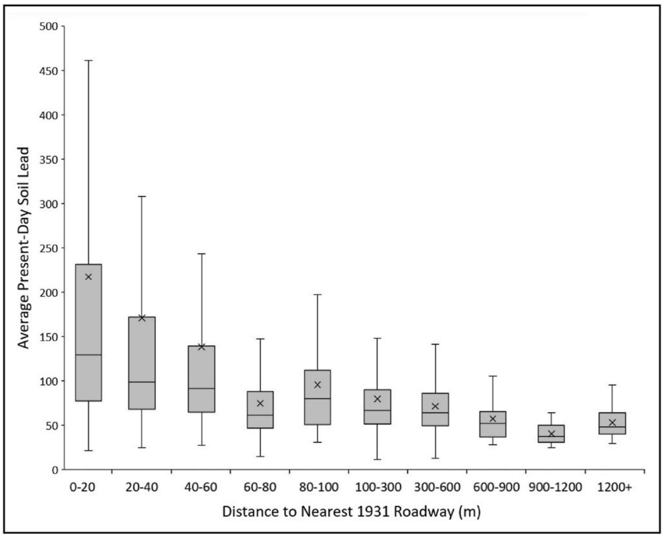

Fig. 3. Boxplots of soil-lead concentrations (2018) at various distances from roadway network, using 1931 roadway network in Santa Ana, CA as example. The centerline and "X" symbols indicate the median and mean, respectively, while the lower and upper boundaries of each box indicate the interquartile ranges (IQRs) and the lower and upper whiskers indicate the minimum and maximum data points after excluding outliers.

illustrates the declining concentrations of lead as the distance to the roadways increases. As demonstrated, soil-lead shows the greatest relative concentration when examining distances within 60 m of the road compared to further distances. Within this distance range of 60 m from roadways (see Fig. 4), a linear trend (r = −0.94) was exhibited from distances between 0-20 m and 80–100 m. At greater distances, decreasing average lead concentrations were still observed, however the slope was less steep. A similar pattern as that shown in Figs. 3 and 4 was observed across all other historical roadway networks examined in this study (see Figure S1 in supplemental materials section).

Historical traffic counts were also shown to be correlated with contemporary soil-lead contamination when examining both the 1931 and 1960 traffic count data. Correlations using the 1931 traffic counts were very similar across all buffer sizes, ranging from r = 0.29 (500 m buffer) to r = 0.31 (250 m buffer), while correlations using the 1960 traffic counts ranged from r = 0.16 (100 m buffer) to r = 0.31 (750 m buffer). Shown as an example in Fig. 5 are boxplots of soil-lead concentrations observed with increasing vehicle counts (from 1931 map) using a 500 m buffer size. The boxplots exclude outliers as defined as Q1 ±1.5 × IQR and Q3±1.5 × IQR. While a correlation of r = 0.99 was observed when plotting mean lead concentrations by mean vehicle count, the trend of increasing lead concentrations with increasing vehicles counts is also evident when examining the median concentrations (positive trend), as well as the increase in the interquartile ranges and maximum concentrations within each increasing traffic count category. A similar graph using the 1960 vehicle count data is presented as Figure S2 of the supplemental materials section, again showing a positive trend. Of note, while mean values strictly increase with each increase in traffic count category, the pattern for median values is not so strict (e.g, 1931 vehicle count exhibits a dip for highest "40+" category). Analyses examining lead concentrations within various buffer sizes and their overlap with historical city footprints of Santa Ana yielded correlation coefficients (r = 0.26–0.34) comparable to those described for vehicle counts (see Table S1 in supplemental materials section).

Fig. 6 demonstrates average soil-lead concentrations according to (a) average building age (year of construction) and (b) number of buildings within a 100 m buffer of the soil samples, and the corresponding Pearson correlation coefficients. As depicted, the number of buildings within a 100 m buffer was not readily correlated (r = −0.19) with soil-lead concentrations, whereas the consideration of building age was highly correlated (r = −0.92) with contemporary soil-lead.

Since the location of old buildings is closely correlated with location of historical roadways, an exposure mixture model was employed to estimate the relative potential contributions of gasoline- and paint-related sources to the contemporary distribution of soil contamination in Santa Ana. In the present case, Fig. 7 depicts the mean and range of the estimated percent contribution (summing to 100%) of traffic-, building-, and industry-related variables that were included in the mixture analysis. Overall, the average percent contribution of traffic count was 57.2% (range: 39.2–73.4%), while the average contribution of building age was 41.2% (range: 26.6–58.2%). The ranges of these values represent the upper and lower ends of the distribution of five separate modeling outputs that took into account alternative buffer sizes (100–500 m) and map periods (years 1931 & 1960) for the traffic count variable. Combined, a 10% increase in traffic and building age was associated with a 46.1 ppm increase in soil-lead concentrations on average (range: 35–58.1 ppm increase). Distance to the industrial corridor (in 10% changes) was associated with a negligible increase in soil-lead concentrations that was both slightly positive and slightly negative (~|2 ppm|), depending on the model.

Fig. 8 compares average soil-lead concentrations in residential areas where an irrigated system (e.g., garden hose, sprinklers, etc.) was observed as being either present or not. Samples collected in areas with no observed irrigation system present had approximately 34% higher soil-lead concentrations on average compared to sites with irrigation systems. The pattern was similar when comparing median concentrations. This relative difference could not be explained by differences in landuse type and/or income level as this pattern was very similar when examining irrigation while stratifying by both income and landuse type.

Fig. 8 also shows different soil-lead concentrations for different locations within a residential property (dripline, side of the house, backyard, etc.). Soil samples collected near the dripline and side of the house were characterized by the highest average soil concentrations (~150 ppm), whereas the front and back of the house contained lower average concentrations of approximately 130 ppm and 110 ppm, respectively. The pattern was similar when comparing median concentrations, except for the "back" area median which was the highest across all categories. All boxplots presented in Fig. 8 contained at least 150 measurement observations.

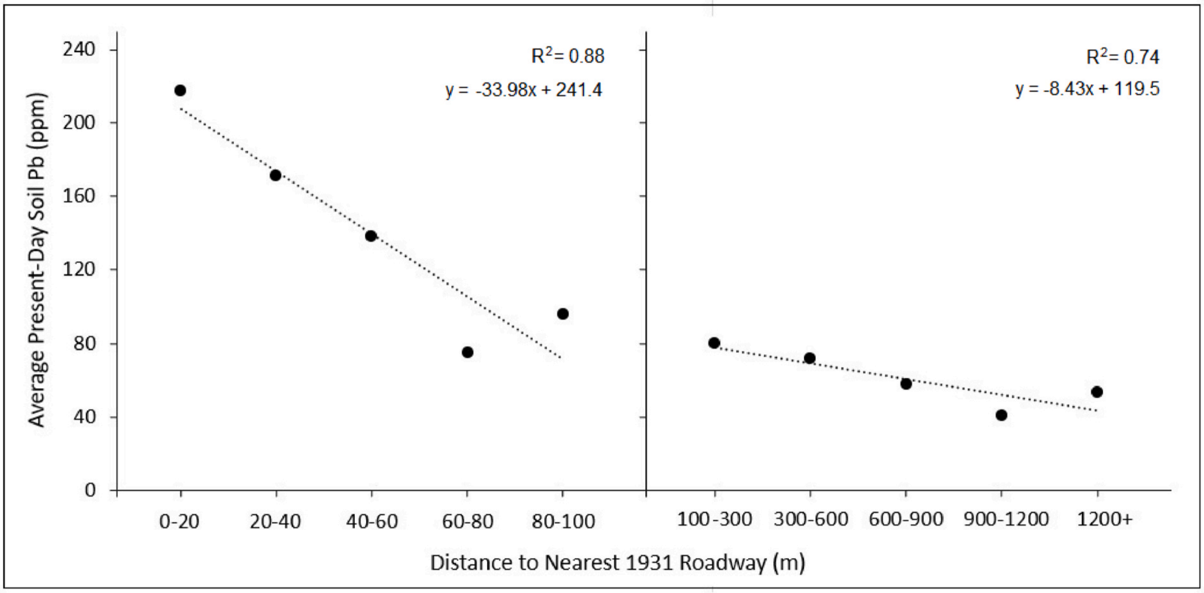

Fig. 4. Scatter plot of average soil-lead concentrations (2018) at various distances from the 1931 roadway network in Santa Ana, CA, showing linear decrease in soil-lead concentrations with increasing distance and change in slope over shorter *vs.* longer distances.

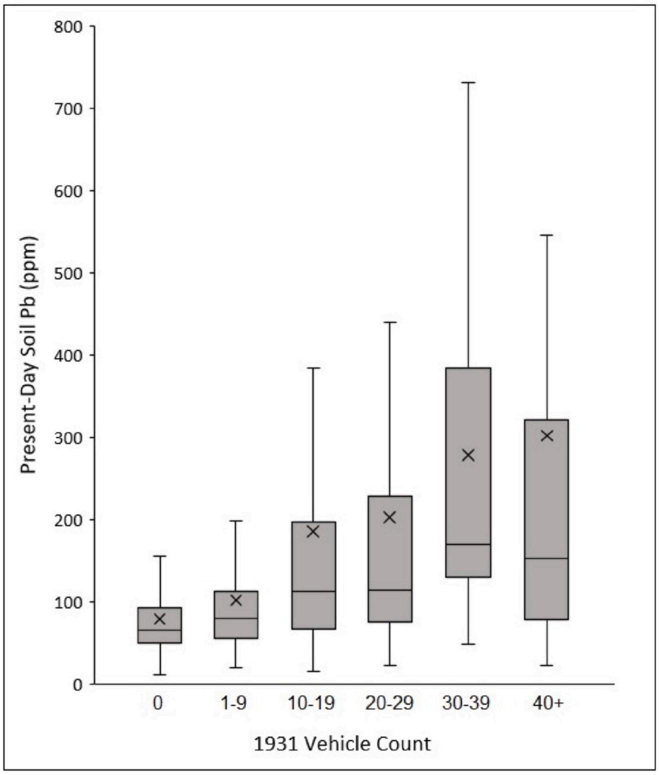

Fig. 5. Boxplots of soil-lead concentrations (2018) plotted for each "total vehicle count" category (within 500 m buffer) according to 1931 map of Santa Ana, CA. The centerline and "X" symbols indicate the median and mean, respectively.

4. Discussion

4.1. Leaded gasoline

This study makes an important methodological contribution to the field of exposure assessment within public health. The analysis underscores the necessity of considering historical, in addition to contemporary, roadway features when seeking to understand the sources of modern-day lead contamination in urban environments. Contemporary roadway network data for the U.S. is readily available and provided in a digital and geo-referenced format and, therefore, tends to be the most widely used in environmental health studies. Had this study only used contemporary roadway data, the association between historical roadway features and contemporary soil contamination would have been missed.

Specifically, when we assessed the contemporary (2020) roadway network, soil-lead concentrations showed virtually no correlation ($r = -0.06$) with "proximity to the nearest road." In contrast, the correlation was over three-times higher (moderate correlation) when the analysis was carried out using older roadways networks, particularly those older than the 1960s. Our analysis also shows that this correlation decreases linearly with time as we examine newer roadway networks. Of note, since leaded gasoline was still in heavy use during the 1960s and later, the absence of a correlation between contemporary soil-lead concentrations and proximity to roadways during the later decades does not mean that traffic during the latter period did not contribute to soil-lead contamination. Rather, given the expansion of the city in concentric circles around its historic downtown, one can expect soil-lead concentrations to be lower in the newly built peripheral city roads. These areas were exposed to car emissions over a relatively short period of time compared to the older city center. Santa Ana's historic downtown area, by contrast, experienced higher traffic volumes over a longer period of time.

Moreover, the historical record provides additional evidence that Santa Ana was situated at the crossroads of an important traffic route in the period preceding the construction of the Interstate-5 and the Pacific Coast Highway (ACSC, 1929). Maps produced by the Automobile Club of Southern California in the 1920s and 1930s show that the primary road to travel from San Diego to Los Angeles (the historical 101 highway) ran directly through Santa Ana. Consequently, the city's downtown area, particularly 1st Street, 5th Street, and Main Street, were considered highway arteries (Midget Map, 1923). These traffic patterns were corroborated with a manual traffic count that we conducted of vehicles on the roads at two moments in history (1931 and 1960) as captured in aerial photographs provided by Orange County Public Works. These counts showed that the aforementioned streets received the greatest

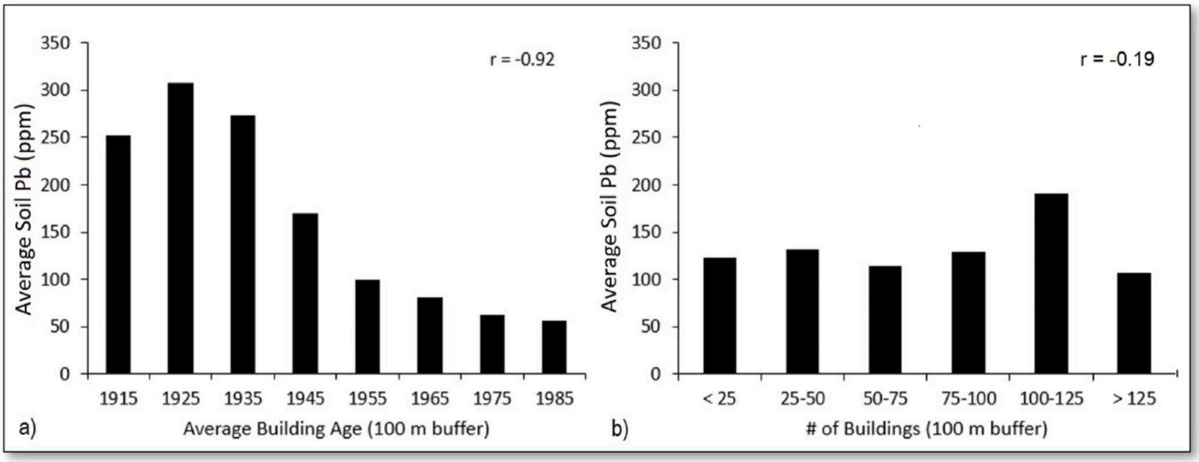

Fig. 6. Average soil-lead concentrations (2018) according to (a) average building age and (b) number of buildings within 100 m buffers in Santa Ana, CA. Pearson correlation coefficients relate to average lead concentrations plotted against (a) average building age and (b) the midpoint of each building number range (bound by 0–150).

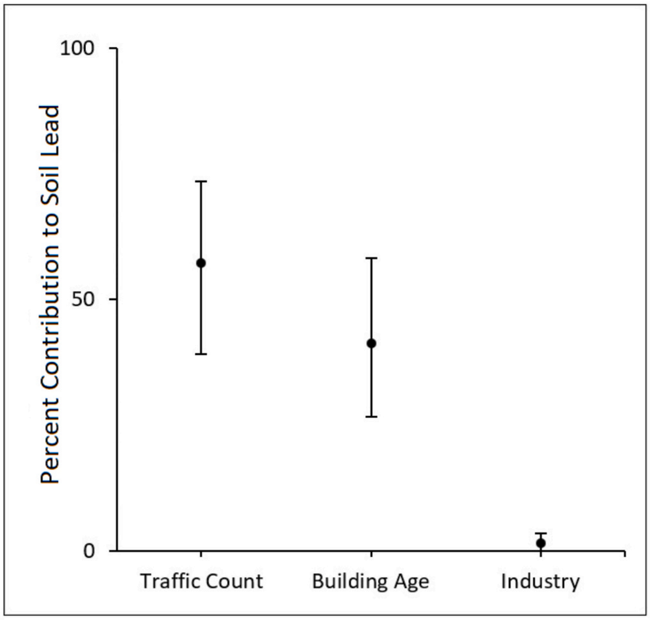

Fig. 7. Mean (black dots) and range (upper and lower bars) of the percent contribution of traffic, building age and distance to industrial land use to soil-lead concentrations (2018), as determined by mixture modeling output, Santa Ana, CA.

traffic volume.

Collectively, this study provides evidence that historical roadways and their traffic patterns likely contributed to modern day lead contamination in the soil of Santa Ana, CA. This finding is consistent with the history of vehicle-related lead emissions. Leaded gasoline was widely used in the United States between the time that it was introduced by the Ethyl Corporation in 1923 and its phaseout throughout the 1970s and 1980s (Newell and Rogers, 2003; Nriagu, 1990). Additionally, our results are consistent with studies estimating the amount of lead released into the environment during this period that identified leaded gasoline as the primary contributor of lead in the atmosphere and soil (USEPA, 1986; Sciences, 1993; Mielke et al., 2011).

Our analysis also showed that average soil-lead concentrations are higher in locations that are within 60 m of the nearest road, relative to larger buffer areas. In general, within these closer distances, the average soil-lead concentration increased in a linear fashion as the distance to the nearest roadway decreased. Assuming a contribution of soil-lead from historical on-road vehicles, this finding suggests a greater contribution near the initial site of emissions (i.e., active vehicle exhaust pipes). These findings are consistent with studies that have shown heavy-metal concentrations in the soil decrease with increasing distance from sources of atmospheric emission (Johnston et al., 2007; McNew-Birren, 2012).

Affirming historical vehicle traffic as a key factor underlying modern-day soil-lead contamination are studies that have found (after accounting for building ages) higher soil-lead concentrations near contemporary roadways (Machemer et al., 2007; Ahmad et al., 2019) and inner cities/downtown areas (Mielke et al., 2008). Studies employing chemical analyses have come to similar conclusions. In one study by Tighe et al. (2019), soil samples containing high lead showed no detection of bismuth, a key element known to occur in tandem with lead in the environment (including paint), but which does not occur in gasoline (removed during manufacturing process). Moreover, a recent isotopic study of soil-lead particles in the city of London showed that historical gasoline-derived lead remains an important source of lead in the urban environment due to its persistence and continuous remobilization (Resongles et al., 2021).

4.2. Other lead sources

This study found that the number of buildings within a buffer was not readily correlated with soil-lead concentrations, while the average construction year of buildings within buffers exhibited a strong negative correlation (younger buildings correlated with lower soil-lead). This finding lends weight to the potential importance of buildings as a contributor to soil-lead contamination (i.e., through shedding of lead paint). Previously, the presence of old buildings, and therefore old paint, near documented cases of lead poisoning has been interpreted as confirmation that lead paint is the main source of lead poisoning and, by extension, of environmental lead. However, as other scholars have pointed out, and as this study confirms, the location of old buildings can overlap with the locations of historical roadways, as it does in the case of Santa Ana, which can lead to a spurious inference (Mielke and Reagan, 1998). Given this overlap, disentangling the extent to which historical traffic- and building-related sources contribute to modern day soil contamination remains an ongoing challenge.

In an effort to address this challenge and identify the respective contributions of these potential historical sources to contemporary soil-lead concentrations, we performed a statistical mixture model analysis.

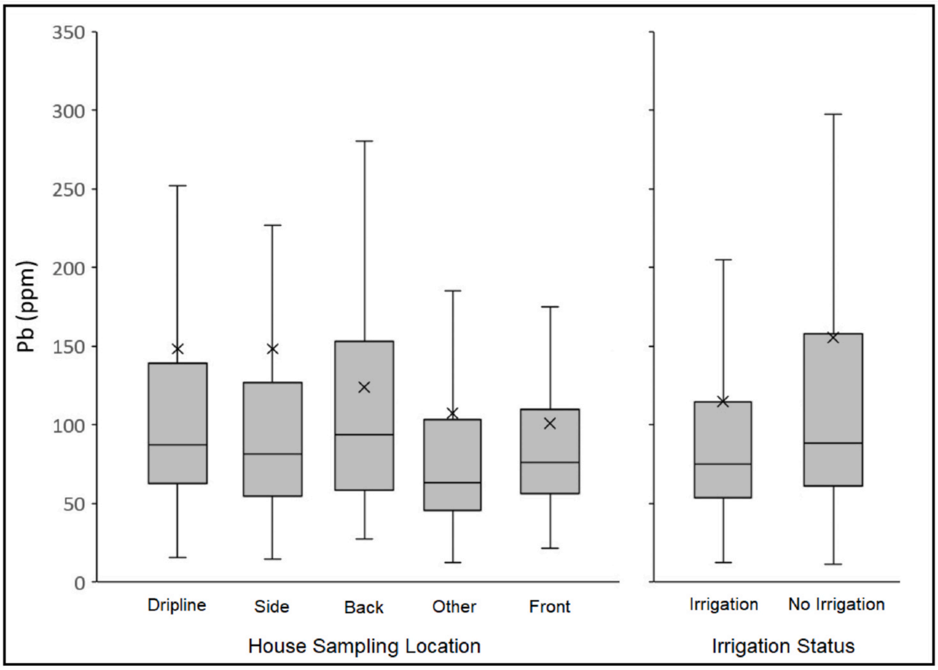

Fig. 8. Boxplots of soil-lead concentrations (2018) collected at various locations around residential structures along with lead concentrations in areas where an irrigation system was either present or not, Santa Ana, CA. The centerline and "X" symbols indicate the median and mean, respectively.

After averaging results over five separate modeling runs, traffic-related variables were shown to explain 57% of the variability in lead contamination, which is slightly more than the relative contribution of average building age (41%). While this finding supports the body of literature that posits traffic-related emissions are the predominant source of soil contamination in urban environments, it does not allow for the rejection of building-related sources as a main contributor.

The specific locations from which soil samples were drawn in relation to individual building structures were also examined. For residential areas, soil samples collected near the dripline and side of the house showed the highest average soil concentrations, whereas concentrations near the front and back of the houses were lower. Notably, the high soil-lead concentrations identified on the side of the residential units may be linked with lead runoff from the dripline of the residential unit of focus or a neighboring residence given that the side yard samples were relatively close to driplines. This is consistent with a study by Clark and Knudsen (2014), which reported lead concentrations in the soil to be over two-times higher when collected at the dripline compared to other yard areas across 71 properties (Clark and Knudsen, 2013). Elevated soil-lead concentrations measured at the dripline may suggest lead contribution from two noteworthy sources either alone or in combination. Lead may arise from the flaking of lead paint from the exterior of homes built before 1978 and/or the accumulation of lead from rainwater dripping off the home roof. The latter phenomenon can both remove lead-containing particles deposited onto roof surfaces following dry deposition as well as remove particles from the atmosphere through so-called "atmospheric washout" during precipitation events, both of which would result in the accumulation of lead in the soil at the dripline of the home.

In terms of irrigation, samples collected in areas with no observed irrigation system present had substantially higher lead concentrations on average compared to sites with observed irrigation systems. One explanation for this may be that irrigation leads to the eventual dilution of lead in the surface soil by carrying away the soluble fraction of soil-lead into other regions of the environment (e.g., deeper into the soil). Alternative explanations may be that irrigation systems nurture vegetation, which draws lead up from the soil and into the biomass of the vegetation where it may ultimately reside for years or be removed by landscape maintenance (e.g., discarded lawn trimmings). Lastly, soils with irrigation systems may also be those that have undergone renovation, which may bring in fresh soil and/or compost, in turn diluting soil-lead concentrations. Whether these explanations are in fact the reason for the reduced lead concentrations observed in areas with irrigation systems is beyond the scope of the present study. However, such findings underscore the importance of giving serious consideration to these explanatory factors when considering possible avenues for soil-lead remediation in Santa Ana and other areas afflicted by soil-lead contamination.

These findings have important implications for environmental justice and lead-poisoning prevention efforts. In practice, programs linked with the Childhood Lead Poisoning Prevention Acts of 1986 and 1989 often focus on leaded paint and lead in consumer products, overlooking the contribution of historical traffic to child lead exposures. Moreover, the monitoring and intervention mechanisms used by these programs focus on drawing blood and identifying lead exposure once it has already occurred (secondary prevention). Understanding the nature of soil-lead contamination in urban spaces, by contrast, is crucial for addressing the root causes of lead poisoning (primary prevention) and is, therefore, paramount in the fight for environmental justice.

Our findings also suggest that, beyond Santa Ana, other cities with a similar history of traffic flow may have substantial amounts of soil-lead in their urban environments. In the case of southern California, the fact that heavily transited historical routes (e.g., Los Angeles to San Diego) are robustly associated with contemporary soil-lead concentrations indicate that other communities, such as the cities of Fullerton, La Habra, and parts of Los Angeles, may be affected with high concentrations of soil-lead. In this case, regional and state actors are important stakeholders to hold accountable in efforts to remediate soil-lead in California.

The reality that soil-lead presents an environmental crisis at the city level demands a community-level response from local, regional, and state actors. Some of the policies that this study recommends are: (1) recognizing the issue of soil-lead and the role of historical traffic as important sources of lead exposure, (2) facilitating community-driven and cross-sectoral planning to remediate soil-lead (e.g., bringing together affected communities, public health, city planners, regional and state transit planners), (3) conducting soil testing at the community level, (4) providing access to blood lead testing for residents exposed to high levels of soil-lead, and (5) remediating soil where lead levels exceed 80 ppm, the recommended limit for areas where children play.

4.3. *History and legacy of the lead contamination*

To prevent future environmental contamination, we must understand the complexities of historical pollution and the interconnected roles of industry, science, and politics. With lead, this history supports our findings of gasoline as the predominant contributor of soil lead in Santa Ana.

Lead's economic expansion was enabled by dedicated marketing by the Lead Industries Association (LIA), which launched the highly successful lead paint campaign in the early twentieth century, accompanied by consumer demand (Markowitz and Rosner, 2000). Worldwide concern about lead in paint and the desire for less toxic alternatives, however, helped decreased lead paint consumption from its peak of 1.2 million tons (1929) to 0.2 million tons in 1959 (and banned in 1978). Meanwhile, the introduction of leaded gasoline in 1923 and, in particular, the rapid post-WWII growth in the automobile industry offered a larger and more attractive market for the LIA (Service, United States Public Health, 1925; Rosner and Markowitz, 1985: Mielke and Reagan, 1998; Markowitz and Rosner, 2014).

By the 1950s, with the expansion of road networks and suburban development, gasoline surpassed paint as the primary use of lead in the U.S. despite continued research on lead's adverse health effects. With episodes of lead poisoning, lead paint became the scapegoat, as attested to by the LIA who in 1969 agreed that the primary objective of their Policy and Program on Childhood Lead Poisoning should be "to keep attention focused on old leaded paint as its [lead poisoning's] primary source and to make clear that other sources of lead are not significantly involved" (Markowitz and Rosner, 2014). Between 1940 and 1960, lead in gasoline increased eightfold, with an estimated 4.6 to 6 million metric tons of lead emitted by motor-vehicles in the U.S. before being phased out throughout the 1980s and 1990s (USEPA, 1986; Mielke and Reagan, 1998; Mielke et al., 2011).

The dire health implications of industry's effort to retain lead in gasoline is underscored by its phaseout being accompanied by the U.S. average child blood lead level declining to 2 μg/dL by the early 1990s (compared to a pre-phaseout average of ~15 μg/dL in 1976) (Markowitz and Rosner, 2014). During this phaseout, however, exposure continued to disproportionately fall on Black and low-income urban communities, with Black children being six-times more likely to suffer from elevated blood lead levels relative to White children (Lin-Fu and Jane, 1982; Markowitz and Rosner, 2014). Similarly, 2% of rural children showed elevated levels in contrast to 11% of inner-city children. The legacy of lead production in the twentieth century is therefore one that continues, but is particularly borne among communities of color and urban communities across the U.S.

5. Conclusion

This study drew on methodological approaches from the fields of history and public health to evaluate the impact of multiple lead emissions sources on contemporary soil-lead concentrations in Santa Ana, CA. It used archival materials to generate data about historical roadways, traffic flows in the past, and the growth of city's urban space in the twentieth century.

Our findings suggest that leaded gasoline was the most likely and most prominent contributor to contemporary soil-lead contamination in Santa Ana, CA. These results are consistent with the historiography and the historical record of the lead industry, which have shown that leaded gasoline represented the largest source of lead emissions into the environment in the twentieth century. This study also provides evidence that building structures (i.e., lead paint) are an important source of soil-lead contamination. Although it was not possible to completely isolate the lead contribution of one source over the other, the application of a mixture model affirmed that roadway sources' contributions were relatively greater than building sources' contributions.

This paper demonstrates the value of applying historical research for preventing lead poisoning and addressing environmental injustices. A close examination of historical traffic patterns is a valuable tool for determining where soil-lead contamination is more acute and, hence, where primary and secondary prevention interventions are needed the most. This kind of methodology can contribute to the design of community-level interventions that address the root causes of lead poisoning and, hence, address the pressing environmental injustices tied to the history of lead.

Funding

This study received support from the Ridge to Reef Graduate Training Program funded by NSF-NRT award DGE-1735040 between August 1st, 2020 and June 30th, 2021.

Data availability

Historical geospatial shapefiles created in this study are available at: https://github.com/jmrubio56/historicalsantaana.

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.

Acknowledgements

We thank the following individuals and organizations for their support: Jóvenes Cultivando Cambios, Orange County Environmental Justice, Yenni Diaz, Oladele Ogunseitan, Manuel Escamilla, the Ying Lab, and the countless individuals who have joined community conversations and have organized to understand and address environmental justice concerns in Santa Ana, CA, USA. We also thank UCI students who participated in research opportunities associated with the ¡Plo-NO Santa Ana! Lead-Free Santa Ana! soil study. We are grateful to the ¡Plo-NO! Santa Ana! Lead-Free Santa Ana! residents who participated in this study. We would also like to acknowledge the work of Orange County Public Works, and of William Hussung in particular, in digitizing and georeferencing historical aerial images.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2022.113478.

References

Lanphear, Bruce, Weitzman, M Michael, Winter, Nancy, Eberly, Shirley, Yakir, Benjamin, Tanner, Martin, Emond, Maiy, Matte, Thomas D., 1996. Lead-contaminated house dust and urban children's blood lead levels. Am. J. Publ. Health 86 (10), 1416–1421. https://doi.org/10.2105/AJPH.86.10.1416.

Agency for Toxic Substances and Disease Registry (ATSDR), 2002. Toxicological Profile for Lead." ATSDR's Toxicological Profiles. https://doi.org/10.1201/9781420061888_ch106. Atlanta.

Ahmad, I., Khan, B., Asad, N., Mian, I., Jamil, M., 2019. Traffic-related lead pollution in roadside soils and plants in khyber pakhtunkhwa, Pakistan: implications for human health. Int. J. Environ. Sci. Technol. 16 (12), 8015–8022. https://doi.org/10.1007/s13762-019-02216-7.

Aizer, Anna, Currie, Janet, Simon, Peter, Vivier, Patrick, 2018. Do low levels of blood lead reduce children's future test scores? Am. Econ. J. Appl. Econ. 10 (1), 307–341. https://doi.org/10.1257/app.20160404.

Automobile Club of Southern California (ACSC), 1929. Coast and Inland Routes. Los Angeles to San Diego, 1929. https://digitallibrary.usc.edu/Share/4y44wx2s6fdk86unb55616scb0004214?FR_=1&W=1280&H=606.

California Department of Public Health (CDPH), 2012. Number of Individual Children Screened for Lead, by Highest Level. California 2012, Sacramento, CA.

Carr, R., Zhang, C.S., Moles, N., Harder, M., 2008. Identification and mapping of heavy metal pollution in soils of a sports ground in galway city, Ireland, using a portable XRF analyser and GIS. Environ. Geochem. Health 30, 45–52. https://doi.org/10.1007/s10653-007-9106-0.

City of Santa Ana, 2021. GeoSpatial Open Data, 2021. https://gis-santa-ana.opendata.arcgis.com/.

Clark, Jeffrey, Knudsen, Andrew, 2013. Extent, characterization, and sources of soil lead contamination in small-urban residential neighborhoods. J. Environ. Qual. https://doi.org/10.2134/jeq2013.03.0100.

Díaz-Barriga, Fernando, Batres, Lilia, Calderón, Jaqueline, Lugo, Andrés, Galvao, Luiz, Lara, Irma, Pedro, Rizo, Elena Arroyave, María, McConnell, Rob, 1997. The El Paso smelter 20 Years later: residual impact on Mexican children. Environ. Res. 74 (1), 11–16. https://doi.org/10.1006/enrs.1997.3741.

Geier, David, Kern, Janet, Geier, Mark, 2018. A cross-sectional study of the relationship between blood lead levels and reported attention deficit disorder: an assessment of the economic impact on the United States. Metab. Brain Dis. 33, 201–208. https://doi.org/10.1007/s11011-017-0146-6.

Griffith, D., Johnson, D., Hunt, A., 2009. The geographic distribution of metals in urban soils: the case of syracuse, NY. Geojournal 74 (4), 275–291. https://doi.org/10.1007/s10708-008-9233-x.

Instruments, Spetcro Analytical. n.d. "Analyzing Trace Elements in Pressed Pellets of Geological Materials Using ED-XRF." APPLICATION BRIEF. (https://www.spectro.com/landingpages/xrf-xepos-application-analyzing-trace-elements-in-pressed-pellets-of-geological-materials).

Johnston, Jill, Franklin, Meredith, Roh, Hannah, Austin, Christine, Arora, Manish, 2007. Source identification of lead contamination in residential and undisturbed soil adjacent to a battery manufacturing facility. Environ. Forensics 8 (1–2), 77–95. https://doi.org/10.1080/15275920601180602.

Jusko, Todd, Henderson, Charles, Lanphear, Bruce, Cory-Slechta, Deborah, Parsons, Patrick, Canfield, Richard L., 2008. Blood lead concentration <10 Mg/DL and child intelligence at 6 Years of age. Environ. Health Perspect. 116 (2), 243–248. https://doi.org/10.1289/ehp.10424.

Keil, Alexander, Buckley, Jessie, O'Brien, Katie, Ferguson, Kelly, Zhao, Shanshan, White, Alexandra, 2020. A quantile-based g-computation approach to addressing the effects of exposure mixtures. Environ. Health Perspect. 128 (4), 1–10. https://doi.org/10.1289/EHP8739.

Kovarik, William, 2005. Ethyl-leaded gasoline: how a classic occupational disease became an international public health disaster. Int. J. Occup. Environ. Health 11 (4), 384–397. https://doi.org/10.1179/oeh.2005.11.4.384.

Lanphear, Bruce, Dietrich, Kim, Auinger, Peggy, Cox, Christopher, 2000. Cognitive deficits associated with blood lead concentrations <10 microg/DL in US children and adolescents. Publ. Health Rev. 115 (6), 521–529, 1974.

Lanphear, Bruce, Hornung, Richard, Ho, Mona, Howard, Cynthia, Eberle, Shirley, Knauf, Karen, 2002. Environmental lead exposure during early childhood. J. Pediatr. 140 (1), 40–47. https://doi.org/10.1067/mpd.2002.120513.

Lebrón, Alana, Torres, Ivy, Valencia, Enrique, Dominguez, Miriam López, Garcia-Sanchez, Deyaneira Guadalupe, Logue, Michael, Wu, Jun, 2019. The state of public health lead policies: implications for urban health inequities and recommendations for health equity. Int. J. Environ. Res. Publ. Health 16 (6), 1–28. https://doi.org/10.3390/ijerph16061064.

Levin, Ronnie, Brown, Mary Jean, Kashtock, Michael, Jacobs, David, Whelan, Elizabeth, Rodman, Joanne, Schock, Michael, Alma Padilla, Sinks, Thomas, 2008. Lead exposures in U.S. Children, 2008: implications for prevention. Environ. Health Perspect. 116 (10), 1285–1293. https://doi.org/10.1289/ehp.11241.

Lin-Fu, Jane, 1982. Children and lead. N. Engl. J. Med. 307 (10), 615–617. https://doi.org/10.1056/NEJM198209023071009.

Machemer, Steven, Hosick, Theresa, Ingamells, Robin, 2007. Source apportionment of lead contamination in residential, undisturbed, and roadside soil (Part II). Environ. Forensics 8 (1–2), 97–105. https://doi.org/10.1080/15275920601180628.

Maliki, Ali Al, Al-lami, Ahmed Kadhim, Hussain, H.M., Al-Ansari, Nadhir, 2017. Comparison between inductively coupled plasma and X-ray fluorescence performance for Pb analysis in environmental soil samples. Environ. Earth Sci. 76, 2–7. https://doi.org/10.1007/s12665-017-6753-z.

Markowitz, Gerald, Rosner, David, 2000. 'Cater to the children': the role of the lead industry in a public health tragedy, 1900-1955. Am. J. Publ. Health 90 (1), 36–46. https://doi.org/10.2105/ajph.90.1.36.

Markowitz, Gerald, Rosner, David, 2014. Lead Wars: the Politics of Science and the Fate of America's Children. University of California Press. https://www.ucpress.edu/book/9780520283930/lead-wars.

Masri, S., Kang, C.-M., Koutrakis, P., 2015. Composition and sources of fine and coarse particles collected during 2002–2010 in boston, MA. J. Air Waste Manag. Assoc. 65 (3), 287–297. https://doi.org/10.1080/10962247.2014.982307.

Masri, Shahir, LeBrón, Alana, Logue, Michael, Valencia, Enrique, Abel Ruiz, Reyes, Abigail, Lawrence, Jean M., Wu, Jun, 2020. Social and spatial distribution of soil lead concentrations in the city of Santa Ana, California: implications for health inequities. Sci. Total Environ. 743 https://doi.org/10.1016/j.scitotenv.2020.140764. November.

Masri, Shahir, LeBrón, Alana, Logue, Michael, Valencia, Enrique, Abel Ruiz, Reyes, Abigail, Wu, Jun, 2021. Risk assessment of soil heavy metal contamination at the census tract level in the city of Santa Ana, CA: implications for health and environmental justice. Environ. Sci.: Process. Impacts. https://doi.org/10.1039/D1EM00007A. May.

McNew-Birren, Jill, 2012. The impacts of lead contamination on the community of herculaneum, Mo. Dissert. Abstr. Int. Sec.: Humanit. Soc. Sci. 72 (12-A), 4504. http://ovidsp.ovid.com/ovidweb.cgi?T=JS&PAGE=reference&D=psyc9&NEWS=N&AN=2012-99110-034.

Meyer, Pamela, Brown, Mary Jean, Falk, Henry, 2008. Global approach to reducing lead exposure and poisoning." *mutation research/Reviews in mutation research*. In: Proceedings of the 5th International Conference on Environmental Mutagens in Human Populations (ICEMHP), 659, pp. 166–175. https://doi.org/10.1016/j.mrrev.2008.03.003, 1.

Midget Map of Santa Ana, 1923. Los Angeles: Pacific Southwest Trust and Savings Bank https://www.davidrumsey.com/luna/servlet/detail/RUMSEY~8~1~215617~5502475:Santa-Ana,-California?sort=Pub_List_No_InitialSort%2CPub_Date%2CPub_List_No%2CSeries_No&qvq=q:santa ana.

Mielke, H., Reagan, P., 1998. Soil is an important pathway of human lead exposure. Environ. Health Perspect. 106 (Suppl. 1), 217–229. https://doi.org/10.1289/ehp.98106s1217.

Mielke, H., Powell, E., Shah, A., Gonzales, C., Mielke, P., 2001. Multiple metal contamination from house paints: consequences of power sanding and paint scraping in new orleans. Environ. Health Perspect. 109 (9), 973–978. https://doi.org/10.1289/ehp.01109973.

Mielke, Howard, Gonzales, Christopher, Powell, Eric, Paul, Mielke, 2008. Urban soil-lead (Pb) footprint: retrospective comparison of public and private properties in new orleans. Environ. Geochem. Health 30 (3), 231–242. https://doi.org/10.1007/s10653-007-9111-3.

Mielke, Howard, Laidlaw, Mark, Gonzales, Chris, 2010. Lead (Pb) legacy from vehicle traffic in eight California urbanized areas: continuing influence of lead dust on children's health. Sci. Total Environ. 408 (19), 3965–3975. https://doi.org/10.1016/j.scitotenv.2010.05.017.

Mielke, Howard, Laidlaw, Mark, Gonzales, Chris, 2011. Estimation of leaded (Pb) gasoline's continuing material and health impacts on 90 US urbanized areas. Environ. Int. 37 (1), 248–257. https://doi.org/10.1016/j.envint.2010.08.006.

Newell, R., Rogers, Kristian, 2003. The US Experience with the Phasedown of Lead in Gasoline. Resources for the Future, Washington, DC.

Nriagu, Jerome, 1990. The rise and fall of lead in gasoline. Sci. Total Environ. 92, 13–28.

Pell, M., Schneyer, Joshua, 2016 August. Reuters Finds Lead Levels Higher than Flint's in Thousands of Locales. Reuters. http://www.reuters.com/investigates/special-report/usa-lead-testing/.

Rees, Nicholas, Fuller, Richard, 2020. The Toxic Truth." UNICEF. https://www.unicef.org/reports/toxic-truth-childrens-exposure-to-lead-pollution-2020.

Rosner, David, Markowitz, Gerald, 1985. A 'gift of god'?: the public health controversy over leaded gasoline during the 1920s. Am. J. Publ. Health 75 (4), 344–352. https://doi.org/10.2105/ajph.75.4.344.

Sayer, J., Charney, E., Vostal, J., et al., 1974. House and hand dust as a potential source of childhood lead exposure. JAMA 127 (2), 167–170. https://doi.org/10.1001/archpedi.1974.02110210017002.

Sciences, National Academy, 1993. Measuring Lead Exposure in Infants, Children, and Other Sensitive Populations. of. National Academy Press. http://files/7026/National Academy of Sciences - National Research Council - 1993 - Measuring Lead Exposure in Infants, Children, and .pdf.

Service, United States Public Health, 1925. Proceedings of a conference to determine the whether or not there is a public health question in the manufacture, distribution, or use of tetraethyl lead gasoline. Publ. Health Bull. 158. August. https://catalog.hathitrust.org/Record/002138769.

The City of Santa Ana, 2020. Santa Ana Facts and Figures. Library Services. https://www.santa-ana.org/library/services/facts-and-figures, 2020.

U.S. Census Bureau, 2020. Census 2020 California Hard-To-Count Fact Sheet, Santa Ana City in Orange County.

U.S. Environmental Protection Agency (USEPA, 1986. Air Quality Criteria for Lead: Final Report, vol. 2. U.S. Environmental Protection Agency.

Wang, Hui Li, Chen, Xiang Tao, Yang, Bin, Ma, Fang Li, Wang, Shu, Tang, Ming Liang, Hao, Ming Gao, Ruan, Di Yun, 2008. Case control study of blood lead levels and attention deficit hyperactivity disorder in Chinese children. Environ. Health Perspect. 116 (10), 1401–1406. https://doi.org/10.1289/ehp.11400.

Wu, Jun, Edwards, Rufus, He, Xueqin (Elaine), Liu, Zhen, Kleinman, Michael, 2010. Spatial analysis of bioavailable soil lead concentrations in Los Angeles, California. Environ. Res. 110 (4), 309–317. https://doi.org/10.1016/j.envres.2010.02.004.