



One map: Using geospatial analysis to understand lead exposure across humans, animals, and the environment in an urban US city

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ARTICLE INFO

Keywords:

Environmental lead contamination
One health
Conservation medicine
GIS
Lead exposure
Public health

ABSTRACT

Environmental lead contamination negatively impacts human, animal, and ecosystem health, yet there is a lack of research in this area that incorporates a One Health framework – examining co-exposures among species through their shared environment. The purpose of this study was to integrate human and animal data with public soil lead levels to better understand lead exposure patterns across species in an urban US city. Over 200 soil samples were collected, analyzed for lead, and mapped in combination with other risk factors pulled from the literature to identify areas of highest risk. Human socio-demographic data, dog, and house sparrow density data were mapped to investigate the association between these variables and soil lead levels. Geospatial analysis software was used to visualize the geospatial distribution of soil lead levels and known risk factors for environmental lead contamination, and a block group risk score was calculated and mapped. Associations between human and animal-associated variables and soil lead levels and block risk scores were assessed using Spearman's correlations. Positive, statistically significant associations were found between soil lead levels and higher population density, higher education levels, and higher median household income. Areas with higher soil lead levels and lead exposure risk scores were associated with greater dog density and greater house sparrow density. This study fills an important knowledge gap on the risk of environmental lead exposure to humans, domestic animals, and wildlife.

1. Introduction

Industrialization has increased the concentrations of lead and other heavy metals in the environment, especially in urban centers with older housing stock [1]. Urban lead poisoning is linked to many sources which overlap and provide opportunities for humans and non-human animals to act as sentinels for one another [2,3].

A main source for human exposure is lead-based paint in older homes [4]. In animals, exposure mainly occurs when the animal ingests contaminated paint, soil, and feed [5]. In most vertebrates, lead poisoning affects the reproductive, gastrointestinal, cardiovascular, neurologic, musculoskeletal, and renal systems [5,6]. In humans, lead poisoning is often a chronic issue that leads to irreversible effects including cognitive deficits, nerve damage, and kidney failure [6].

Several studies have shown that childhood lead exposure is associated with an increased risk of violent crime, aggression, attention deficit hyperactivity disorder, and lower IQ due to damage in the brain [7–9]. Although any child exposed to lead is at risk for lead poisoning, several sociodemographic variables (i.e., low socioeconomic status, living in an older urban home, ethnic or racial minority) place these children at higher risk for exposure [10]. Research has also shown that soil lead exposure and toxicosis, particularly in children, increases in the summer and autumn months when urban soils are dry which increases soil dust deposits (i.e., resuspension) [11,12].

Most research on lead in soil focuses on areas near homes that tend to have high lead concentrations secondary to sources such as paint and gasoline. This has led to maximum allowances of lead in soil set by state and federal agencies for gardening, play and unrestricted public use

Abbreviations: SLL, Soil lead levels; XRF, X-Ray fluorescence analyzer.

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<https://doi.org/10.1016/j.onehlt.2021.100341>

Received 26 July 2021; Received in revised form 22 October 2021; Accepted 23 October 2021

Available online 27 October 2021

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[13,14]. However, there is a lack of information on how lead may disperse through an urban environment. Studies on urban gardening and backyard chicken ownership highlight the importance of understanding how lead may cycle in the urban environment and illuminate a lack of policy surrounding these practices [15–17]. Sources of lead contamination in the United States are likely to change over the next century since lead was banned and removed from many household products, increasing the significance of other sources of exposure such as contaminated urban soil.

The purpose of this study was to develop a One Health lead exposure assessment map of an urban city to understand how and where environmental lead contamination may impact different species coexisting in a shared ecosystem. As lead continues to impact all species, there is a growing need for research that incorporates human, animal, and environmental health data to combat environmental lead contamination [2,3,18].

2. Methods

2.1. Study area

The city of Somerville, Massachusetts is an urban area 4.12 mi² in size, located northwest of Boston, with a population of 75,754 people and 33,720 housing units [19] (Fig. 1). Somerville was first settled in 1630, and over 90% of the city's buildings were built prior to the consumer lead-based paint ban of 1978 [20,21]. Somerville was selected because it is a highly urbanized and historical city, with a variety of pet

ownership and urban farming activity, as well as unique habitats for urban wildlife [22].

2.2. Soil sampling

To obtain soil lead levels (SLL) across the city, a 240-m by 240-m fishnet grid was overlaid onto the city using ESRI ArcMap 10.4 (Fig. 1). Each grid cell had a centroid point that determined the sampling location, totaling 219 centroids. From each centroid, one soil sample was obtained from the nearest publicly accessible location, with respective GPS coordinates collected using a handheld Garmin 64S GPS unit. Sampling locations included patches of soil found among paved areas including sidewalks and parking lots, parks, and other open spaces. Samples were collected in the summer of 2017 using a trowel to obtain a handful of ground soil from a depth of 2.5–7.5 cm. After collection, samples were air dried on paper plates for up to two days, manually homogenized, and stored dry in a clean plastic bag until analysis.

2.3. Soil analysis

Soil samples were analyzed for lead concentrations at Boston University's School of Public Health's Exposure Biology Laboratory using the Innov-X Alpha Series portable handheld X-Ray fluorescence analyzer (XRF) in a stationary stand. This was performed in accordance with previously published protocols, as well as the EPA Method 6200 for field portable XRF spectrometry used for the concentration of different

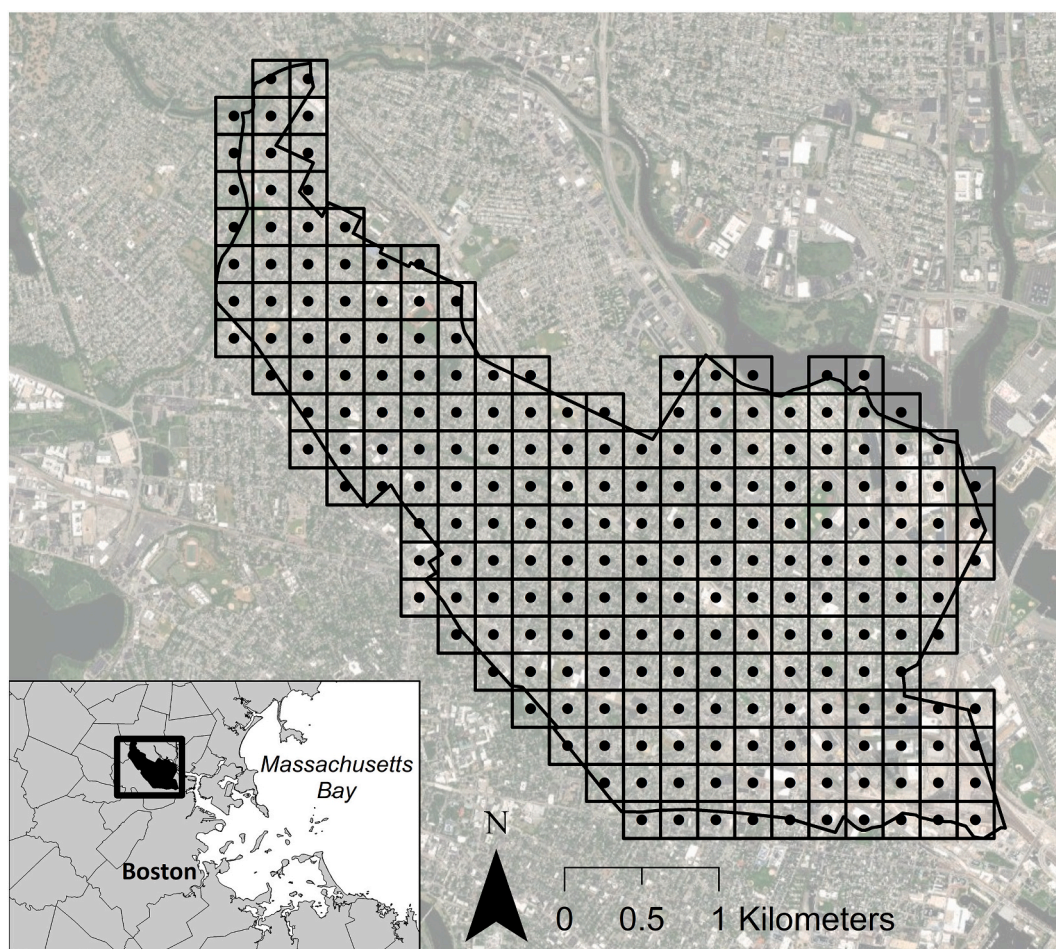


Fig. 1. The City of Somerville, Massachusetts (black in the inset map), is located northwest of the City Boston. A close up of Somerville, MA illustrates centroids used to determine soil sampling sites. A 240 m × 240 m grid (black squares) of Somerville, MA was created using GIS to identify centroids (black dots) for systematic soil sample collection throughout the city.

elements in soil and sediment [23,24]. The XRF was calibrated with a National Institute of Standards and Technology (NIST) standard reference sample provided by the manufacturer prior to analyzing samples. Due to expected minor variability within a single sample, three readings were taken per sample, and an average of the three readings was used for analysis.

2.4. Geospatial analysis

ESRI ArcMap 10.4 was used for geospatial risk analyses. For the purpose of this study, “risk” is defined as an estimated likelihood of exposure. Along with soil data, three other factors known to be predictive of elevated environmental lead contamination were selected for the analysis: density of gas stations, proximity to major roadways, and year of building construction on a parcel. Gas stations and roadways were selected due to historical use of lead in gasoline and the risk of lead deposition into the soil from car emissions [11,25]. Areas of high gas station density and areas closer to major roadways were considered higher risk. Year of building construction was selected due to the historical use of lead in paint and the risk of lead deposition into the soil from exterior paint on buildings [11]. Buildings constructed prior to 1978 were considered higher risk [26].

Soil data were interpolated using the inverse distance weighting (IDW) geostatistical method at a default power parameter of 2 [27]. Somerville gas stations were mapped using the kernel density tool [28]. The distance from major roadways was analyzed using Euclidean distance. The roadways used for this analysis were those classified by MassDOT as Classes 1–4: highways, numbered routes, and major roads [29]. These three analyses automatically produced raster datasets to be used for further analysis. Assessor information was obtained from the city and linked with the parcel data to identify the year of building construction [21,30]. The polygon-to-raster tool was used to convert the original parcel layer into a raster layer representing the year buildings were constructed [31]. All factors were reclassified into five raster classes ranging from 1 (low risk) to 5 (high risk) using natural breaks classification, except the year of building construction, which was reclassified into two classes based on whether buildings were constructed before 1978 (high risk = 2) or after (low risk = 1).

To obtain the adjusted lead exposure assessment map, the raster calculation was weighted using the following formula: $[Soil\ Lead * 0.45] + [Gas\ Stations * 0.15] + [Roads * 0.15] + [Year * 0.25]$. This formula allowed the variables to be differentially weighted according to their estimated importance in lead exposure risk. The weights used for each variable for the raster calculation were selected based on our assessment of their importance to lead exposure through a review of the literature, but the actual numbers used to weight the importance of each variable were arbitrarily selected based on the desired weighted proportion of all the variables used in the calculation (i.e. some variables were intentionally weighted more heavily in the calculation than others). Since public soil is the primary sample collected for this analysis and the focus of the paper, it was weight more heavily (e.g. 45%) compared to the other variables used. Year the home was built was identified as the next most important variable given numerous studies have documented this variable as a major predictor of lead in the home [4]. We also wanted to account for gas stations and roads which have also been associated with environmental lead exposure in the published literature [11,25]. The weighted lead exposure assessment map was aggregated to the census block group level using the zonal statistics tool in order to calculate average block group lead exposure scores. The final adjusted lead exposure assessment map at the block group level was used to explore associations between dog and house sparrow density as well as human sociodemographic variables.

2.5. Human socio-demographic data

Demographic data were obtained from the United States Census

Bureau and the American Community Survey at the block group level for use in statistical analyses and included: 1) Race: proportion of total population that is white, black, or other; 2) Human population density; 3) Age: total population \geq 25 years old; 4) Education: proportion of adults with no high school diploma, a high school diploma/GED, an associate degree, a bachelor degree, a graduate/professional degree; 5) Median household income. Sex was not included in the analysis as it is not known to be related to lead exposure.

2.6. Canine and house sparrow density data

Dog license data at the address level was obtained through the town clerk and imported into ArcMap as individual points, and the density of dogs per block group was calculated for analysis. House sparrows (*Passer domesticus*) were chosen because of their ubiquitous urban year-round presence and that they are frequently in direct contact with the ground and potentially lead-contaminated soil. House sparrows were observed in the summer of 2017 through five-minute point counts at each soil sampling location to obtain an estimate of house sparrow density [32]. Observers would stand at the point where they obtained the sample for each location and observe house sparrows at a variable distance in the early evenings, counting those in direct contact with soil. Any individuals that were in contact with houses or buildings were noted, but not included in the point count. The results of the point counts were imported into ArcMap, then a density calculation was obtained for each block group for statistical analysis.

2.7. Statistical analysis

Spearman’s correlations were used to identify associations at the block group level between SLLs and dog density, house sparrow density, and human demographic variables, as well as between these variables and block group lead exposure scores. A false discovery rate correction using the Benjamini-Hochberg procedure was conducted to reduce type 1 error. All statistical analyses were performed in JMP Pro version 14.

3. Results

3.1. Soil samples

Soil samples were obtained from 210 centroids. Nine samples were not collected due to a lack of accessible soil in the sample grid. Thirty-one centroids fell outside of Somerville city limits but were still collected for the spatial analysis. The average SLL across all 210 samples was 242 ppm, and 217 ppm in Somerville samples. Of the 210 samples, 69 samples (32.9%) had SLLs that exceeded the Massachusetts 200 ppm maximum allowance for lead in soil of unrestricted use. A total of 26 samples (12.4%) were above the EPA’s 400 ppm maximum allowance for lead in bare soil where children play (Table 1, Fig. 2). Soil sample data can be viewed at <https://arcg.is/1LKL140>.

3.2. Geospatial analysis

While eastern and southern Somerville show the highest SLLs, most areas (67.1%, $n = 141$ samples) had public SLLs under 200 ppm.

Table 1
Summary statistics for lead levels in public soil samples.

Statistic	All Samples	Somerville Samples
Total number of samples	210 samples	179 samples
Mean	242 ppm	217 ppm
Standard deviation	424 ppm	362 ppm
Median	132 ppm	131 ppm
Range	15 ppm–4282 ppm	15 ppm–4282 ppm
Above 200 ppm	69 samples (32.9%)	56 samples (31.3%)
Above 400 ppm	26 samples (12.4%)	19 samples (10.6%)

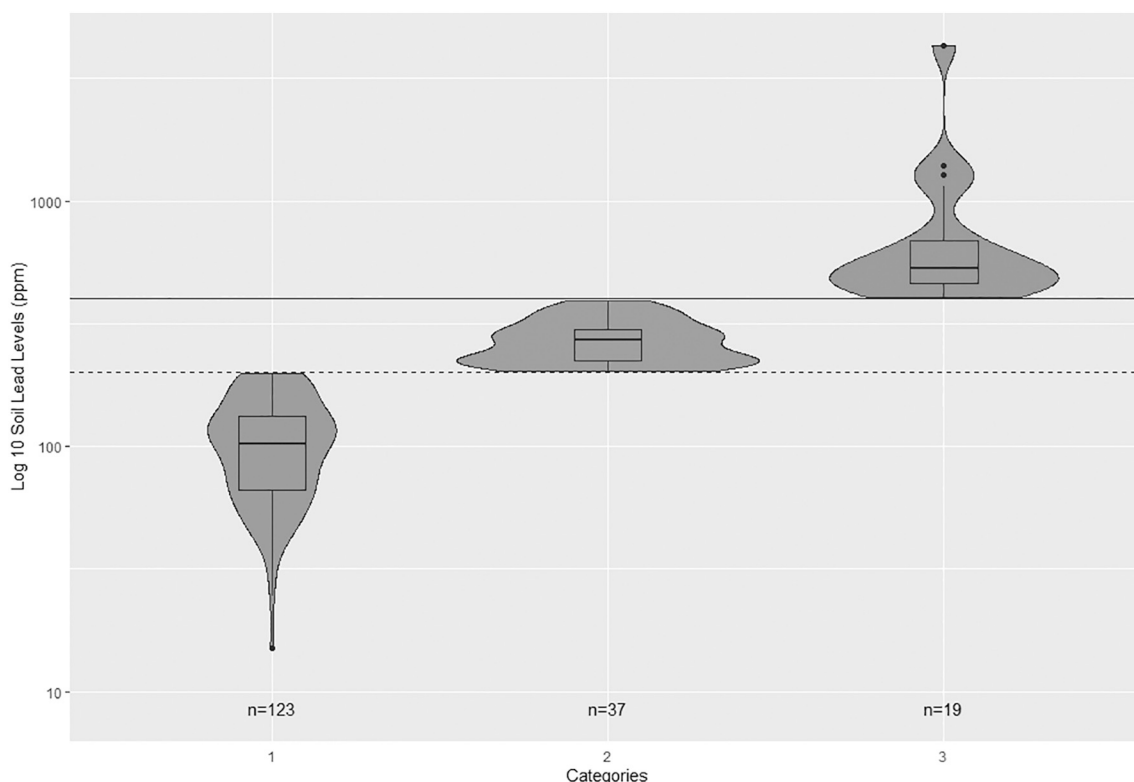


Fig. 2. A violin plot with embedded box plots of lead levels in parts per million (ppm) on a log₁₀ scale from the 179 public soil samples collected throughout Somerville, MA illustrating variation in the range of lead concentrations obtained throughout the city. Category 1 represents the 123 samples with lead levels below the Massachusetts 200 ppm maximum allowance for lead in soil of unrestricted use (dashed line) [15]. Category 2 represents the 37 samples with lead levels above the Massachusetts 200 ppm maximum, but below the EPA’s 400 ppm maximum allowance for lead in bare soil where children play (solid line) [14]. Category 3 represents the 19 samples with lead levels above the EPA’s 400 ppm maximum.

Interpolating these SLLs found clustered areas of elevated SLLs such as

East Somerville, Ward Two, and Davis Square (Fig. 3). After combining the four spatial variables, elevated risk of exposure to environmental lead was observed across multiple regions of Somerville (Fig. 4). These results suggest a heterogenous distribution for environmental lead exposure across the entire city.

3.3. Dog and house sparrow density

In 2018, 1688 dogs were licensed. During the 2017 sampling collection period, 664 individual house sparrows were documented during point observations across all soil collection locations. The dog and house sparrow density estimates were overlaid on the weighted risk map (Fig. 5). Higher dog and house sparrow densities were observed in areas identified as higher risk for lead exposure.

3.4. Associations with public soil lead levels and block group risk score

We found that public SLLs were positively associated with higher human population density, higher proportion of the population with a graduate/professional degree, higher median household income, and higher dog density. All One Health indicator variables were found to be significantly associated with the block group risk score, with the exception of race (Table 2). Public SLLs were also positively associated with block group risk score (Spearman’s coefficient = 0.3728, $p < 0.0001$).

4. Discussion

Our findings demonstrate that human, canine, and house sparrow density all increased in regions of the city that had elevated SLLs and weighted lead exposure scores (Table 2, Fig. 4), highlighting the

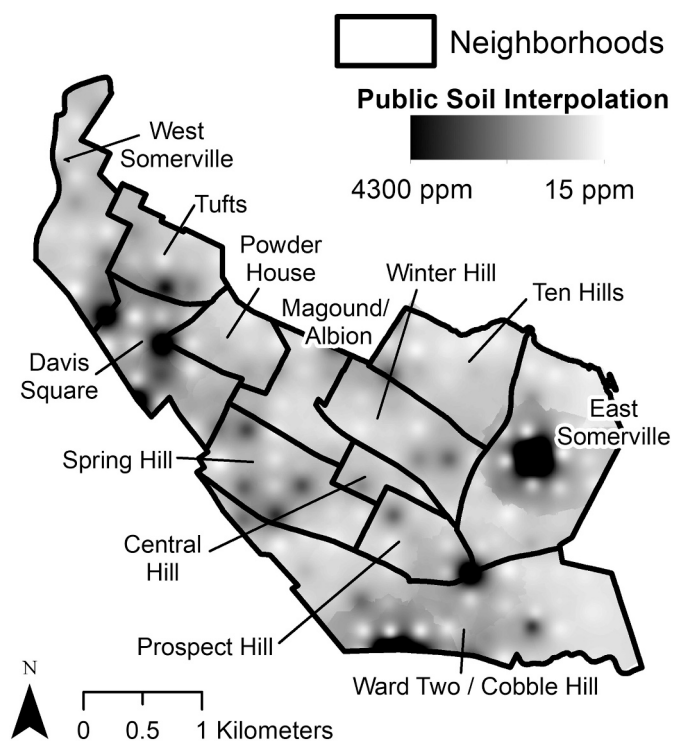


Fig. 3. A map of the interpolated public soil lead levels in Somerville, MA where dark is higher lead levels and light is lower lead levels.

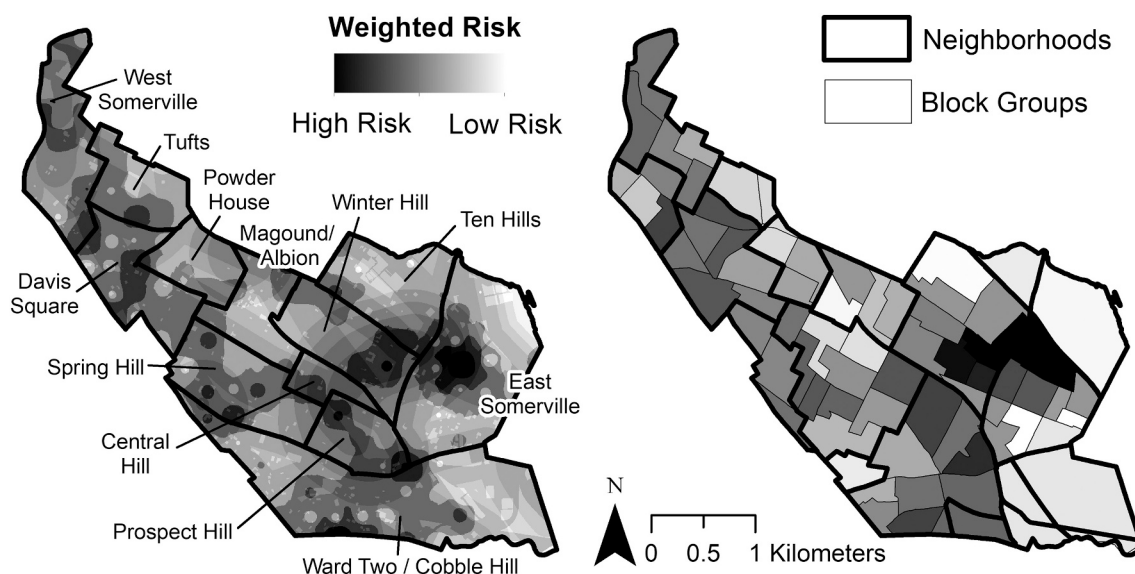


Fig. 4. Maps of the weighted lead exposure assessment for the city of Somerville where dark is higher risk and light is lower risk. a) Weighted lead exposure throughout the city; b) Weighted lead exposure averaged at the census block group level.

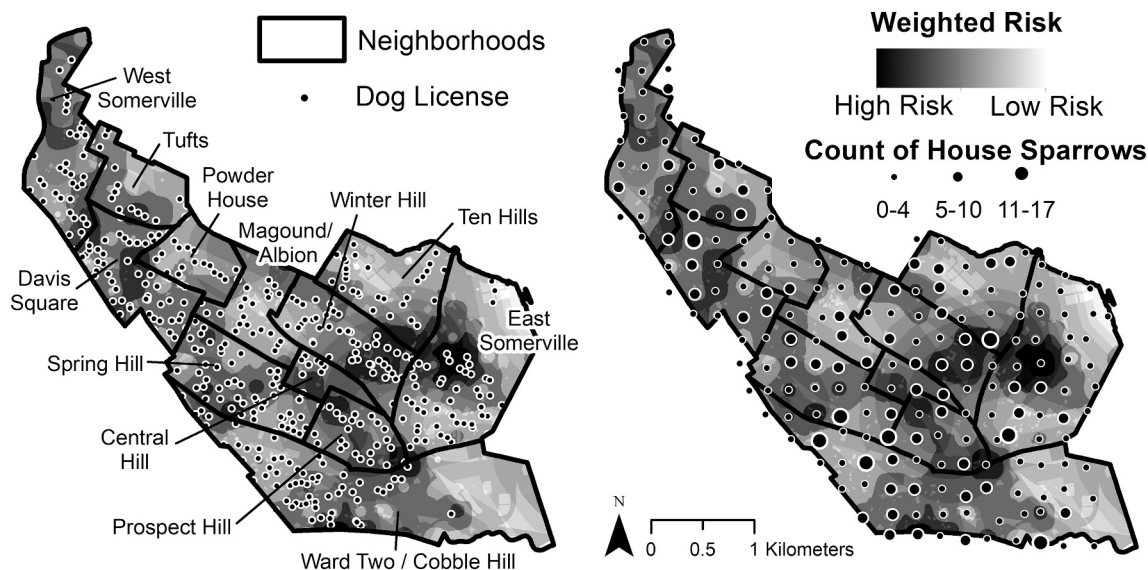


Fig. 5. Animal density data points overlaid on the weighted lead exposure assessment map for the city of Somerville. a) Map of the dog density where each circle signifies an individual dog license; b) Map of House Sparrow density where the size of the circle is equivalent to the number of House Sparrows observed at each sampling location.

growing need for integrated lead exposure assessments and the potential for One Health intervention strategies [2,3,18].

4.1. Environmental lead exposure similarly threatens human, domestic, and wild urban inhabitants

The positive association between dog density and public SLLs, as well as dog density and block group risk score, is consistent with trends observed in the human literature where lead poisoning is higher in more densely populated areas [33]. While Somerville is not a large city by population or area, it has an almost 50% higher population density per square mile than Boston, Massachusetts [34]. In addition, while dogs may be exposed to lead dust inside the home, they spend significant time in close contact with public soil (i.e., on walks and at parks). No data exists on the long-term health effects of chronic low-level lead exposure in dogs, but it has been shown to have negative health consequences in

humans [4,6]. Because the dog data utilized for this study were for owned, licensed dogs, these results show that owned, domestic animals are likely, if not more, exposed to environmental lead contamination than their owners. This is important for future research investigating the impact of environmental lead contamination and other sources of lead to domestic animals, as well as the potential for using domestic animals as a sentinel for human exposure and vice versa [2].

The positive association between block group lead exposure scores and house sparrow density, in conjunction with the results of our spatial analysis, has implications for the health of this species and other urban wildlife as they are not directly exposed to sources within a home. As urbanization continues to grow, and interactions with human-transformed urban landscapes and urban wildlife increase, soil may be a primary source of lead exposure to these animals. This could have a sufficient impact on their behavior and fecundity as lead is known to alter both parameters in humans and other animals [5,8,35,36]. Our

Table 2

Results from Spearman's correlations between indicator variables and soil lead levels and block group risk scores. An asterisk indicates a p -value of <0.05 , which was arbitrarily selected as the level of statistical significance for this study.

Variable	Soil Samples		Block Group Risk Score	
	Spearman's Coefficient	P-value	Spearman's Coefficient	P-value
Race, proportion of population that is				
White population	0.09	0.25	0.25	$<0.001^*$
Black population	0.08	0.25	0.13	0.08
Other population	0.14	0.07	0.15	0.039*
Population density	0.17	0.021*	0.24	0.001*
Age: Total	0.10	0.20	0.36	$<0.001^*$
population ≥ 25 Years Old				
Education, proportion of population with				
No high school diploma	0.06	0.41	0.19	0.012*
High school diploma/GED	0.05	0.48	0.18	0.014*
Associate/bachelor's degree	0.19	0.11	0.30	$<0.001^*$
Graduate/professional degree	0.21	0.004*	0.37	$<0.001^*$
Median household Income	0.17	0.026*	0.42	$<0.001^*$
Dog density	0.22	0.003*	0.35	$<0.001^*$
House sparrow density	0.09	0.23	0.22	0.003*

data demonstrate that, like humans, wildlife and domestic animals are exposed to lead in urban environments and support the need for investigation into how environmental lead contamination can impact an entire ecosystem. Reframing environmental lead research to focus on the ecosystem can result in explorations into how interventions targeted more broadly at ecosystem health may be more cost-effective in the long term to reduce exposure to environmental lead across species lines [3,18].

4.2. Correlations between SLLs/block group lead exposure scores and sociodemographic variables do not follow the same directionality as similar associations reported in human literature

Our analysis of socio-demographic factors demonstrate that Somerville is unlike other urban cities where the majority of soil lead research has taken place [37–39]. Somerville is predominantly a racially white, non-Hispanic community with a median income of over \$90,000, and nearly two-thirds of the population have received a higher education degree [34]. We identified at least two potential reasons for the association between SLLs and the percent of residents with a graduate or professional degree. First, because Somerville is associated with a university and because two-thirds of homes are rental properties, it is possible that professors and graduate students may be renting homes and apartments in areas with more lead contamination [19]. Another possibility is that, since median income is often positively associated with the percent of people with graduate and professional degrees, wealthier and more educated households may be more likely to renovate homes and disturb the property (i.e., scrape paint), which is a known risk factor for increasing SLLs, especially if lead sources are not carefully removed during renovation [40].

The positive association between income and SLLs was surprising considering that low income populations are known to be at higher risk for exposure to lead because of access to poor housing [10]. This discrepancy may reflect unequal lead dispersal characteristics within the environment (i.e., indoor versus outdoor) since only public soil was

considered, that typical associations are not true in Somerville, or that other unmeasured variables mediate this interaction [41]. However, prior research has shown that fetal exposure to lead does not vary according to socioeconomic status, supporting our finding that high-income neighborhoods can also be at risk for lead exposure [42]. Another unique finding was that areas with a higher proportion of black residents were not significantly associated with higher block group lead exposure scores, in contrast with the results of numerous previous studies that found minority populations are at higher risk for lead exposure [10,43–46]. These results highlight a need for localized lead exposure assessments to better understand high-risk populations within each unique urban center.

4.3. In some areas, public SLLs exceed state and federal safety limits

The findings of this research demonstrate that there are many publicly accessible areas with SLLs that put children, adults, and animals at risk for lead exposure. This raises additional concerns for exposure to children outside of their home and should prompt further investigation when identifying sources of lead exposure in children. Additionally, the threshold for SLLs for child play areas defined by the EPA (400 ppm) is likely too high because it is based on a child blood lead level reference value of >10 $\mu\text{g}/\text{dL}$ being considered as elevated [47]. More recently, the upper reference range for acceptable blood lead levels in children has been reduced to 5 $\mu\text{g}/\text{dL}$ [48], and the WHO now states that there is no level of exposure to lead that is known to be without harmful effects [49]. Because of this discrepancy, federal and state governments and agencies should work together using the most recent scientific data to determine a more accurate and widely accepted measure for lead-safe soil levels to better understand who is at risk.

4.4. Study strengths and limitations

The spatial analysis allowed us to study lead exposure risk spatially for not just humans, but for animals as well. This study combined and proposed a method to account for the importance various factors play in environmental lead contamination. While many of the statistical correlations were not strong, various human and animal-associated variables were found to be significantly associated with SLLs and/or risk scores, some of which are not commonly identified as being associated with increased SLLs. These analyses can be broadened to other regions of the country and the world, helping to identify communities and populations at risk for lead exposure.

However, there are limitations to this analysis – one being variations in soil contamination. While 240 m is a relatively small distance between sampling locations on a city-wide scale, it likely is not sufficient to account for variations between and within specific properties. Additionally, because paint inside a home is the primary source of exposure for children, public soil samples are likely only a secondary exposure. However, paint in the home is likely not the primary source for animals, and we may see a shift in the primary source for children in the coming years as lead-based paint and plumbing is more frequently removed from or encapsulated in urban homes. This is particularly important given past research that has linked SLLs to lead levels in dust on home floors, and found soil dust to contribute to upwards of 80% of household leaded dust [50,51]. In addition, this study examined SLLs at a single point in time and spatial variables included in the geospatial analysis were collected using modern databases. Changes over time in gas station location, parcel development, road work, and other factors related to urban planning could lead to variations within SLLs. A recent One Health assessment of lead seasonality in the environment highlights a need to study SLLs temporally as well as spatially [18]. Finally, this analysis looked at one calculation for weighing factors in the geospatial analysis, providing opportunity for future investigations into other variations of calculations for the weighted risk analysis.

5. Conclusion

This study demonstrated the importance of using a One Health framework to study environmental lead contamination in urban soil. We identified neighborhoods within a single city that have high risk for lead exposure from public soil coupled with known risk factors such as proximity to roadways and gas stations, and year of building construction. Our data suggests that humans, domestic animals, and wildlife may be exposed to elevated lead levels through contact with public soil and highlight a need to better understand relationships between environmental exposure to lead and health and behavior outcomes across all species.

Funding sources

This work was supported by the Tufts Institute for the Environment (TIEF20171805) and the National Institutes of Health Short Term Training Grant (OD010963). The project described was supported by the National Center for Advancing Translational Sciences, National Institutes of Health, Award Number UL1TR001064. The content is solely the responsibility of the authors and does not necessarily represent the official views of the NIH.

Declaration of Competing Interest

None

Acknowledgements

Thanks to Ashley Ronzio, Catherine Ressijac, Ryan Weaver, and Alyssa McDonagh for assistance with soil collection and testing. Thanks to Boston University School of Public Health Exposure Biology Laboratory for providing the x-ray fluorescence analyzer for sample analysis.

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