Systematic review and meta-analyses of lead (Pb) concentrations in environmental media (soil, dust, water, food, and air) reported in the United States from 1996 to 2016

Jessica J. Frank\textsuperscript{a,b,*}, Antonios G. Poulakos\textsuperscript{c}, Rogelio Tornero-Velez\textsuperscript{b}, Jianping Xue\textsuperscript{b}
\textsuperscript{a}Oak Ridge Institute for Science and Education, U.S. Environmental Protection Agency, Research Triangle Park, NC 27709, United States of America
\textsuperscript{b}National Exposure Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC 27709, United States of America
\textsuperscript{c}ASRC Federal ASMS Contractor, US. Environmental Protection Agency, Office of Research and Development, National Exposure Research Laboratory, Boston, MA 02109, United States of America

Abstract

Environmental lead (Pb) contamination is a persistent public health issue that prominently impacts communities across the United States. Multimedia Pb exposure assessments are utilized to provide a holistic evaluation of Pb exposure and inform the development of programs and regulations that are protective of human health. To conduct multimedia exposure assessments, robust, media-specific environmental Pb concentration data are necessary. To support this effort, systematic review and meta-analysis methods were used to conduct a comprehensive synthesis of research measuring Pb in multiple environmental media (soil, dust, water, food, and air) over a 20-year period within the United States. The breadth of the resulting database allowed for the evaluation of sample characteristics that can serve as indicators of environmental Pb contamination. Random effects models run on literature and national survey datasets generated overall mean estimates of Pb concentrations that can be used for multimedia Pb exposure modeling for general and high-exposure-risk populations. Results from our study highlighted several important trends: 1) The mean estimate of Pb in residential soils is three times higher for urbanized areas than non-urbanized areas; 2) The mean estimate of Pb in produce reported in the literature is approximately three orders of magnitude greater than commercially-sourced raw produce monitored in national surveys; 3) The mean estimate of Pb in soils from shooting ranges is two times greater than non-residential Pb contaminated Superfund sites reported in the literature; 4) Research reporting...
environmental Pb concentrations for school and daycare sites is very limited; 5) Inconsistent sample collection and reporting of results limited synthesis efforts; and 6) The U.S. EPA’s Air Quality System was the most robust, publicly available national survey resource. Results from these analyses will inform future multimedia Pb exposure assessments and be useful in prioritizing future research and program development.

**GRAPHICAL ABSTRACT**

![Graphical Abstract](image)

**Keywords**
Multimedia exposure assessment; Heavy metals; Systematic review; Meta-analysis; Random effects model; Lead (pb)

1. **Introduction**

The United States Environmental Protection Agency (U.S. EPA) has prioritized reducing childhood lead (Pb) exposure (NIH, 2016; U.S. EPA, 2018). As part of this prioritized effort, the Lead and Copper Rule and the Dust-Lead Hazard Standards are under review to reduce Pb exposure (U.S. EPA, 2016,2018). To inform public health decision-making and the development of benchmarks for Pb in the environment, U.S. EPA scientists developed a coupled exposure-dose model to evaluate exposure from multiple environmental media sources and pathways that are applicable to infants and young children (U.S. EPA, 2016; Zartarian et al., 2017). The Stochastic Human Exposure and Dose Simulation (SHEDS) Multimedia model was coupled to the Integrated Exposure Uptake Biokinetic (1EUBK) model to assess how different concentrations of Pb in drinking water contribute to the overall blood lead level (BLL) in children when probabilistic Pb exposure from multiple sources and pathways were considered. In addition to the evaluation of the Lead and Copper Rule (LCR) standards, the agency recently evaluated and proposed updates to the dust lead hazard standards (U.S. EPA, 2018).

Using a multimedia approach to characterize exposures from the total environment provides a more complete picture of aggregate and cumulative exposures to inform the development of programs and standards that are more protective of human health. Comprehensive Pb concentration data are needed for exposure modeling to effectively represent the distribution of Pb levels to which individuals may be exposed. Several U.S. national surveys have been conducted to measure Pb in the environment. For example, the U.S. Department of Housing and Urban Development (HUD) conducts surveys collecting nationally representative Pb data for household soil, dust, and paint; the U.S. Food and Drug Administration (FDA) monitors commercially available food products for Pb contamination as part of their Total...
Diet Study (TDS) and has done so for several decades; and the U.S. EPA maintains the Air Quality Monitoring System (AQS), a national monitoring network that has air Pb data from the 1980s to the present. When national survey data are not available, or targeted sampling characteristics are not represented in national surveys, then systematic review and meta-analysis of peer-reviewed literature can be used as a source for generating model inputs or to validate inputs generated from national survey data.

The objective of this manuscript is to report the systematic review and meta-analyses undertaken in support of U.S. EPA’s Pb multi-media exposure modeling effort. A database was created that included Pb concentration data for multiple environmental media (air, soil, dust, water, and food) and associated sample collection characteristics for samples collected in the United States from 1996 to 2016 and published in peer-reviewed and grey articles. Random effects models were run on subgroups that shared similar sample collection characteristics to generate single group mean summaries. The results from the random effects meta-analyses were then compared to data from national surveys. Finally, sensitivity analyses were conducted by running the meta-analyses on the combined national survey and literature datasets. Resulting synthesized data can be used for Pb exposure modeling for general and vulnerable populations, as well as support the development of public awareness campaigns and guidelines applicable to the U.S.

2. Background

Environmental lead (Pb) exposure is not a new issue. Pb deposition from mining and smelting activities dating to the Roman Empire can be measured in ice cores (McConnell et al., 2018). These geological records correlate with historic economic and political records, indicating the long-term significance of Pb. Records of Pb poisoning date back over 2500 years and persist throughout the last millennia demonstrating the remarkable impact of Pb poisoning over time (Hernberg, 2000). Advances in medicine, technology, and laboratory methods have improved our ability to detect Pb in the environment and in blood, refining our understanding of the health impacts of Pb exposure. A BLL of 80 μg/dL used in the mid-to-late 20th century was thought to be protective of Pb poisoning. The reference value has substantially declined over time as subclinical effects of Pb exposure were observed at lower BLLs. The BLL reference value is updated every four years by the Centers for Disease Control and Prevention and is based on the 97.5th percentile BLL distribution from children surveyed in the latest two National Health and Nutrition Examination Surveys. The current reference value of 5 μg/dL has been in use since 2012. Monitoring of children’s BLLs is common practice within the U.S. Still, no safe BLL has been identified, and research shows that low BLLs can have notable physiological and mental health consequences at all life stages (McMichael et al., 1986; Schwartz, 1994; Gilbert and Weiss, 2006; U.S. DHHS, 2012; U.S. EPA, 2013; Lanphear et al., 2018).

Regulatory interventions have resulted in significant declines of Pb emissions into the environment, and reductions in Pb exposure demonstrated by declines in national BLLs can be attributed to successful regulatory, remediation, and public awareness campaigns (Ringquist, 1993; Hernberg, 2000; Tsoi et al., 2016). Nevertheless, environmental Pb contamination and exposure risk continues to be a complex public health issue that present...
consequential regulatory challenges. Recent Pb related public health crises include instances of Pb contaminated drinking water in Flint, MI (Hanna-Attisha et al., 2016) and Washington D.C. (Edwards et al., 2009), as well as soil Pb contamination in East Chicago, IN (West Calumet Housing Complex, U.S. EPA). The regulatory management of environmental Pb contamination and exposure in the U.S. is a multi-agency task coordinated by the U.S. EPA, the Department of Housing and Urban Development (HUD), the FDA, the Consumer Product Safety Commission (CPSC), and the Occupational Safety and Health Administration (OSHA) (Table A). Present sources of environmental Pb include: 1) industrial activities such as mining, historical primary and secondary smelting, as well as manufacturing of lead batteries, automobiles, ships, solder, and lead pigments; 2) legacy sources such as Pb-based paint and deposition from leaded gasoline (in use by small aircraft), as well as recalcitrant drinking water infrastructure; and 3) contaminated consumer products such as ceramic cookware, food, spices, toys, cosmetics, antiques, herbal medicines, and leaded ammunition. The wide-spread sources for potential Pb exposure call attention to the need to better understand which factors are contributing to the current BLLs seen in vulnerable populations, such as children and women of child-bearing age, individuals with increased predisposition for developing disease, or individuals with pre-existing conditions that can be made worse with Pb exposure. Synthesizing current research to quantify multimedia Pb concentrations supports exposure assessments and helps identify populations and exposure sources of concern to inform future regulatory and public health awareness campaigns, as well as identify data gaps that can inform future research and monitoring efforts.

### 3. Methods

#### 3.1. Literature search & database creation

A systematic literature search was conducted in Web of Science and ProQuest using advanced search logic to identify qualifying articles meeting specified criteria (Table 1). The article title, keywords, and abstract were searched. The search logic was written to improve the precision of the search results by accounting for the ubiquity of the word “lead” and to include multiple environmental media in one search. A sensitivity analysis on the search results was used to determine the appropriate NEAR/x value to use. Reference citations were exported to EndNote (Version X7.0.1) and the deduplication feature was used to identify references listed in replicate. Two screening events were conducted independently by two researchers to determine article eligibility based on inclusion-exclusion criteria. During the first screen, title and abstract were reviewed to determine if the article should advance to the second full article screen. Prior to the second screening, research efforts focused on environmental media, and publications reporting BLLs were reviewed to determine eligibility based on environmental criteria (Fig. 1). When insufficient summary statistics were reported for inclusion, but the sample size was greater than 110, we reached out to the corresponding authors to request the summary statistics. About 20 corresponding authors were contacted, and necessary summary statistics were received for eight publications. To address potential duplicate publication bias, close review of methods and data were conducted to reduce possibility of duplicate data being recorded from multiple publications using the same sampling events. When duplication was identified, the article with the larger
sample size (typically most recent publication), or the one which reported the most relevant sample information was selected for inclusion. Additionally, sample and data sources were reviewed and excluded if the data from the literature contributed to, or was derived from, a national survey that was being used for comparison. National surveys used in this study included the HUD National Survey of Lead and Allergens in Housing (NSLAH; Clickner et al., 2001) and American Healthy Homes Survey (AHHS; U.S. HUD, 2011) reports, U.S. FDA Total Diet Study (TDS), U.S. Geological Survey (USGS) Geochemical Survey, and U.S. EPA Air Quality Monitoring System (AQS) (Table 2). Additionally, a publication that provided national distribution of residential soil Pb from HUD surveys was included in the national survey comparison (Elless et al., 2008).

All data recorded from eligible articles were reviewed by a second researcher to ensure accuracy of transcription. Required information such as summary statistics, sample size, publication year, media type, and citation were recorded. Characteristic sample information reported by authors was recorded from the publication when available and included details about sampling period, sample location (e.g., city, county, and state or region), sampling location features (e.g., residential, urbanized or non-urbanized, and collection from or nearby sites designated by the U.S. EPA to be Superfund sites contaminated with Pb, shooting ranges, or food gardens), and sample collection characteristics (e.g., for drinking water samples the type of water draw). Consistent with the U.S. Census definition, sample locations were classified as an urbanized area if the census designated area had a predicted population size of 50,000 or more during the time of sampling, or time of publication if the sample year was not reported.

3.2. Data preparation and statistical methods

For articles that reported raw data in lieu of statistics, summary statistics (mean, standard deviation, and standard error) were calculated from the data provided. Standard error was also calculated when not reported. Detailed records of the calculations were recorded and reviewed by a second researcher for quality review. For instances where sample size was not reported in the original publication, the 25th percentile for the sample size across all observations was used ($n_{25\%ile} = 5$). Characteristic sample information was used to subset the data for analysis when sufficient data were available.

Due to the known heterogeneity of Pb contamination in the environment, a random effects model was used to account for the variability between observed Pb concentrations across studies (true variation) and the variance within studies (random error). The random effects model was written in SAS software, Version 9.4 for Windows (SAS Institute Inc., Cary, NC, USA) following the detailed methodology outlined in *Introduction to Meta-Analysis* (Borenstein et al., 2011). The inverse of standard error squared was used to weight each study observation, and the study variance was the sum of the within study and between study variance. The random effects meta-analysis results (single group summaries) represent an estimate of the overall true mean Pb concentration generated from true sample populations observed means. The single group standard error summary (and the 95% CI) is the variance for the estimated overall mean of means. Random effects meta-analysis was run for each environmental media subgroup. The resulting single group summaries were compared.
amongst other subgroups within the same environmental media type, and to national survey
data when available.

4. Results and discussion

The environmental media type is discussed in order of robustness of the data (i.e., soil/
sediment, dust, water, food, and air). Appendices B-H provide further details for the
literature data used in each of the meta-analyses summarized below.

4.1. Literature search results and discussion

A total of 17,487 references were exported to EndNote from Web of Science and ProQuest
(Fig. 1; Version X7.0.1). Using the deduplication feature within EndNote reduced our total
number of references to 14,282. The first screening was a review of title and abstract where
1144 articles were identified for full article review. Focusing our efforts on environmental
media, we conducted a full article review of all article categories and determined 183
publications were eligible for inclusion. Sixteen of the included articles reported Pb
concentration for multiple environmental media types.

Arithmetic descriptive statistics were the predominate way authors reported summary data
for all media types, apart from Pb dust concentration and dust Pb loading publications where
arithmetic and geometric descriptive statistics were reported. For dust Pb literature, the
geometric summary statistics were reported in higher frequency, though there were sufficient
arithmetic data to be analyzed for this study. For drinking water, several publications
censored the data by not reporting summary statistics or by only reporting Pb concentration
percentiles without variance, making those articles unusable for this study. Insufficient data
were available to conduct any temporal analyses.

The distribution of Pb research across media types and location is notable. The total number
of research articles returned for each environmental media type may represent the scientific
priority for environmental Pb concentration research. For example, the large number of
articles reporting Pb concentration in soil in contrast to air, can indicate a shift away from
this historically important exposure pathway because air quality regulation and national
monitoring have effectively lowered air Pb concentrations. The overall spatial distribution of
sampling events during this period was clustered to similar regions across media types. The
Upper Midwest and Northeastern states had coverage for multiple environmental media
types, whereas a notable number of states in the Central United States had no sample
coverage for any media type (Fig. 2). The spatial clustering of sample locations can indicate
that there is enhanced research interest in those regions. The sample locations are focused in
regions similar to the placement of air Pb monitors, as demonstrated in the air monitor
location map in Schmidt (2010). However, the spatial clustering demonstrates there is
opportunity to broaden the spatial distribution of sample locations for future research.

Several published case studies reported Pb exposure from sources such as cosmetics,
Ayurvedic herbal supplements, ceramic cookware, spices, and vehicle dust \((n_{\text{article}} = 10)\).
However, insufficient data were available to run meta-analyses for these subgroups. While
our search logic was not targeting these potential exposure sources, research describing the
contribution of consumer products to indoor environmental Pb contamination or exposure is not well developed. Pb contamination from consumer products may represent a noteworthy source of Pb exposure for individuals, especially as research has demonstrated that low levels of exposure are associated with negative health outcomes (Gilbert and Weiss, 2006; Lanphear et al., 2018).

4.2. Soil and sediment Pb results and discussion

The majority of samples in this dataset were classified as soil, though a small subset was described as sediment. Samples reported as sediment were predominately associated with either freshwater or roadside sites. The single group summary for all soil samples (excluding Superfund and shooting range samples) was 118 (2) ppm (Table B.1). The soil/sediment dataset included diverse sample characteristics that were used to group data. Examples included urbanized and non-urbanized residential sites, Superfund sites contaminated with Pb, anthropogenically undisturbed (benchmark), and recreational types (i.e., playgrounds, roadside, green spaces, community gardens, and shooting ranges). The soil and sediment sample locations were largely collected in the Eastern and Upper Midwestern United States, with some locations scattered throughout the Pacific and Southwestern states (Fig. 2). The majority of soil/sediment data were for Pb measures from the top 30 cm. In a few instances, top soil was reported with a soil depth greater than 30 cm. Data were only included if the max depth of the soil core did not exceed 50 cm.

4.2.1. Residential soil Pb—Soil Pb concentration data associated with non-Superfund residential locations were collected from 20 studies with 55 sampling events \((n = 8926\); Table B.2). The single group summary for soil Pb from urbanized residential areas \((n = 7440, M = 629 \text{ ppm}, 95\% \text{ CI} = 567, 691)\) was about three times greater than samples collected from non-urbanized residential areas \((n = 284, M = 219 \text{ ppm}, 95\% \text{ CI} = 147, 290; \text{Fig. 3})\). Combining all non-Superfund residential sites resulted in a single group mean summary closer to the urbanized subgroup \((n = 8926, M = 526 \text{ ppm}, 95\% \text{ CI} = 475, 576)\). All single group summary results for the soil Pb at residential sites were well below the U.S. EPA Toxic Substances Control Act (TSCA) soil lead standard of an average of 1200 ppm for non-play areas with bare soil in residential areas, though higher than the CalEPA residential soil Pb screening level of 80 ppm. Only the mean estimate for non-urbanized locations was below the U.S. EPA soil Pb standard of 400 ppm for bare soil in play areas. These patterns were consistent when the analyses were run with literature data combined with the national survey data, though the residential urbanized summary \((n = 8861, M = 610 \text{ ppm}, 95\% \text{ CI} = 550, 671)\) was about four times greater than the non-urbanized locations \((n = 473, M = 153, 95\% \text{ CI} = 114,191)\). When all residential literature and survey data were combined, the single group mean summary was closer in value to the urbanized literature single group summary, and greater than the national survey summary statistics for residential locations \((n = 15,044, M = 451 \text{ ppm}, 95\% \text{ CI} = 413,489)\). Residential soil Pb concentrations reported in the HUD NSLAH and AHHS surveys were closer to the non-urbanized single group mean summary. The combined urbanized/non-urbanized analyses were comparable to the nationally representative LA-1400 HUD dataset reported in Elless et al. (2008). The residential soil Pb data from the USGS Geochemical Survey was comparable to the soil Pb found in low impacted benchmark areas (Table 2 and Fig. 4).
The results of our residential Pb analyses support the finding that urbanized areas have a higher soil Pb burden compared to non-urbanized areas. Urbanized areas may have an increased soil Pb burden because urban centers tend to be older and have more dense development and traffic, which would result in an increase of Pb into the soil over time from Pb-based gasoline and paint. Additionally, urban areas may have inputs from brownfield sites and historical industrial activities that contribute to the elevated levels. The urbanization pattern held with the addition of the national survey data, though there was a notable decrease in the non-urbanized single group summary with the addition of the residential USGS national survey data. The change in single group summary for the non-urbanized group can be a consequence of a larger weight being assigned to the USGS geochemical survey because of the larger sample size and smaller variance for these data in conjunction with the low soil Pb concentrations reported in the survey. The low soil Pb concentration in the USGS geochemical survey reflects the intention of the survey to provide baseline soil geochemistry measures. The HUD surveys (NSLAH and AHHS) had summary statistics closer to the non-urbanized literature data, whereas the LA-1400 dataset from Elless et al. (2008) had a mean closer to the single group mean summary for the combined residential literature dataset. Running a meta-analysis on the literature and national survey datasets produced a single group summary representative of residential soil Pb concentrations \((n = 15,044, M = 451 \text{ ppm}, 95\% \text{ CI} = 413, 489)\). While all subgroup mean summaries are below the U.S. EPA residential soil Pb standards of an average of 1200 ppm for non-play areas in residential yards, there are several urbanized areas within the literature that are well above this standard, supporting the need for targeted public awareness campaigns and remediation of residential urban areas.

4.2.2. Recreation related soil Pb—The range of single group mean summaries for soil subgroups that can be associated with outdoor recreational activities was 11 ppm to 3604 ppm (Fig. 4). All recreation related soil subgroups had single group mean summaries below the U.S. EPA standard for play areas with bare soil (400 ppm) except for the shooting range subgroup. All recreational subgroups had small single group standard error summaries.

4.2.2.1. Benchmark and green spaces: Subgroups associated with greenspace defined as benchmark, near fresh water, forested, and open space areas were below the CalEPA residential soil Pb screening level (80 ppm). Samples designated as benchmark by authors represented locations with minimal anthropogenic impacts and were collected from five studies with five sample events (Table B.3). The benchmark subgroup had the lowest Pb concentration reported across all soil subgroups for both literature and national survey data \((n = 93, M =11 \text{ ppm}, 95\% \text{ CI} = 7,15)\). Soil and sediment Pb collected in association with freshwater sources \((n = 595, M=63 \text{ ppm}, 95\% \text{ CI} = 58, 67)\) were collected from 16 studies with 47 sample events (Table B.4). The single group summary for the soil Pb subgroup associated with freshwater was strongly influenced by the samples collected from West Point, New York, which is associated with a military base. Removing these observations from the analysis resulted in a drop of the single group mean and standard error summaries from 63 (2) to 23 (1) ppm. For the forest and open space subgroup \((n = 1828, M=77 \text{ ppm}, 95\% \text{ CI} = 73, 81)\), data were collected from 15 studies with 89 sampling events (Table B.5).
The single group mean and standard error summaries for the forests and open space subgroup were stable with the inclusion of the USGS Geochemical Survey data (Fig. 4). The USGS national survey is the most comprehensive and representative of national baseline surface soil Pb levels prior to anthropogenic disturbance. Soil Pb associated with natural space has a relatively low soil Pb burden, compared to residential sites. Differences seen in Pb concentrations between residential and natural space can be attributed to potential increased soil burial rates (due to increased input of organic matter in natural spaces) following historical deposition of air Pb and reduced sustained Pb inputs from anthropogenic sources such as Pb-based paint seen with aging pre-1978 housing stock and Pb-based ammunition seen in outdoor shooting ranges. The natural space and benchmark literature groups were the only groups at or below the California health-based screening level of 80 ppm for residential soil Pb.

4.2.2.2. Schoolyards and playgrounds: There were eight studies that reported soil Pb from schoolyards and playgrounds ($n = 182, M = 87$ ppm, 95% CI = 70,104) with 14 sampling events (Table B.6). Sample locations within the schoolyards and playground subgroup were predominantly classified as urbanized areas, with one serving as a control sample for a Superfund site contaminated with Pb. The summary result for schoolyards and playgrounds was just over the CalEPA standard for residential locations and below the U.S. EPA standard for bare soil in play areas (Fig. 4). The California standard represents the soil Pb concentration that has “...no more than a 2.5% probability of decreasing IQ by more than 1 point in a 90th percentile child or fetus” (CalEPA, 2009). The single group mean summary for schoolyards and play-grounds from urbanized play areas is above the California standard, suggesting screening of soil Pb in play areas would be protective of children’s health. Additionally, because the overall sample size for this group is small and limited predominantly to urbanized areas, investigation into soil Pb concentrations at these sensitive sites needs to be explored further.

4.2.2.3. Roadsides: There were eight studies that collected roadside soil Pb samples with 17 sampling events (Table B.7). Roadside sample locations were predominantly from urbanized areas ($n = 1048, M = 115$ ppm, 95% CI = 96,134). Authors within this soil group largely attributed the roadside sources to historic use of leaded gasoline, though yellow roadway paint (Sheets et al., 2001; LeGalley et al., 2013), housing paint (Wu et al., 2010), and Pb wheel weights (USGS, 2006) were identified as additional sources of soil Pb contamination of roadsides. While historical soil Pb contamination from leaded gasoline and Pb paint have been demonstrated to be the primary sources of roadside soil Pb, localized industrial contamination is evident as well (Nedwed and Clifford, 1998; Eckel et al., 2002; Machemer et al., 2007). Notably, the roadside single group summary is lower than residential soil Pb in urban environments. Further research is necessary to better understand the variation seen between the subgroups. The difference may be attributed to a combination of factors, including: 1) variation in sample location characteristics between subgroups (the residential urban samples were largely collected from older, more densely populated areas compared the roadside group); 2) sustained source of Pb paint found on older housing stock co-localized with residential yards; 3) difference in sample methodologies or seasonal timing for when the sample was collected; or 4) differences in the transport of soil Pb at
roadside locations compared to residential yards. Laidlaw et al. (2012) demonstrated that turbulence from automobile traffic can contribute to the transport of roadside soil and dust levels, suggesting these sites can experience regular disturbances that result in rapid movement of soil Pb along roadsides.

Participating in recreational activities alongside roads can contribute to Pb exposure. Exposure pathways of concern would be inhalation of small particles (especially with traffic creating turbulent air) and hand-to-mouth ingestion for youth. Temporary pop-up parks, typically associated with urban areas, are a relatively new phenomenon where areas used for vehicle traffic are temporarily closed to create play areas for neighborhood youth. These temporary play spaces are valuable in that they provide access to play areas, promote physical activity, and create community cohesion (Salvo et al., 2017). Educational out-reach regarding mitigation of Pb exposure from roadside recreational activities could reduce pollution exposure related to these activities in urban environments and further promote access to healthy play areas.

4.2.2.4. Residential and community gardens: The residential and community garden subgroup represents samples collected from active gardens and had the second highest single group mean summary for recreation related categories (n = 2082 M = 293 ppm, 95% CI = 228, 358). If considering the shooting ranges to be an outlier, the recreational soil Pb range becomes 11 ppm to 293 ppm with community and residential gardens having the highest soil Pb concentration. Data for this subgroup were collected from 8 studies with 21 sampling events (Table B.8), and the sample locations were classified as urbanized areas. In addition to the community garden studies, there were two studies that reported soil Pb from commercial food production sites, which had a single group mean summary comparable to the natural spaces (n = 668, M = 25, SE = 10, 95% CI = 5, 45).

The single group mean summary for residential and community gardens in urbanized areas is lower than the single group summary for residential soil Pb. The difference in Pb concentration seen between these subgroups can be attributed to garden practices such as composting and soil importation. The majority of authors in this subgroup reported that composting was used at the sampled gardens, which has been shown to reduce soil Pb concentrations (Attanayake et al., 2014). In 2014, a technical review workgroup published recommendations for reducing exposure to lead contaminated soils when gardening (U.S. EPA, 2014). Insufficient data were available to provide risk-based recommendations for Pb in garden soils, however the working group provided guidelines for reducing Pb exposure in gardening. Soil Pb concentrations lower than 100 ppm were classified by the working group as low risk, and garden soils with Pb concentrations between 100 and 400 ppm were classified as potential risk. The single group mean summary for gardens in our study are within the potential risk category. Behavioral interventions are recommended that include relocating the garden, composting, raising beds, and reducing soil tracking and adherence on vegetables.

Soil Pb collected from sites associated with commercial food production had a substantially lower Pb concentration compared to community and residential gardens. While the sample size was small for commercial food production sites, this pattern appears to be supported by
the produce analyses discussed in Section 4.5.2, suggesting that exposure to soil Pb and food Pb from residential and community gardens may be an important source of total exposure for gardeners. Community and residential gardens are often co-located to housing, or located on abandoned or recovered lots, which may increase the risk of soil Pb contamination from Pb-based paint or brownfields. Furthermore, due to the nature of gardening (e.g., digging and planting in the soil, and potential adsorption and uptake by produce) there is a higher risk of Pb exposure from ingestion of contaminated soil or produce. Community gardens are important in creating community resiliency by promoting community cohesion, equity, physical activity, and healthy eating habits (Castro et al., 2013; Soga et al., 2017; Veen et al., 2016). Creating programs that support education and remediation to mitigate Pb exposure and risk will help protect this vulnerable group and conserve the important practice of gardening. Further research and monitoring are needed to better describe potential exposure risks for this recreational group.

4.2.2.5. Outdoor shooting ranges: Data for the outdoor shooting range subgroup was collected from 10 studies with 51 sampling events (Table B.9). The single group mean summary for soil Pb collected in association to shooting ranges was two times higher than the non-residential Pb Superfund samples discussed in Section 4.7.1 ($n = 563$, $M = 3604$ ppm, 95% CI = 3497, 3712). While the majority of samples collected for the shooting range subgroup may represent hotspots at these sites because samples were predominantly collected from berms, the results suggest that soil Pb concentrations from outdoor shooting ranges can parallel Pb soil concentrations found at Pb Superfund sites. Assessments to determine the geographic extent of Pb contamination and remediation requirements resulting from the use of Pb ammunition is still needed, and indications suggest it will be a complex process (U.S. EPA, 2003a). For example, a private outdoor shooting range may have hotspot soil Pb associated with berms, where a public outdoor hunting grounds will have random Pb shot scattered throughout the grounds, with possible remnant game contaminated with Pb. Shooting on private lands may have a multi-use pattern associated with target practice and hunting. Furthermore, mobilization, migration, and remediation of Pb at outdoor locations relates to various site-specific hydrogeological properties which will require targeted strategies for determining the extent of contamination and for developing remediation plans (U.S. EPA, 2003a; Dermatas et al., 2006; Sanderson et al., 2012). For indoor shooting ranges, concentrated Pb dust and spent bullets are the dominant source of Pb exposure, requiring another unique management strategy compared to other sites.

The USGS Minerals Yearbooks from 1993 to 2015 show that in the U.S. over 3.3 billion pounds of Pb have been consumed from lead ammunition in 12 years (over 275 million pounds per year) making it the second largest source of lead consumed in the United States (USGS, 2017). The National Institute for Occupational Safety and Health (NIOSH) estimates there are 16,000–18,000 indoor firing ranges operating within the U.S., and about 20 million (about 6% of the total U.S. population) are target shooters (NIOSH, 2009). Using these metrics, we can coarsely characterize the impact of Pb releases related to ammunition. For example, we can estimate that over 165 pounds of environmental Pb per shooter over a 12-year period is emitted into the environment. Alternatively, assuming equal distribution of Pb ammunition use across the estimated number of shooting range sites, there would be
183,532 to 206,474 pounds of environmental Pb deposited per site over a 12-year period. Yet another way to conceptualize the extent of impact is to compare Pb ammunition emissions to regulated point source air emissions (understanding there are different implications for air Pb versus ammunition Pb releases, as well as non-point source versus point source releases). According to Schmidt (2010) the Doe Run primary smelter in Missouri was the largest point source emitter of Pb until its closure in 2013. Between 2005 and 2008 Doe Run released 44,800 to 118,000 pounds of Pb into the air annually. In comparison, the average annual Pb ammunition releases would equate to about 2333 to 6145 smelter facilities releasing similar Pb quantities compared to the last and worst primary smelter polluter in the U.S.

While the extent of environmental contamination from ammunition is not well characterized, scientific consensus that Pb ammunition poses substantial threats to ecological and public health is certain (Bellinger et al., 2013; Bernhoft et al., 2014; Arnemo et al., 2016). Pb from ammunition is highly bioaccessible (Bannon et al., 2009). Pb poisoning has been implicated in the deaths of critically endangered species from ingestion of Pb shot or ingestion of contaminated game remnants (Church et al., 2006; Fisher et al., 2006; Haig et al., 2014; Arnemo et al., 2016). Regulation prohibiting the use of Pb shot for waterfowl hunting was successfully enacted in the 1980’s following evidence that Pb shot ingestion caused 2 million waterfowl deaths annually (Department of the Interior, 1977). Mounting evidence demonstrates that the use of Pb ammunition is a serious public health issue associated with elevated BLLs in shooters (Lévesque et al., 2003; NIOSH, 2009; Johansen et al., 2006; Laidlaw et al., 2017). The current reference BLL for adults is 5 μg/dL, with BLL greater than 10 μg/dL to be considered elevated (NIOSH, 2018). According to the 2009–2010 National Health and Nutrition Examination Survey (NHANES), the average BLL for adults was 1.2 μg/dL (NIOSH, 2018). In a review of research on Pb exposure at firing ranges, 31 of 36 studies reviewed reported shooters to have elevated BLLs over 10 μg/dL, with 15 of the studies reporting elevated BLLs over 40 μg/dL (Laidlaw et al., 2017). Research of BLLs in law enforcement before and after training showed increases in the mean BLLs from 6.5 to 50.4 μg/dL after 3 months (NIOSH, 2009). Exposure can occur through inhalation of Pb aerosols discharged during the use of guns, and BLLs are associated with caliber size and number of bullets discharged (Laidlaw et al., 2017). Dust Pb from discharged weapons has been shown to contaminate clothing and skin, resulting in elevated environmental Pb concentrations in spaces outside of shooting ranges, including living spaces (NIOSH, 2009). In a case study examining exposure for law enforcement trainees, elevated air Pb concentrations in personal breathing zones for shooters and janitorial staff were found to range from 2.7 to 220 μg/m³, concentrations that are 90 to 7333 times greater than the average indoor air Pb found in our study (Fig. 9). Further exposure can occur for groups that hunt using Pb shot because they are at higher risk of ingestion of Pb remaining in game meat or they are at risk of eating game with acute Pb poisoning due to the ingestion of Pb shot from the environment (Fisher et al., 2006; Tsuji et al., 2008; Iqbal et al., 2009).

The synthesis of research suggests that groups that use Pb ammunition are at increased risk of having elevated BLLs, especially when indoor shooting ranges with inadequate exposure controls are frequented. Women of childbearing age and youth using Pb ammunition, or sharing a household with someone who uses Pb ammunition, are particularly vulnerable to Pb exposure (Laidlaw et al., 2017). Research demonstrating correlations between Pb exposure...
exposure and cognitive function and criminal behavior (Nevin, 2007; Mielke and Zahran, 2012; NTP, 2012; Feigenbaum and Muller, 2016) suggest that social risks associated with Pb ammunition should also be considered for this population group. Fortunately, there are alternatives to Pb ammunition that are comparable in price and quality (Thomas, 2013; Gremse et al., 2014). Research identifying the benefits and barriers to adoption of ammunition alternatives could help direct the development of effective outreach programs to reduce Pb exposure for this recreational population, while mitigating future ecological and economic impacts. Additionally, further research is necessary to characterize the impact of recreational shooting on BLL, and the contribution of shooting range soil Pb concentrations to environmental exposures of neighboring populations.

4.3. Dust Pb results and discussion

Dust was the second most robust media type with sample locations solely associated with residential settings and predominantly collected from the Northeastern and Upper Midwestern states (Fig. 2). Residential dust samples were either reported by sample location (e.g., floors, window sills or window troughs) or as general indoor measures. Data were sufficient to run analyses for both Pb loading and Pb concentration literature data, and to run subgroup analyses based on sample collection location. Aggregate analyses were run that included data from all residential indoor sample locations, which was intended to be analogous to the general indoor measures reported in the literature.

While research on dust Pb was extensive over the 20-year period used in our search, the variation in sample methods and reporting of the results required that distinct subgroups be made for our meta-analysis. Dust Pb studies reporting Pb loading versus Pb concentration were analyzed separately, and further groups were made based on how the results were reported (i.e., arithmetic versus geometric summary statistics). These divisions significantly reduced the number of studies included in each subgroup. For these analyses, we focused on the studies that reported arithmetic summary statistics to be consistent with the other media types, though there are sufficient Pb loading and Pb concentration data reported in geometric summaries for future analyses.

4.3.1. Dust Pb loading—The majority of residential dust Pb loading samples were collected from urbanized areas, and as a result, a comparison of dust loading by population density could not be made. Floors were the most frequently sampled location within residences, followed by window sills, and then window troughs. However, mean Pb dust loading is typically higher in order of window troughs, window sills, and then floors, and there tends to be a larger variance across sample locations in the same order (Table 2, Fig. 5). Since window troughs are thought to be a source for dust Pb within the home (Layton and Beamer, 2009), collecting window samples in conjunction with floor samples would better characterize the sources of Pb dust and to inform site-specific remediation strategies.

A proposed change to the U.S. EPA household dust Pb hazard standard for floors and window sills was made in July 2018 (U.S. EPA, 2018). The final rule announced in June 2019 changes the dust hazard standards of 40 and 250 μg/ft² to 10 and 40 μg/ft² for floors and window sills, respectively. These proposed changes take into account the latest research
that demonstrates that health effects occur from exposure to lower levels of Pb than previously recognized. The proposed standards aim to be more protective of all children’s health and help inform where intervention resources should be directed.

The single group summary for dust Pb loading on floors ($n = 535, M = 13 \mu g/ft^2, 95\% CI = 7, 20$) was under the previous U.S. EPA standard of 40 $\mu g/ft^2$ and greater than the new standard of 10 $\mu g/ft^2$. This result remained stable with the addition of the HUD NSLAH and AHHS national survey data ($n = 5560, M = 13 \mu g/ft^2, 95\% CI = 8, 17$; Fig. 5). The mean Pb dust loading for floors was similar between the literature and national survey data. Running the meta-analysis with both datasets did not change the single group summary mean, and it slightly improved the single group standard error, which was already comparatively small. This agreement suggests the meta-analysis result that combines the literature with the two HUD national surveys are representative of the dust Pb loading found on sampled floors.

The single group mean summary for window sills was under the previous U.S. EPA dust loading standard for window sills of 250 $\mu g/ft^2$, though the upper bound for the confidence interval surpassed that standard ($n = 380, M = 214 \mu g/ft^2, 95\% CI = -7, 434$). The single group summary for window sills was greater than the new standard of 40 $\mu g/ft^2$. Adding the HUD NSLAH national survey data to the window sill analyses reduced the single group mean and standard error summaries ($n = 2682, M = 186 \mu g/ft^2, 95\% CI = 71, 302$), while remaining within the range of the literature data. The single group summary for the window trough Pb measures for the literature and HUD national survey are substantially higher than the U.S. EPA standard ($n = 1725, M = 1712 \mu g/ft^2, 95\% CI = 872, 2551$). There were a small number of articles that reported dust Pb loading for window sills and troughs that matched the criteria for this study. For window sills, the single group mean summary for dust Pb loading was higher with a larger single group standard error for the literature data compared to the national survey data. Combining the literature data with the national survey data resulted in a lower single group mean summary, though the single group summary for the standard error was higher compared to the national survey data. The meta-analysis for the combined datasets encompasses the sample mean reported for the national survey data, though the CI is larger for the predicted mean. These results, in conjunction with the insufficient literature data for window troughs, suggest the national survey dust Pb loading...
data for window sills and troughs are more representative than the literature data. Furthermore, the arithmetic literature data were inadequate at providing additional subgroup characteristic information beyond what is provided by the national survey data. There were more articles reporting geometric summary statistics for dust Pb loading for window sills compared to articles reporting arithmetic summary statistics, though the number of articles reporting geometric dust Pb loading for window troughs was still very low. The meta-analysis results for both window sills and troughs, and the summary statistics for the national survey data, show that the mean dust Pb loading is at or substantially above the standards for window sills and troughs. These results further support the concept that future research should include window sample locations in studies of indoor dust loading, as these sites can be an important source of Pb dust within the home at levels above the national standard.

4.3.2. Dust Pb concentration—The literature reporting dust Pb concentrations for floor samples were predominantly collected from non-urbanized areas (Table D.1). The literature single group mean summary for dust Pb on floors \((n = 185, M = 176 \text{ ppm}, 95\% \text{ Cl} = 126, 227)\) was higher than the national survey data (Fig. 6). National survey data for residential dust Pb concentrations were only available for floors from the HUD AHHS survey \((n = 1131, M = 104, SE = 4; \text{Table 2})\). Running the floor dust Pb meta-analysis with the national survey and the literature data resulted in a value closer to the literature data \((n = 1316, M=153 \text{ ppm}, 95\% \text{ Cl} = 118, 188)\). The pattern seen between urbanized and non-urbanized soil Pb concentrations should hold true for the dust Pb concentrations since soil Pb can be a major source of Pb dust (Layton and Beamer, 2009). Since the meta-analysis results are outside the bounds for the national survey data, and because the dust Pb concentrations should follow a similar urban pattern to soil Pb, it is probable that the national survey data under-reports the national floor dust Pb concentration. More data are needed to elucidate sample location characteristics that are associated with dust Pb concentrations, such as urbanized versus non-urbanized areas.

While only dust Pb from floor locations were reported for the national survey data, dust Pb concentration data were reported in more diverse residential sample locations for the literature dataset, which included sample locations identified as general indoor and outdoor entry. Literature data reported as general indoor values \((n = 468, M = 302 \text{ ppm}, 95\% \text{ Cl} = 152, 452)\) had a higher single group mean and standard error summary compared to the aggregate indoor value. The aggregate indoor literature results only included floor and general indoor measures \((n = 892, M = 212 \text{ ppm}, 95\% \text{ Cl} = 162, 261)\). The aggregate data for residential dust Pb concentration were collected from a mix of urbanized and non-urbanized areas (Table D.3). When running the aggregate indoor analysis with the AHHS national survey, the single group summaries were similar to the floor values \((n = 2023, M =153 \text{ ppm}, 95\% \text{ Cl} = 145, 219)\). Dust Pb collected from outdoor entryways \((n = 90, M = 359 \text{ ppm}, 95\% \text{ Cl} = 110,609)\) had concentrations higher than general indoor and aggregate indoor single group summaries. Unfortunately, there were insufficient window related Pb concentration data for inclusion. As with the dust Pb loading data, floors were less impacted compared to other sample locations such as general indoor and outdoor entryways, and the standard error increased in the order of floors, general indoor, and outdoor entryway.
4.4. Water Pb results and discussion

The water dataset includes drinking water collected from the tap and freshwater (surface and ground waters) and reported in the literature. The publications do not include state or national compliance data. The majority of samples for the water media type were collected in the Northeast and Upper Midwest. For the drinking water studies, there were sufficient data to run the meta-analysis for flushed and first draw sample groups. Several of the drinking water publications did not meet our inclusion criteria by reporting Pb drinking water concentration percentiles without variance, making those articles unusable for meta-analysis.

4.4.1. Pb in drinking water—Two types of water sampling methods were used in studies reporting Pb in drinking water. These two sampling types are described as first draw or flushed. First draw samples refer to water samples collected after a period of stagnation (typically the stagnation period is at least 6 h). Flushed samples refer to water samples that are collected after the water has run for a determined period of time. The type of sample collection (first draw or flushed) provides information about the plumbing infrastructure that is in contact with the water. First draw samples collected from the tap are used for lead and copper compliance monitoring (40 CFR 141.86(b)(2)). The stagnation and flush times were not consistently reported across studies. Studies reporting flush times, included flush times from 30 s to 2 min.

Flushed drinking water data were collected from nine studies with 20 sampling events, and first draw data were collected from ten studies with 16 sampling events (Tables E.1 and E.2). The majority of flushed drinking water samples were collected from urbanized areas, whereas the first draw samples were almost equally collected from urbanized and non-urbanized areas. There were insufficient data to subset the analyses by urbanized and non-urbanized areas. Flushed samples \( n = 6889, M = 2.0 \text{ ppb}, 95\% \text{ CI} = 1.6,2.4 \) had a single group mean and standard error summary less than first draw samples \( n = 5900, M = 8.8 \text{ ppb}, 95\% \text{ CI} = 6.8,10.9 \), with the single group mean summary for flushed samples being about four times less than the first draw drinking water samples (Fig. 7). Pb concentrations measured in drinking water are largely influenced by the sampling method used (e.g., flushed versus first draw). The pattern associated with sampling methods was confirmed in our study, which showed that flushed samples with a short flush time scale have lower Pb concentrations and standard errors compared to samples first drawn from a system after a period of stagnation. Research has shown that the flush time can have site-specific effects associated with the drinking water infrastructure (Cornwell and Brown, 2018). For example, longer flush times can increase the Pb concentration in the drinking water for homes serviced by Pb service lines, as the water sampled after a long flush period have been in contact with service lines. These results suggest that flushing strategies need to be evaluated for site-specific recommendations.

The Second Six-Year Review of National Compliance Monitoring represents the largest national dataset of Pb in drinking water. For this dataset, the U.S. EPA requested (on a voluntary basis) the 90th percentile tap water compliance monitoring results for systems from each state (U.S. EPA, 2010). The mean and standard deviation or standard error are the
summary statistics used in our meta-analyses. The 90th percentile statistic is not compatible for this synthesis effort. The average 90th percentile for the compliance monitoring data for this second review was reported to be 0.89 ppb, substantially lower than the single group mean summary meta-analysis result and the regional National Human Exposure Assessment Survey (NHEXAS) study that reported average drinking water Pb concentrations of 3.88 and 1 ppb for first draw and flushed samples, respectively (Supplemental material, Zartarian et al., 2017). State agencies collect individual sample data from public water systems and could theoretically provide summary statistics of the compliance monitoring data to create a comprehensive national database for drinking water Pb. Having more statistically descriptive monitoring information would be compatible for broader analyses, including exposure research used to inform the creation of regulatory standards.

The maximum contaminant level goal (MCLG) set forth by the U.S. EPA for Pb in drinking water is zero (U.S. EPA, 2016). MCLGs are non-enforceable health-based standards considered to be the level where no adverse health effects are likely to occur. The current action level of 15 ppb based on the 90th percentile of samples collected during a monitoring period is currently used for compliance monitoring for public water systems. The action level is considered to be a technology-based requirement (U.S. EPA, 2015 and 2016). Currently the U.S. EPA is evaluating the potential use of a health-based household action level in the revised Lead and Copper Rule. As part of this evaluation effort, Zartarian et al. (2017) used multimedia exposure modeling to estimate the maximum daily average of Pb in drinking water that would keep the BLLs for the 95th and 97.5th percentiles of children aged 0–7 years old under the 3.5 and 5 μg/dL. This work was conducted to inform the potential development of residential health-based standards for Pb in drinking water. Their modeling results demonstrated the maximum daily average for Pb in drinking water that would keep the 95th percentile BLL below 3.5 and 5 μg/dL are 2 and 13 ppb, respectively, when considering aggregate Pb exposure from multiple environmental sources. In this study, the meta-analysis results for both drinking water sampling groups are below 13 ppb. However, only the flushed samples single group mean summary was at the level of 2 ppb necessary to achieve the 95th percentile BLL of 3.5 μg/dL. Furthermore, according to their analysis, to keep the 97.5th percentile BLL below the CDC action level of 5 μg/dL would require a maximum daily average of Pb in drinking water to be 5 ppb or less - a concentration only reflective in the mean single group summary for the flushed samples reported in the literature.

The drinking water samples largely reflect samples collected from residential sites, though there were two studies that measured Pb in drinking water at schools. Compliance monitoring for the LCR do not require monitoring of schools and daycare facilities unless the school manages their own drinking water system. While the U.S. EPA does not currently require testing at schools and daycare facilities, the agency does provide guidance for reducing Pb in drinking water at these sensitive sites (U.S. EPA, 2005 and 2006). A recent survey conducted by the U.S. Government Accountability Office (GAO, 2018) found that 59% of schools did not test, or were unsure if they tested, for Pb in tap drinking water. Of the 41% of schools that did test for Pb in drinking water, 37% found elevated levels. School districts varied in the threshold used for determination of elevated Pb. School districts reported using either the 15 ppb standard for compliance monitoring for public water
systems, or the 20 ppb action level suggested in the 3Ts for Reducing Lead in Drinking Water in Schools (U.S. EPA, 2006) guidance document for schools and daycares, while others reported using more conservative action levels than 15 ppb. The difference in the LCR and 3Ts standards is reflective of the difference in goals. The LCR standards are intended to identify system-wide problems to inform water treatment protocols, whereas the guidance for schools and daycares are intended to identify issues with specific drinking water outlets (U.S. EPA, 2006). Identifying the extent of Pb contamination at schools and daycares is essential to understanding the exposure burden for children from their total environment. Currently there is very limited data available for levels of Pb in drinking water at schools and daycares. The availability of multi-media exposure data is even more limited for these sites. In our review, we identified Pb concentration data in soil and drinking water for a limited number of school sites. Our review did not identify data sources for dust Pb loadings at U.S. schools. Considering the substantial amount of time that children spend at these alternative locations, it is imperative that there is a better understanding of potential Pb exposure at these sites to successfully reduce Pb exposure and overall BLLs for this vulnerable population.

4.4.2. Pb in surface water and groundwater—Surface water samples were collected from river and lake sources. Data for the surface subgroup was collected from eight studies with 25 sampling events (Table E.3). There were a mix of urbanized and non-urbanized locations sampled. The surface water single group mean summary had very small standard error \( n = 557, M = 4.6 \text{ ppb}, 95\% \text{ CI} = 4.5 \); Fig. 7). For the groundwater subgroup, data was collected from two studies with eight sampling events (Table E.4). The single group standard summary for the groundwater sample was larger compared to the other water subgroups \( n = 1661, M = 13.4 \text{ ppb}, 95\% \text{ CI} = 5.22 \). Surface water and groundwater subgroups had concentrations that clustered by sample location, while Pb concentrations in tap water clustered independent of location. These results suggest there are site-specific parameters that drive Pb concentrations in ground and surface water, including Pb source and Pb mobility factors. Understanding environmental Pb contamination in natural water sources is of ecological importance and provides insight into the transport of Pb through the environment. Furthermore, according to the 2015 U.S. Census Bureau’s American Housing Survey, over 13 million households in the U.S. supply their own drinking water from private groundwater wells. Private drinking water systems are not regulated by the U.S. EPA, so monitoring and treatment falls to the owner of the system. Research has shown that testing, treatment, and perception of water quality are barriers for reducing exposure to contaminated drinking water for this population (Zheng and Ayotte, 2015). In addition to anthropogenic sources of Pb, site-specific geology can contribute to the contamination of aquifers (Pieper et al., 2015). Considering the significance of groundwater as a source of drinking water that is largely unmonitored for contaminants of concern, more research should be conducted to identify the extent and impact of Pb contamination of groundwater resources used for drinking water.

4.5. Food Pb results and discussion

The number of articles reporting Pb concentration in foods followed the water group closely in frequency. Food samples were predominantly collected in the Northeast and Upper
Midwest regions (Fig. 2). Food samples from the literature were predominately from community or residential food production, or wild-caught foods (i.e., fish, shellfish, and large game). The food sample types with sufficient data for meta-analysis could be grouped into produce (leafy greens, herbs, and fruit), poultry (chicken and game-bird), poultry eggs (chicken only), fish, and shellfish (bivalves only). A subset of the fish samples and all the shellfish samples were collected at or nearby Superfund designated areas contaminated with Pb and are discussed in Section 4.7.3. Due to lack of available data, there were no poultry or poultry egg samples associated with Pb Superfund designated areas included in the analyses.

The FDA has evaluated the amount of Pb in food that would raise an individual’s BLL to a level of concern (FDA, 2019). Factors such as amount of food consumed daily and the CDC’s blood reference level were considered. The FDA established a maximum daily intake for Pb called the Interim Reference Level (IRL). The IRL for children and adults is 3 μg/day and 12.5 μg/day, respectively. The IRL values can be used to provide context for the single group mean summaries for food.

4.5.1. Pb in wild-caught and livestock food—For the non-Superfund fish subgroup, there were seven studies with 31 sampling events (Table F.1). Fish samples collected from fresh and brackish water sites were included in the analysis. The sample types were classified as muscle/fillet or whole tissue. Eating 10 g of fish with the single group mean summary for wild-caught fish of 0.3 ppm would reach the children’s IRL of 3 μg/day (n = 195, \( M = 0.3 \text{ ppm}, 95\% \text{ CI} = 0.23, 0.32; \) Fig. 8). Pb concentrations for poultry were reported in two studies with 10 sampling events (Table F.2). The sample types included muscle, kidney, and liver samples from chickens raised at small, rural gardens as well as blood samples from the game-bird called the American Woodcock. Eating about 21 g at the single group mean summary Pb concentration would reach the children’s IRL of 3 μg/day for maximum daily Pb intake (n = 42, \( M = 0.14 \text{ ppm}, 95\% \text{ CI} = 0.09, 0.2; \) Fig. 8). The Pb concentration in poultry eggs was reported in two studies with seven sampling events (Table F.3). The samples were associated with residential food production. The dataset included samples from urban gardens, as well as samples from rural gardens with known Pb-based paint hazards and from control sites with no known Pb-based paint hazards. Eating 75 g of poultry eggs at the single group mean summary Pb concentration would be required to reach the children’s IRL (n = 82, \( M = 0.04 \text{ ppm}, 95\% \text{ CI} = 0.02, 0.06; \) Fig. 8).

The wild-caught and livestock literature data were not comparable to the national TDS data because they were raw, single food items, whereas the TDS data represent heterogenous cooked meals. The data available for this exposure pathway were limited, which was further compounded by the heterogeneity of the sample types reported. Research targeting hotspot areas and foods of concern should be conducted to expand the representation of data. For example, residential and community food gardens have been shown to be potential hotspots for Pb exposure from soil and produce. Additionally, expanded sampling of livestock associated with these sites should occur to better understand these potential exposure pathways. More expansive sampling of poultry would be beneficial, especially considering poultry feeding behavior and the high frequency of residential cultivation of chickens for food. Wild-caught food hunted with Pb ammunition have been shown to be a potential source of Pb exposure (Iqbal et al., 2009). Unfortunately, there were insufficient large game
Pb concentration data compatible with our analysis to evaluate this exposure source. Additional research evaluating Pb exposure from large game would contribute to understanding the cumulative impacts of exposure from Pb ammunition (Section 4.2.2.5).

### 4.5.2. Pb in produce

Produce samples were predominantly collected from urbanized areas (Table F.4). The majority of the produce data from the literature were collected from residential and community gardens. Included in the final analysis were data collected from three studies with 19 sample events. Two of the three studies were from garden locations, and the majority of gardens sampled had soil Pb levels greater than 400 ppm. The literature data included leafy greens, herbs, and fruit (seed bearing structures). Eating between 4 and 5 g of produce at the single group mean summary Pb concentration would reach the FDA’s IRL for children of 3 μg/day \( (n = 271, M = 0.65 \text{ ppm, } 95\% \text{ CI} = 0.53, 0.77; \text{ Fig. 8}) \). Additionally, the produce meta-analysis result is three orders of magnitude greater than the national survey data \( (n = 448, M = 0.0005, SE = 0.0002) \). The large difference in Pb concentration between the literature and national survey data can be attributed to differences in sample characteristics. Literature samples were predominantly collected from urban gardens with a higher likelihood of Pb contamination, whereas the TDS national survey samples were collected from commercially grown produce. The meta-analysis which included both the literature and TDS national survey data resulted in a single group summary that fell between the individual literature and national survey meta-analysis results \( (n = 719, M = 0.04 \text{ μg/m}^3, 95\% \text{ CI} = 0.53, 0.76) \). The large difference between the meta-analysis results demonstrates these data are not robust or stable around a single group mean summary. The large difference in Pb concentration and distinct sample characteristics between the literature and national survey data for produce suggest these datasets are representative of two different sources of Pb exposure and should be considered separately.

The studies reporting Pb concentrations for produce identified by this study are too limited in scope to be considered representative of produce Pb concentrations found at all community gardens (e.g. sample locations were predominantly urban with elevated soil Pb concentrations). However, these results indicate that community gardeners may be at increased risk of exposure from food Pb and soil Pb at levels of concern. Monitoring of produce grown on smaller scales, as seen in community and urban agriculture practices, should be considered a priority to better understand the Pb exposure risk associated with consuming these foods. Additionally, outreach campaigns to help practitioners identify potential Pb hotspots at community and residential garden sites, as well as mitigation behaviors to reduce exposure, would be beneficial.

### 4.6. Air Pb results and discussion

Literature reporting Pb concentrations in air were very limited, though there were sufficiently unique data (data not reported to AQS) to run analyses on outdoor and indoor subgroups. There were seven studies with 18 sampling events (Table G.1) and three studies with three sampling events (Table G.2) for the outdoor and indoor air meta-analyses, respectively. Both air literature subgroups were below the U.S. EPA air standard for Pb. Indoor air had a higher single group mean and standard error summary \( (n = 338, M = 0.035 \mu g/\text{m}^3, 95\% \text{ CI} = -0.026, 0.096) \) compared to outdoor air \( (n = 1918, M = 0.005 \mu g/\)
m^3, 95% CI = 0.0015, 0.0085). Adding the AQS data to the outdoor literature data resulted in a higher single group mean summary and smaller single group standard error summary (n = 493,388, M = 0.085 μg/m^3, 95% CI = 0.003, 0.079).

The AQS contains the most comprehensive, publicly available, ambient air pollution monitoring data available. Criteria for collecting and reporting the air quality data are established to ensure the data are comparable across a national scale, providing high quality data. These highly reliable data are used for evaluating air quality to inform compliance actions and planning, and to evaluate and inform policy. The literature data provided additional insight into indoor air Pb concentrations that were not available in AQS; however, these data were substantially limited in scope and highly variable. Additional research into the state of indoor air quality is required to have a more precise understanding of the impact and source of indoor air Pb.

4.7. Pb contaminated Superfund designated areas results and discussion

4.7.1. Soil within Pb contaminated Superfund designated areas—The majority of the top soil samples collected from Superfund areas were collected from residential locations. There were six studies and 12 sampling events included in the residential soil Pb Superfund meta-analysis (Table H.1). The majority of the observations were collected from non-urbanized areas. Residential samples were predominately collected from sites where remediation had been initiated or completed. The residential Pb single group summary was well below the U.S. EPA non-play area residential standard of an average 1200 ppm for bare soil and just below the 400 ppm standard for residential play areas (n = 6055, M = 358 ppm, 95% CI = 307,408; Fig. 10). Clean-up targets for Superfund sites are not based on the TSCA soil lead standards of 400 and 1200 ppm. While a clean-up level of 400 ppm of Pb in soil for residential sites has been used for Pb contaminated Superfund sites, cleanup levels are based on site-specific evaluations and IEUBK model results at these sites (U.S. EPA, 2003b). When the analysis was run to only include non-urbanized Pb contaminated Superfund locations, the single group mean and standard error summaries only slightly changed from 358 (26) ppm to 345 (30) ppm. Most of the residential sites had undergone partial or complete remediation, which suggests the meta-analysis results are not representative of residential soil Pb concentrations at Pb contaminated Superfund sites prior to remediation. While the remediated sites were predominately classified as non-urbanized areas, the single group mean summary was more similar to the urbanized, non-Superfund soil Pb concentrations. These results suggest that remediation is effective at reducing the soil Pb concentrations, though these levels are higher than their non-Superfund, non-urbanized counterparts.

There were three studies and 16 sampling events included in the non-residential Pb Superfund meta-analysis (Table H.2). The single group mean summary was higher than the U.S. EPA standard of an average 1200 ppm (n = 105, M = 1868 ppm, 95% CI = 1450, 2285). A large subset of the non-residential Superfund measures from Hansen et al. (2011) were associated with freshwater bodies in Idaho (n = 77, M = 2205 ppm, 95% CI = 1317, 3092). The sampled non-residential Superfund locations had substantially elevated soil Pb concentrations compared to the natural space single group mean summary that would be...
typical of these sites prior to anthropogenic disturbance. Remediation efforts at Pb contaminated Superfund sites are usually challenged by the large geographic area requiring remediation and by co-contamination of other environmental resources such as ground and surface waters. Remediation efforts often take several decades to complete. While non-residential sites may represent a lower risk for human exposure compared to residential sites, the natural spaces can have cultural importance for subsistence and/or recreation.

4.7.2. Household dust within Pb contaminated Superfund designated areas — There were insufficient dust Pb loading data from Superfund areas for arithmetic meta-analysis, however, there were sufficient dust Pb concentration data. The majority of samples were collected from non-urbanized residential locations. There were three studies and 9 sampling events included in the aggregate residential indoor Superfund dust concentration analysis ($n = 443$, $M = 718$ ppm, 95% CI = 358, 1078; Table H.3). Two of these studies and seven of the sampling events were from residential floors ($n = 318$, $M = 744$ ppm, 95% CI = 339, 1149; Table H.4). Murgueytio et al. (1998) reported the residential dust samples were collected from play areas, though did not provide further details as to the sample location within a play area. These samples were treated as a general indoor dust measure, though the samples may represent floor samples collected from play areas. Residential sites included in this subgroup had completed, or were near completion of soil Pb remediation, which is considered to be a major contributor to Pb in household dust. Despite the status of remediation, the single group summary for dust Pb concentration for residential Superfund sites is four to five times the non-Superfund counterpart, suggesting that soil Pb remediation may not be sufficient at reducing the household Pb dust levels. However, this finding should be considered preliminary because of the limited number of distinct studies available for inclusion in this analysis. Dust Pb loading was not provided for most studies in this subgroup, however Spalinger et al. (2007) did provide the dust Pb loading rate. Dust Pb loading, the product of dust loading and dust concentration, is used as a federal action level for residential dust because it is considered to be a better metric for exposure (U.S. EPA, 1995). Knowing the dust loading and Pb dust concentration provides the most complete information for a home’s dust Pb status and can inform remediation strategies.

4.7.3. Wild-caught fish and shellfish within Pb contaminated Superfund designated areas — There were three studies and 105 sampling events for the wild-caught fish samples collected from Pb contaminated Superfund areas in three different states. The biological sample type collected from animals varied across studies and included whole tissue, muscle/fillet, blood, or organ tissue. Eating about 8 g of fish with this single group mean summary would reach the FDA’s IRL for maximum daily intake for children of 3 μg/day ($n = 528$, $M = 0.37$ ppm, 95% CI = 0.34, 0.40; Table H.5). The shellfish subgroup only included bivalve measures from one study with 21 sampling events from three locations in two states ($n = 103$, $M = 2.6$ ppm, 95% CI = 2.1, 3.1; Table H.6). Eating about 1 g of bivalves at the single group mean summary Pb concentration of 2.6 ppm would reach the FDA’s IRL for children.

The sample sizes for both the wild-caught fish and shellfish subgroups were comparatively small, which limits the conclusions that can be drawn from these datasets. The movement of
Pb within the environment is strongly driven by the chemical properties of the Pb compound and hydrogeological features of the abiotic environment. These environmental factors combined with life histories and behaviors of the ecological species, as well as the bioavailability of Pb, would determine the degree of exposure. Within this study, the wild-caught fish Pb concentrations within Pb contaminated Superfund designated areas were only slightly higher in concentration compared to fish caught outside the Pb contaminated Superfund designated areas. More information is required to draw conclusions on why the results were similar between these two site types. For the shellfish subgroup, there were only Pb concentration information available for animals within a Pb contaminated Superfund designated area. The high Pb concentration for these bivalves relative to fish may be attributed to their suspension feeding behavior. The lack of comparable information for this subgroup for non-Superfund designated areas restricts the conclusions that can be drawn. The results of these analyses demonstrate that cultural related food practices, such as subsistence or recreational food activities, can contribute to Pb exposure within and outside Pb contaminated Superfund designated areas. More research is needed to determine the extent of the impact these practices have on exposure.

4.8. Articles excluded based on quality considerations

Two articles included in the database that satisfied the inclusion and exclusion criteria were removed based on data quality considerations. Finster et al. (2004) data were not included in the produce meta-analysis because the limit of detection (LOD) for the study was very high at 10 ppm and more than half of the samples were under the LOD. While the produce data were unsuitable for inclusion in the meta-analysis, the article contributes to the discussion about gardening in older dense urban environments. Edible portions of the food sampled that tested above the LOD had considerably high concentrations of Pb (min = 12 ppm and max = 81 ppm) demonstrating that some food gardens have Pb concentrations at levels to be a public health concern. Soil samples reported in Finster et al. (2004) were included in the soil meta-analysis and all samples reported were well above the LOD.

Data from Sangster et al. (2012) were not included in the soil meta-analysis for community gardens or Superfund sites. The samples within this study were collected from a community garden in a Superfund area and analyzed by 45 undergraduate students raising concerns with the consistency of sample processing. Additionally, all the necessary summary statistics were not provided, and we were unable to replicate the summary statistics that were provided based on the raw data reported. While this study was not included in the meta-analysis, it does provide unique insight into community gardens in Superfund designated areas. This is the only study identified in our search that met our inclusion and exclusion criteria that reported soil and produce Pb concentrations from a community garden within a Superfund designated area. The raised garden beds in this study were heavily amended with compost. Still, the Pb concentrations reported for produce were consistently higher than the national survey data (min = 0.32 ppm and max = 23.4 ppm) and the soil Pb concentrations fell within the “potential risk” category within the guidance for community gardens provided by the U.S. EPA (2014).
5. Conclusions and future directions

Environmental Pb exposure remains to be a pervasive public health issue. Legacy inputs of Pb paint and gasoline persist in the environment, while economic and technological incentives prioritize continued use and emission of Pb, making it part of our daily lives in the form of electronics, batteries, paints and dyes, glaze, make-up, and ammunition. Multimedia exposure modeling describes the burdens from different exposure pathways and is used to inform the development of standards and programs that are protective of public health. Robust environmental Pb data are necessary to conduct multimedia exposure assessments. National surveys that monitor environmental Pb concentrations provide useful data for population-level analyses, although the national scale of these efforts can result in loss of descriptive data that are important for exposure assessment. Systematic review and meta-analysis proved effective at synthesizing research to generate comprehensive datasets useful for multimedia exposure assessments for the general population and vulnerable groups.

Considerable data and knowledge gaps were identified and provide insight for future research opportunities. Multimedia Pb concentration from school sites was very limited. Understanding exposure sources at these sites is necessary for determining the total potential exposure experienced by children. Future multimedia research and monitoring campaigns should target school sites and daycares to improve the quality of children’s total environment by reducing Pb exposure.

Research on residential and community gardens focused on urban areas and the meta-analysis results suggest Pb levels in the soil and produce from these sites are substantially higher compared to commercial food production. Additional research and monitoring at residential and community gardens in diverse settings is needed. Public health campaigns promoting and highlighting best practices (i.e. planting produce away from the house dripline, using raised beds, composting, importing soil, and thoroughly washing produce) can reduce Pb exposure for gardeners.

Analysis of soil Pb concentrations at shooting range locations were two times the concentration reported for literature-derived data from non-residential Superfund sites. Unlike legacy sources of environmental Pb from gasoline and house paint, Pb from ammunition continues to be emitted into the environment with limited capacity for recovery. Research demonstrates there are significant and negative ecological and public health consequences associated with the use of Pb ammunition. However, research demonstrating the extent of environmental contamination, exposure, and the economic impacts of Pb ammunition are limited. Considering the persistence of Pb in the environment, the high bioavailability of Pb from ammunition, and economic challenges with site-specific remediation, Pb exposure and contamination from ammunition needs to be addressed through research, regulatory, and public health campaigns.

Data trends confirm that older urban areas and rural areas with Pb-related industrial activities tend to have higher levels of Pb in soil compared to non-urbanized and natural spaces. Synthesis of literature-derived data from residential Superfund sites demonstrated
that remediation has been effective at lowering soil Pb levels, although the results are still higher than typical for non-urbanized areas. Dust analyses suggest Pb levels remain persistently high at residential Superfund locations following soil Pb remediation at these sites. Further research is needed to better characterize the persistence of dust Pb levels at residential Superfund sites.

Considerable effort has been made to measure environmental Pb contamination. However, inconsistency in how results are reported across studies reduced the robustness of these data for synthesis, especially for the dust and water subgroups. Similarly, several studies measuring Pb in drinking water did not report summary statistics necessary for those datasets to be used for meta-analysis. Consistent sample collection protocols and robust data reporting across studies would allow for those datasets to be used in synthesis efforts. Furthermore, consideration should be given to include summary statistics for both dust loading and concentration when possible.

The U.S. EPA’s AQS database is the most robust publicly available data resource across all environmental media types. Data collected by EPA, state, local, and tribal air pollution control agencies are reported to the central system and are used to support air quality assessments and inform compliance activities. Similar systems could be designed and maintained for other environmental media types such as soil, water, and food. Such an effort would support consistent sample collection, analysis, and reporting, while considerably increasing the impact of research and monitoring efforts.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

The views expressed in this paper are those of the authors and do not necessarily reflect the views or policies of the US Environmental Protection Agency. We are grateful to Valerie Zartarian, Bryan Groza, Carrie Misenheimer, Hongtai Huang, Nicolle Tulve, and Timothy Barzyk for their guidance and review. Additionally, we are thankful to Annette Guiseppi-Elie, Megan Meahaffey, Kiran Alapaty, Michele Burgess, Ann Carroll, Charles Bevington, Stiven Foster, Erick Helm, Heather Klemick, Larry Zaragoza, Bruce Rodan, Gene Gunn, Joyce Donohue, Eric Burneson, and Barbara Soares for their review. This project was partially supported by an appointment at the U.S. Environmental Protection Agency Office of Research and Development National Exposure Research Laboratory, administered by the Oak Ridge Institute for Science and Education. It has undergone Agency administrative review and is approved for publication. Mention of trade names or commercial products does not constitute endorsement.

References

Arnemo JM, Andersen O, Stokke S, Thomas VG, Krone O, Pain DJ, Mateo R, 2016 Health and environmental risks from lead-based ammunition: science versus socio-politics. EcoHealth 13 (4), 618–622. [PubMed: 27663438]
Attanayake CP, Hettiarachchi GM, Harms A, Presley D, Martin S, Pierzynski GM, 2014 Field evaluations on soil plant transfer of lead from an urban garden soil. J. Environ. Qual. 43 (2), 475–487. [PubMed: 25602649]
Bannon DI, Drexler JW, Fent GM, Casteel SW, Hunter PJ, Brattin WJ, Major MA, 2009 Evaluation of small arms range soils for metal contamination and lead bioavailability. Environmental Science & Technology 43 (24), 9071–9076. [PubMed: 20000496]
Barsan ME, Boeniger MF, Crouch KG, Esswein EJ, Kardous CA, Khan A, 2009 Preventing occupational exposures to lead and noise at indoor firing ranges. NIOSH.

Bellinger DC, Bradman A, Burger J, Cade TJ, Cory-Slechta DA, Doak D, ... Hu H, 2013 Health Risks From Lead-based Ammunition in the Environment - A Consensus Statement of Scientists.

Bernhoft A, Boobis A, Cromie R, Devineau O, Antonio Donazar J, Duffus J, Thomas VG, 2014 Wildlife and Human Health Risks from Lead-based Ammunition in Europe a Consensus Statement by Scientists.

Borenstein M, Hedges LV, Higgins JP, Rothstein HR, 2011 Introduction to meta-analysis. John Wiley & Sons.

California Environmental Protection Agency, 2009 Branch. I. R. A (Revised California Human Health Screening Levels for Lead. Retrieved from). https://oehha.ca.gov/media/downloads/crnr/leadchhsl091709.pdf.

Castro DC, Samuels M, Harman AE, 2013 Growing healthy kids: a community garden-based obesity prevention program. Am. J. Prev. Med. 44 (3), S193–S199. [PubMed: 23415183]

Church ME, Gwiazda R, Risebrough RW, Sorenson K, Chamberlain CP, Farry S, ... Smith DR, 2006 Ammunition is the principal source of lead accumulated by California condors re-introduced to the wild. Environmental Science & Technology 40 (19), 6143–6150. [PubMed: 17051813]

Clickner RP, Marker D, Viet SM, Rogers CJ, Broene P, 2001 National survey of lead and allergens in housing. Volume I. Analysis of Lead Hazards. Westat US Department of Housing and Urban Renewal, Washington, DC.

Cornwell DA, Brown RA, 2018 Evaluation of Flushing to Reduce Lead Levels. The Water Research Foundation Retrieved from. http://www.waterrf.org/PublicReportLibrary/4584.pdf.

Dermatas D, Cao X, Tsaneva V, Shen G, Grubb DG, 2006 Fate and behavior of metal (loid) contaminants in an organic matter-rich shooting range soil: implications for remediation. Water, Air, & Soil Pollution: Focus 6 (1–2), 143–155.

Eckel WP, Rabinowitz MB, Foster GD, 2002 Investigation of unrecognized former secondary lead smelting sites: confirmation by historical sources and elemental ratios in soil. Environ. Pollut 117 (2), 273–279. [PubMed: 11916041]

Edwards M, Triantafyllidou S, Best D, 2009 Elevated blood lead in young children due to lead-contaminated drinking water: Washington, DC, 2001–2004. Environmental Science & Technology 43 (5), 1618–1623. [PubMed: 19350944]

Elless MP, Ferguson BW, Bray CA, Patch S, Mielke H, Blaylock MJ, 2008 Collateral benefits and hidden hazards of soil arsenic during abatement assessment of residential lead hazards. Environ. Pollut. 156 (1), 20–28. [PubMed: 18328607]

Feigenbaum JJ, Muller C, 2016 Lead exposure and violent crime in the early twentieth century. Explor. Econ. Hist. 62,51–86.

Finster ME, Gray KA, Binns HJ, 2004 Lead levels of edibles grown in contaminated residential soils: a field survey. Sci. Total Environ. 320 (2–3), 245–257. [PubMed: 15016510]

Fisher IJ, Pain DJ, Thomas VG, 2006 A review of lead poisoning from ammunition sources in terrestrial birds. Biol. Conserv. 131 (3), 421–432.

Gilbert SG, Weiss B, 2006 A rationale for lowering the blood lead action level from 10 to 2 μg/dL. Neurotoxicology 27 (5), 693–701. [PubMed: 16889836]

Gremse F, Krone O, Thamm M, Kiessling F, Tolba RH, Rieger S, Gremse C, 2014 Performance of lead-free versus lead-based hunting ammunition in ballistic soap. PLoS One 9 (7), e102015.

Haig SM, D’Elia J, Eagles-Smith C, Fair JM, Gervais J, Herring G, ... Schulz JH, 2014 The persistent problem of lead poisoning in birds from ammunition and fishing tackle. Condor 116 (3), 408–428.

Hanna-Attisha M, LaChance J, Sadler RC, Champney Schnepp A, 2016 Elevated blood lead levels in children associated with the Flint drinking water crisis: a spatial analysis of risk and public health response. Am. J. Public Health 106 (2), 283–290. [PubMed: 26691115]

Hansen JA, Aude D, Spears BL, Healy KA, Brazzle RE, Hoffman DJ, ... Beyer WN, 2011 Lead exposure and poisoning of songbirds using the Coeur d’Alene River Basin, Idaho, USA. Integr. Environ. Assess. Manag. 7 (4), 587–595. [PubMed: 21538831]

Hernberg S, 2000 Lead poisoning in a historical perspective. Am. J. Ind. Med. 38 (3), 244–254. [PubMed: 10940962]

Sci Total Environ. Author manuscript; available in PMC 2020 December 01.
Iqbal S, Blumenthal W, Kennedy C, Yip FY, Pickard S, Flanders WD, … Brown MJ, 2009 Hunting with lead: association between blood lead levels and wild game consumption. Environ. Res. 109 (8), 952–959. [PubMed: 19747676]

Johansen P, Pedersen HS, Asmund G, Riget F, 2006 Lead shot from hunting as a source of lead in human blood. Environ. Pollut. 142 (1), 93–97. [PubMed: 16280190]

Laidlaw MA, Zahran S, Mielke HW, Taylor MP, Filippelli GM, 2012 Re-suspension of lead contaminated urban soil as a dominant source of atmospheric lead in Birmingham, Chicago, Detroit and Pittsburgh, USA. Atmos. Environ. 49, 302–310.

Laidlaw MA, Filippelli G, Mielke H, Gulson B, Ball AS, 2017 Lead exposure at firing ranges—a review. Environ. Health 16 (1), 34. [PubMed: 28376827]

Lanphear BP, Rauch S, Auinger P, Allen RW, Hornung RW, 2018 Low-level lead exposure and mortality in US adults: a population-based cohort study. Lancet Public Health 3 (4), e177–e184. [PubMed: 29544878]

Layton DW, Beamer PI, 2009 Migration of contaminated soil and airborne particulates to indoor dust. Environmental Science & Technology 43 (21), 8199–8205. [PubMed: 19924944]

LeGalley E, Widom E, Krekeler MP, Kuentz DC, 2013 Chemical and lead isotope constraints on sources of metal pollution in street sediment and lichens in southwest Ohio. Appl. Geochem. 32, 195–203.

Lévesque B, Duchesne JF, Gariépy C, Rhains M, Dumas P, Scheuhammer AM, … Dewailly É, 2003 Monitoring of umbilical cord blood lead levels and sources assessment among the Inuit. Occup. Environ. Med. 60 (9), 693–695. [PubMed: 12937194]

 Machemer SD, Hosick TJ, Ingamells RL, 2007 Source identification of lead contamination in residential and undisturbed soil adjacent to a battery manufacturing facility (part I). Environ. Forensic 8 (1–2), 77–95.

McConnell JR, Wilson AI, Stohl A, Arienzo MM, Chellman NJ, Eckhardt S, … & Steffensen JP (2018). Lead pollution recorded in Greenland ice indicates European emissions tracked plagues, wars, and imperial expansion during antiquity. Proc. Natl. Acad. Sci., 201721818.

McMichael AJ, Vimpani GV, Robertson EF, Baghurst PA, Clark PD, 1986 The Port Pirie cohort study: maternal blood lead and pregnancy outcome. J. Epidemiol. Community Health 40 (1), 18–25. [PubMed: 3711766]

Mielke HW, Zahran S, 2012 The urban rise and fall of air lead (Pb) and the latent surge and retreat of societal violence. Environ. Int. 43, 48–55. [PubMed: 22484219]

Murgueytio AM, Evans RG, Roberts D, 1998 Relationship between soil and dust lead in a lead mining area and blood lead levels. J. Expo. Anal. Environ. Epidemiol. 8 (2), 173–186. [PubMed: 9577749]

National Institute of Environmental Health Sciences, 2016 Key Federal Programs to Reduce Childhood Lead Exposures and Eliminate Associated Health Impacts, 1–60 Retrieved from. [PubMed: 9577749]

National Institute of Occupational Safety and Health (NIOSH), Centers for Disease Control, 2018 Adult Blood Lead Epidemiology and Surveillance (ABLES). Retrieved from. [PubMed: 9577749]

Nedwed T, Clifford DA, 1998 A survey of lead battery recycling sites and soil remediation processes. Waste Manag. 17 (4), 257–269.

Nevin R, 2007 Understanding international crime trends: the legacy of preschool lead exposure. Environ. Res. 104 (3), 315–336. [PubMed: 17451672]

NTP (National Toxicology Program). NTP Monograph on Health Effects of Low-level Lead (2012). See https://ntp.niehs.nih.gov/pubhealth/lat/noms/lead/index.html.

Pieper KJ, Krometis LAH, Gallagher DL, Benham BL, Edwards M, 2015 Incidence of waterborne lead in private drinking water systems in Virginia. J. Water Health 13(3), 897–908. [PubMed: 26322775]

Rinquist EJ, 1993 Does regulation matter?: evaluating the effects of state air pollution control programs.J. Polit. 55 (4), 1022–1045.
Salvo D, Banda JA, Sheats JL, Winter SJ, dos Santos DL, King AC. 2017 Impacts of a temporary urban pop-up park on physical activity and other individual- and community-level outcomes. J. Urban Health 94 (4), 470–481. [PubMed: 28646369]

Sanderson P, Naidu R, Bolan N, Bowman M, Mclure S. 2012 Effect of soil type on distribution and bioaccessibility of metal contaminants in shooting range soils. Sci. Total Environ. 438,452–462. [PubMed: 23026152]

Sangster JL, Nelson A, Bartelt-Hunt SL. 2012 The occurrence of lead in soil and vegetables at a community garden in Omaha, Nebraska. International Journal for Service Learning in Engineering, Humanitarian Engineering and Social Entrepreneurship 7 (1), 62–68.

Schmidt CW. 2010 Lead in air: adjusting to a new standard. Environ. Health Perspect. 118 (2), A76. [PubMed: 20123628]

Schwartz J. 1994 Low-level lead exposure and children’s IQ: a meta-analysis and search for a threshold. Environ. Res. 65 (1), 42–55. [PubMed: 8162884]

Sheets RW, Kyger JR, Biagioni RN, Probst S, Boyer R, Barke K. 2001 Relationship between soil lead and airborne lead concentrations at Springfield, Missouri, USA Sci.TotalEnviron.271 (1–3),79–85.

Smith DB, Cannon WF, Woodruff LG, Solano, Federico, Kilburn JE, Fey DL. 2013 Geochemical and mineralogical data for soils of the conterminous United States: U.S. Geological Survey Data Series 801 19 p. https://pubs.usgs.gov/ds/801/.

Soga M, Gaston KJ, Yamaura Y. 2017 Gardening is beneficial for health: a meta-analysis. Prev. Med. Rep. 5, 92–99. [PubMed: 27981022]

Spalinger SM, von Braun MC, Petrosyan V, von Lindern IH. 2007 Northern Idaho house dust and soil lead levels compared to the Bunker Hill Superfund Site. Environ. Monit. Assess. 130 (1–3), 57–72. [PubMed: 17171279]

Thomas VG. 2013 Lead-free hunting rifle ammunition: product availability, price, effectiveness, and role in global wildlife conservation. Ambio 42 (6), 737–745. [PubMed: 23288616]

Tsoi MF, Cheung CL, Cheung TT, Cheung BMY. 2016 Continual decrease in blood lead level in Americans: United States National Health Nutrition and examination survey 1999–2014. Am. J. Med. 129 (11), 1213–1218. [PubMed: 18272204]

Tsuji LJ, Wainman BC, Martin ID, Sutherland C, Weber JP, Dumas P, Nieboer E. 2008 The identification of lead ammunition as a source of lead exposure in First Nations: the use of lead isotope ratios. Sci. Total Environ. 393 (2–3), 291–298. [PubMed: 18272204]

U.S. Department of Health and Human Services/National Toxicology Program. 2012 Health Effects of Low-Level Lead, 1–148 Retrieved from. https://ntp.niehs.nih.gov/ntp/ohat/lead/final/monographhealtheffectsfromlowlevelleaddnew.pdf.

U.S. Department of Housing and Urban Development Office of Healthy Homes and Lead Hazard Control. 2011 American Healthy Homes Survey: Lead and Arsenic Findings, 1–115 Retrieved from. https://www.hud.gov/sites/documents/AHHS_REPORT.PDF.

U.S. Department of the Interior. 1977 Man-Made Disease Kills 2 Million Waterfowl Annually. 1977 Retrieved from. https://www.fws.gov/news/Historic/NewsReleases/1977/19770708.pdf, Accessed date: 9 August 2018.

U.S. Environmental Protection Agency. 1995 Sampling House Dust for Lead: Basic Concepts and Literature Review. Retrieved from. https://www.epa.gov/sites/production/files/documents/r95-007.pdf.

U.S. Environmental Protection Agency. 2003a TRW Recommendations for Performing Human Health Risk Analysis on Small Arms Shooting Ranges, 1–23 Retrieved from. https://semspub.epa.gov/work/HQ/174578.pdf.

U.S. Environmental Protection Agency. 2003b Superfund Lead-Contaminated Residential Sites Handbook, 1–70 Retrieved from. https://semspub.epa.gov/work/HQ/175343.pdf.

U.S. Environmental Protection Agency. 2005 3Ts for Reducing Lead in Drinking water in Child Care Facilities, 1–28 Retrieved from. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=200171VAtx.

U.S. Environmental Protection Agency. 2006 3Ts for Reducing Lead in Drinking water in Schools: Technical Guidance, 1–101 Retrieved from. https://archive.org/details/3tsforreducingle00unit.

U.S. Environmental Protection Agency. 2010 The Analysis of Regulated Contaminant Occurrence Data From Public Water Systems in Support of the Second Six-Year Review of National Primary

Sci Total Environ. Author manuscript; available in PMC 2020 December 01.
Drinking Water Regulations, 1–57 Retrieved from. https://www.epa.gov/sites/production/files/2014-12/documents/815b09006.pdf.

U.S. Environmental Protection Agency, 2013 Integrated Science Assessment (ISA) for Lead (Final Report, Jul 2013). U.S. Environmental Protection Agency, Washington, DC EPA/600/R-10/075F.

U.S. Environmental Protection Agency, 2014 Technical Review Workgroup Recommendations Regarding Gardening and Reducing Exposure to Lead-Contaminated Soils. U.S. Environmental Protection Agency, Washington, DC OSWER 9200.2–142, 2014. Retrieved from. https://semspub.epa.gov/work/HQ/174577.pdf.

U.S. Environmental Protection Agency, 2015 Final Report of the Lead and Copper Rule Working Group to the National Drinking Water Advisory Council. Retrieved from. https://www.epa.gov/sites/production/files/2016-01/documents/ndwaclrwgfinalreportaug2015.pdf.

U.S. Environmental Protection Agency, 2016 Lead and Copper Rule Revisions White Paper, 1–18 Retrieved from. https://www.epa.gov/sites/production/files/2016-10/documents/508_lcr_revisions_white_paper_final_10.26.16.pdf.

U.S. Environmental Protection Agency, 2018 Review of the Dust-Lead Hazard Standards and the Definition of Lead-Based Paint, 83 Fed. Reg. 127 (July 2, 2018). Retrieved from. https://www.epa.gov/sites/production/files/2018-07/documents/2018-14094.pdf.

U.S. Environmental Protection Agency, n.d. Air Quality System (AQS) Data Mart [internet database]. http://www.epa.gov/ttn/airs/aqsdatamart, Accessed date: 19 July 2016.

U.S. Environmental Protection Agency, n.d. West Calumet Housing Complex - East Chicago, Ind. Retrieved from. https://www.epa.gov/uss-lead-superfund-site/west-calumet-housing-complex-east-chicago-ind, Accessed date: 15June 2017.

U.S. Food and Drug Administration, 2014 Total Diet Study Data 2007–2013. FDA-CSFAN data. retrieved from. https://www.fda.gov/downloads/Food/FoodScienceResearch/TotalDietStudy/UCM184301.pdf.

U.S. Food and Drug Administration, 2019 Interim Reference Level. Last retrieved on March 18, 2019 from. https://www.fda.gov/food/metros/lead-food-foodwares-and-dietary-supplements.

U.S. Geological Survey, 2006 Stocks and flows of lead-based wheel weights in the United States. (No. 2006–1111). Retrieved from. https://pubs.usgs.gov/of/2006/1111/2006-1111.pdf.

U.S. Geological Survey, 2017 Lead Statistics and Information. Retrieved from. https://minerals.usgs.gov/minerals/pubs/commodity/lead/, Accessed date: 9 August 2018.

U.S. Geological Survey, 2017 Lead Testing of School Drinking Water Would Benefit from Improved Federal Guidance. Retrieved from. https://www.gao.gov/assets/700/692979.pdf.

Veen EJ, Bock BB, Van den Berg W, Visser AJ, Wiskerke JS, 2016 Community gardening and social cohesion: different designs, different motivations. Local Environ. 21 (10), 1271–1287.

Wu J, Edwards R, He XE, Liu Z, Kleinman M, 2010 Spatial analysis of bioavailable soil lead concentrations in Los Angeles, California. Environ. Res. 110 (4), 309–317. [PubMed: 20219189]

Zartarian V, Xue J, Tornero-Velez R, Brown J, 2017 Children’s lead exposure: a multimedia modeling analysis to guide public health decision-making. Environ. Health Perspect. 125 (9).

Zheng Y, Ayotte JD, 2015 At the crossroads. Hazard assessment and reduction of health risks from arsenic in private well waters of the northeastern United States and Atlantic Canada.
HIGHLIGHTS

- Environment pb concentration data are needed for multimedia exposure studies.
- Systematic review resulted in a comprehensive database of multimedia pb data.
- Data synthesis generated mean estimates of pb in soil, dust, water, food, and air.
- Descriptive datasets can be used as inputs for multimedia exposure modeling.
- Trends in environment pb monitoring were identified to inform future policy.
Fig. 1.
Steps taken to identify articles that met our inclusion-exclusion criteria.
Fig. 2.
Sample location, scale, and sample size by environmental media type for data collected from the literature and used in the meta-analyses.
Fig. 3.

Meta-analysis results for samples collected from residential sites extracted from the literature only and results when literature data were combined with national survey data. For the Literature and National Survey data, the non-urbanized area literature data were combined with data from the USGS Geochemical Survey with a matching classification; urbanized area literature data were combined with the data from the USGS Geochemical Survey and with the LA-1400 dataset from Elless et al., 2008; combined residential single group summary includes all literature data, and national survey data from the USGS Geochemical Survey, LA-1400 dataset from Elless et al., 2008, and the HUD AHHA and NLSAH surveys that had a residential classification. U.S. standards are indicated by dashed lines. CA S1 is the CalEPA soil Pb standard (80 ppm) for residential locations. EPA S1 and EPA S2 are the U.S. EPA bare soil lead standards for play areas (400 ppm) and residential sites (1200 ppm), respectively.

| Single Group Summary                        | Sample Size | Mean (SE) |
|--------------------------------------------|-------------|-----------|
| Non-Urbanized Area Residential Sites       | 284         | 219 (36)  |
| Urbanized Area Residential Sites           | 7440        | 629 (32)  |
| Combined Residential Sites                 | 8926        | 526 (26)  |
| **Literature and National Survey Data**    |             |           |
| Non-Urbanized Area Residential Sites       | 473         | 153 (20)  |
| Urbanized Area Residential Sites           | 8861        | 610 (31)  |
| Combined Residential Sites                 | 15044       | 451 (19)  |
### Recreation Related Soil Pb, Non-Superfund (ppm)

| Single Group Summary                      | Sample Size | Mean (SE) | CAS1 | EPA S1 | EPA S2 |
|-------------------------------------------|-------------|-----------|------|--------|--------|
| **Literature Data Only**                  |             |           |      |        |        |
| Benchmark                                 | 93          | 11 (2)    |      |        |        |
| Associated to Freshwater                  | 595         | 63 (2)    |      |        |        |
| Forests and Open Space                    | 1828        | 77 (2)    |      |        |        |
| Schoolyards and Playgrounds               | 182         | 87 (9)    |      |        |        |
| Roadside                                  | 1048        | 115 (10)  |      |        |        |
| Community and Residential Gardens         | 2082        | 293 (33)  |      |        |        |
| Outdoor Shooting Ranges                   | 563         | 3604 (55) |      |        |        |
| **Literature and National Survey Data**   |             |           |      |        |        |
| Forests and Open Space                    | 4843        | 76 (2)    |      |        |        |

**Fig. 4.**

Meta-analysis results for soil and sediment samples collected at locations associated with recreational activities. The USGS Geochemical Survey was used for the national survey Forests and Open Space data. U.S. Pb standards are indicated by dashed lines. CAS1 is the CalEPA soil Pb standard (80 ppm) for residential locations. EPA S1 and EPA S2 are the U.S. EPA bare soil lead standards for play areas (400 ppm) and residential sites (1200 ppm), respectively.
Fig. 5.
Meta-analysis results for dust Pb loading reported in the literature, and results when the literature data were combined with the national survey data. For Literature and National Survey Data, the floor and aggregate dust Pb loading include national survey data from the HUD NSLAH and AHHA surveys. For window sill and troughs, data from the HUD NSLAH survey were used. U.S. Pb standards are indicated by dashed lines. EPA D1, EPAD2, and EPAD3 are the previous U.S. EPA standards for residential floors (40 μg/ft²), window sills (250 μg/ft²), and window troughs (400 μg/ft²), respectively. EPA DA and DB denotes the updated standards announced June 2019 for floors (10 μg/ft²) and window sills (40 μg/ft²), respectively.

| Residential Dust Pb Loading, Non-Superfund (μg/ft²) | Sample Size | Mean (SE) |
| --- | --- | --- |
| **Literature Data Only** | | |
| Floors | 535 | 13 (3) |
| Aggregate Indoor without Window Troughs | 1160 | 16 (4) |
| Aggregate Indoor with Window Troughs | 1278 | 16 (4) |
| Window Sills | 380 | 214 (113) |
| Window Sills and Troughs Combined | 498 | 241 (115) |
| **Literature and National Survey Data** | | |
| Floors | 5560 | 13 (2) |
| Aggregate General Indoor without Window Troughs | 8487 | 16 (3) |
| Aggregate General Indoor with Window Troughs | 10212 | 18 (4) |
| Window Sills | 2682 | 186 (59) |
| Window Sills and Troughs Combined | 4407 | 414 (111) |
| Window Troughs | 1725 | 1712 (428) |
## Residential Dust Pb Concentration, Non-Superfund (ppm)

| Single Group Summary                  | Sample Size | Mean (SE) |
|---------------------------------------|-------------|-----------|
| **Literature Data Only**              |             |           |
| Floors                                | 185         | 176 (26)  |
| Aggregate General Indoors             | 892         | 212 (25)  |
| General Indoors                       | 468         | 302 (77)  |
| Outdoor Entry                         | 90          | 359 (127) |
| **Literature and National Survey Data** |           |           |
| Floors                                | 1316        | 153 (18)  |
| Aggregate General Indoors             | 2023        | 182 (19)  |

![Graph showing Pb Dust concentrations](image)

**Fig. 6.**
Meta-analysis results for dust Pb concentrations reported in the literature, and results when literature data are combined with HUD AHHA national survey data.
### Water Pb (ppb)

| Single Group Summary         | Sample Size | Mean (SE) |
|------------------------------|-------------|-----------|
| Literature Data Only         |             |           |
| Drinking Water (Flushed)     | 6889        | 2 (0.2)   |
| Drinking Water (First Draw)  | 5900        | 8.8 (1.1) |
| Surface Water                | 557         | 4.6 (0.2) |
| Groundwater                  | 1661        | 13.4 (4.2)|

**Fig. 7.**

Meta-analysis results for Pb in drinking water, surface water, and ground water. The U.S. standard is indicated by a dashed line. EPA W1 represents the U.S. EPA standard for public drinking water systems (15ppb).
Fig. 8.
Meta-analysis results for Pb concentrations measured in different food types in literature data. Fish samples were wild-caught. Poultry measures were predominately associated with residential or community gardens. Produce includes fruits, vegetables, leafy greens, and herbs. Produce measures from the literature were predominately from residential or community gardens. National survey of produce from commercially grown sources had an average of 0.0005 ppm.
Fig. 9.
Meta-analysis results for total suspended particles (TSP) air Pb reported in the literature, and results when the literature data are combined with the AQS TSP national survey data. The U.S. standard is indicated by the dashed line. EPA A1 is the U.S. EPA standard for air Pb (0.15 μg/m$^3$).

| Air Pb (μg/m$^3$)          | Sample Size | Mean (SE)      |
|---------------------------|-------------|----------------|
| **Literature Data Only**  |             |                |
| Indoor Residential        | 388         | 0.03 (0.031)   |
| Outdoor Air               | 1,918       | 0.005 (0.002)  |
| **Literature and National Survey Data** | |                |
| Outdoor Air               | 493,388     | 0.09 (1.4 x 10$^{-9}$) |
### Superfund Pb for Multiple Media (ppm)

| Single Group Summary                                      | Sample Size | Mean (SE) | EPA S1 | EPA S2 |
|-----------------------------------------------------------|-------------|-----------|--------|--------|
| **Soil Pb Literature Data Only**                          |             |           |        |        |
| Residential Sites                                         | 6055        | 358 (26)  |        |        |
| Non-Residential Sites                                     | 105         | 1868 (213)|        |        |
| Associated with Fresh Water Bodies                        | 77          | 2205 (453)|        |        |
| Combined Residential and Non-Residential                  | 6160        | 479 (24)  |        |        |
| **Dust Pb Literature Data Only**                          |             |           |        |        |
| Residential Aggregate General Indoors                     | 443         | 718 (184) |        |        |
| Residential Floors                                        | 318         | 744 (207) |        |        |
| **Food Pb Literature Data Only**                          |             |           |        |        |
| Shellfish                                                 | 103         | 3 (0.2)   |        |        |
| Fish                                                      | 528         | 0.4 (0.01)|        |        |

**Fig. 10.**

Meta-analysis results for soil Pb, dust Pb, and food Pb collected from or nearby Superfund designated areas. Residential samples were collected from locations with varying stages of remediation. Fish and shellfish samples were wild-caught. U.S. Pb standards are indicated by dashed lines. EPA S1 and EPA S2 are the U.S. EPA bare soil lead standards for play areas (400 ppm) and non-play area residential sites (1200 ppm), respectively.

*Sci Total Environ.* Author manuscript; available in PMC 2020 December 01.
Table 1

Search logic and inclusion-exclusion criteria used for the systematic literature search and database creation.

| Article identification strategy |
|---------------------------------|
| **Example search logic**        |
| ((Lead OR Pb OR “Heavy Metal*”) NEAR/3 (level* OR concentration*) NEAR/4 (soil* OR water* OR air OR blood OR dust* OR food* OR atmosphere* OR “PM10” OR “PM2.5” OR TSP OR sediment OR diet* OR vegetable* OR fruit* OR “well water” OR “ground water” OR “drinking water” OR environment* OR tap OR aerosol*)) |

| Inclusion criteria                  |
|------------------------------------|
| • Reference is written in English  |
| • Reference is a peer-reviewed article or government publication |
| • Published between the years 1996–2016 |
| • Study site or population is within the United States |
| • Pb is measured in one of the following environmental media: air, soil, water, dust, food, and blood |
| • Necessary summary statistics are clearly reported |
| • Soil/sediment samples are collected within the top 30 cm layer, with a range up to 50 cm |
| • Samples associated with aquatic environments are from fresh water environments, except in the case of food |
| • Baseline values are used from intervention or remediation studies |
| • If multiple papers use same dataset, we will select the most robust, or most recent and clearly described |
| • Hotspot data, such as Superfund and Brownfield sites need to be clearly marked in database |

| Exclusion criteria                  |
|------------------------------------|
| • Experimentally dosed, modeled, predicted, estimated values, or methodology experiments |
| • Used data from national survey already used in our comparisons |
| • Only radioactive measures are reported (i.e. no mass concentration values are reported) |
National survey data used in the meta-analyses. The soil Pb data from the NSLAH is summarized from the data in the report. For the HUD AHHA survey, the summary data represents statistics from the raw data. The U.S. FDA TDS data are synthesized from summary data. Only the raw, single-food produce items from TDS were used in the meta-analysis.

### Table 2

| National survey | Agency | Sample type | Sample subtype | Sample year | Sample size | Mean (SE) |
|-----------------|--------|-------------|----------------|-------------|-------------|-----------|
| **Soil Pb (ppm)** |        |             |                |             |             |           |
| NSLAH           | HUD    | Residential |                | 1998–1999   | 3566        | 219 (10)  |
| AHHS            | HUD    | Residential |                | 2005–2006   | 942         | 160 (16)  |
| Elless et al., 2008 | HUD    | Residential |                | 2005–2006   | 1400        | 525 (32)  |
| Geochemical Survey | USGS    | Mixed       |                | 2007        | 4841        | 26 (3)    |
| Geochemical Survey | USGS    | Residential | Non-urbanized  | 2007        | 189         | 23 (1)    |
| Geochemical Survey | USGS    | Residential | Urbanized      | 2007        | 21          | 33 (6)    |
| Geochemical Survey | USGS    | Forests and open space | - | 2007 | 3015 | 29 (4) |
| Geochemical Survey | USGS    | Commercial  | Food Production | 2007       | 1341        | 20 (0.51) |
| **Dust Pb loading (μg/ft²)** |        |             |                |             |             |           |
| SLAH            | HUD    | Residential | Floors         | 1998–1999   | 3894        | 14 (8)    |
| NSLAH           | HUD    | Residential | Window sills   | 1998–1999   | 2302        | 195 (35)  |
| NSLAH           | HUD    | Residential | Window troughs | 1998–1999   | 1607        | 1991 (302)|
| AHHS            | HUD    | Residential | Floors         | 2005–2006   | 1131        | 11 (2)    |
| **Dust Pb concentration (ppm)** |        |             |                |             |             |           |
| AHHS            | HUD    | Residential | Floors         | 2005–2006   | 1131        | 104 (4)   |
| **Food (ppm)**  |        |             |                |             |             |           |
| TDS             | FDA    | Commercial  | Produce only   | 2006–2013   | 448         | 0.0005 (0.0002) |
| **TDS**         | FDA    | Commercial  | All food types | 2006–2013   | 7801        | 0.0011 (0.00008) |
| **Air Pb (μg/m³)** |        |             |                |             |             |           |
| AQS             | EPA    | Mixed       |                | 1996–2016   | 491,470     | 0.2 (0.002) |