Community science reveals insights into metal pollution and environmental justice

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Abstract

Heavy metals are often prevalent in urban settings due to many possible legacy and modern pollution sources, and are essential to quantify because of the potential adverse health effects associated with them. Of particular importance is lead (Pb), because there is no safe level of exposure, and it especially harms children. Through our partnership with community scientists in the Marion County (Indiana, United States) area, we measured Pb and other heavy metal concentrations in various household media. Community scientists completed screening kits that were then analyzed in the laboratory via X-Ray fluorescence (XRF) to quantify heavy metal concentrations in dust, soil, and paint to determine potential hazards in individual homes. Early results point to renters being significantly more likely to contain higher concentrations of Pb, zinc (Zn), and copper (Cu) in their soil versus homeowners, irrespective of soil sampling location at the home, and home age was significantly negatively correlated with Pb and Zn in soil and Pb in dust across all homes. Analysis of paired soil, dust, and paint samples revealed several important relationships such as significant positive correlations between indoor vacuum dust Pb, dust wipe Pb, and outdoor soil Pb. Our collective results point to rental status being an important determinant of possible legacy metal pollution exposure in Indianapolis, and housing age being reflective of both past and possibly current Zn and Pb pollution at the household scale in dust and soil. Thus, future environmental pollution work examining rental status versus home ownership, as well as other household data such as home condition and resident race/ethnicity, is imperative for better understanding environmental justice issues surrounding not just Pb, but other heavy metals in environmental media as well.

Keywords: Lead (Pb), heavy metals, community science, citizen science, urban pollution, environmental justice

1. Introduction

Heavy metals in the environment have been studied across multiple environmental media in many locations throughout the world because of their ability to adversely harm humans and other organisms (e.g., Dietrich *et al* 2021, Gillings *et al* 2022, Wade *et al* 2021). Urban areas are well-known for being respositories of elevated concentrations of heavy metals, particularly within dust and soil because of both past and current anthopogenic emissions (e.g., Obeng-Gyasi *et al* 2021, Wade *et al* 2021, Adgate *et al* 1998). However, metal

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pollution in urban settings is notoriously complex, with heterogeneity down to a scale as fine as a household (e.g., Filippelli *et al* 2018).

To better understand this heavy metal pollution heterogeneity, so that more efficient pollution prevention and remediation may be enacted, community science efforts have expanded recently (e.g., Watson *et al* 2022, Ringwald *et al.* 2021, Filippelli *et al.* 2018). Community science offers a chance for local residents to gather important environmental data about their own homes, which can result in useful information both for themselves and researchers. This is particularly imperative for lead (Pb) pollution, as it harms young children and impairs their cognitive development (e.g., Evens *et al* 2015), and concentrations in household dust, water, soil, and paint may vary greatly from home to home depending on the history of the home and/or local area. Additionally, relationships between metal concentrations of different media (i.e., indoor dust and outdoor soil) within the same home may vary and not be easily predictable (Gillings *et al* 2022). Community scientists offer researchers a chance to gather temporal and spatial data at resolutions not easily feasible by individual research efforts alone.

Previous research has illustrated that certain variables such as housing age are key predictors for elevated concentrations of heavy metals like Pb in environmental media (e.g., dust and soil) (e.g., Dietrich *et al* 2022, Yesilonis *et al* 2008, Isley *et al* 2022). However, few studies have examined multiple possible environmental exposure media within a household (i.e., water, soil, dust, paint), and few have examined possible relationships between heavy metal concentrations and rental versus homeowner status. Homeownership status is a particularly important variable to consider, as renters tend to have fewer environmental protection rights and poorer access to environmental remediation, and throughout the U.S. tend to contain a greater proportion of minority and lower household income individuals (e.g., McCabe 2018). However, recent research has shown that homeownership correlation to heavy metal pollution may vary by region. For example, in Santa Ana, CA (U.S.), rental status was related to elevated concentrations of heavy metals in soil such as Pb (Masri *et al* 2021), but this wasn't the case in Philadelphia, PA (U.S.) for both blood lead levels (BLLs) and Pb risk factors (O'Shea *et al* 2021, Caballero-Gómez *et al* 2022), which were more related to home ownership than those renting a home. This was likely because of past housing policy in Philadelphia that was different from that in Santa Ana (Caballero-Gómez *et al* 2022, O'Shea *et al* 2021).

To better understand the relationships between metal concentrations in household environmental media and household characteristics such as housing age and homeownership status, we utilized community science samples collected for a Pb screening project in the Marion County (U.S.) area, funded through the Department of Housing and Urban Development (HUD). We focused on the heavy metals Pb, zinc (Zn), and copper (Cu) to examine: 1) Relationships between these metals in paired paint, dust, and soil samples, 2) To determine the significance of housing age and homeownership status on metal concentrations in each sampled environmental medium, and 3) To illustrate how community science can be beneficial to both participants and researchers, providing essential insight into possible environmental justice issues that may vary throughout the country and globe.

2. Methods

2.1 Sample Collection

Samples were collected by community scientists in predominantly the greater Indianapolis area (Marion County) (Fig. 1) via HUD Pb screening kits passed out at local events, such as at schools, libraries, and by request. The screening kits contained instructions and plastic bags for sampling and could be returned at multiple drop-off locations free of charge. Results were then emailed to participants following analysis in the lab in an easy-to-read format, and also contained recommendations and action steps if elevated Pb was found (Supplementary File A). Additionally, participants were required to complete a consent form that contained several optional questionnaire responses (Supplementary File B). Of most relevance to this study were the approximate age of the home, and whether or not the individual was renting or owned the home being tested.

Specifically, soil samples were collected from the upper 0-5cm in 2mL plastic bags from directly alongside the home (dripline), a play area or garden within the yard, and alongside the roadway or sidewalk. Paint samples were collected with sticky tape on a notecard, inside and/or outside the house if peeling paint was present. Dust samples were collected in two different ways: 1) Via three "Ghost Wipes" (designed specifically for picking up dust and testing for Pb) included within the testing kit, where participants were instructed to wipe 5 different window sills with one wipe, rarely cleaned surfaces such as tops of doors and ceiling fans with another wipe, and then to wipe a door entrance area or porch of the home with the third wipe; 2) Via indoor vacuum cleaner dust (or from a broom/dustpan), which was emptied from the user's vacuum cleaner into a clear plastic bag. Participants were also instructed to fill small, 25mL plastic vials of water for Pb analysis and filter water from their tap through 2L bottles and carbon filter caps (results will be published in a separate manuscript). All sample media instructions for this study are available in Supplementary File C, except for household vacuum dust, where we simply instructed the participants to empty the contents of their vacuum cleaner into a clear plastic bag we provided.

There is inevitably some variability with community scientists in following sampling directions, but larger sample sizes and more generalized interpretations of results help avoid misconceptions regarding general conclusions.

2.2 Sample Analysis

All soil samples were analyzed via a Delta Professional portable X-Ray fluorescence (XRF) in the condition they were collected (no oven drying or sieving) through a plastic bag (same plastic bag material for collecting soil, dust wipes, and paint chips) in "Soil" mode (Supplementary Text 1) for the elements Zn, Cu, and Pb. The thin, 2 mil nature of the plastic sampling bags prevents any significant attenuation of the X-Rays that would prevent analysis or significantly skew results. While soil samples were not prepared under conventional laboratory techniques (e.g., oven drying and sieving), the goal of the project was to evaluate relative Pb hazards as they existed in their current state in the household environment.

Dust wipe samples were analyzed via XRF in "Geochem" mode (Supplementary Text 2) through the plastic bag, but it is noted that the heterogenous and layered surface of the wipes make elemental analysis more semi-quantitative than truly quantitative, and thus those results are less robust and not heavily leaned upon for any meaningful conclusions in this paper. Vacuum dust samples were sieved at 250 µm with stainless steel sieves prior to analysis via XRF in Soil mode through polyethylene food wrap (< 0.5mm).

The paint chip samples were analyzed while on the sticky tape via XRF in Geochem mode through the plastic bags they came in.

2.3 Quality Control

An external standard (NIST 2702—Inorganics in Marine Sediment) was run before every batch of HUD sampling kits in addition to general instrument calibration checks. During the duration of analyzing HUD kit samples, the laboratory also analyzed additional community science kits for Pb and other heavy metals. Since the onset of analyzing HUD projects, the arithmetic mean (average) % error based on the NIST 2702 standard was 15.2 ± 13.6 for Cu, 14.8 ± 11.1 for Zn, and 12.8 ± 14.0 for Pb (n = 77) for all sample XRF run sessions within the laboratory. Two anomalous NIST outliers were excluded.

2.4 Data Processing

Statistical analyses and data graphics were generated in RStudio *(R Core Team 2022)* through the ggplot2 package *(Wickham 2016)*, PerformanceAnalytics package *(Peterson and Carl 2020)*, and EnvStats package *(Millard 2013)*, while GIS mapping was completed in ArcGIS Pro.

3. Results and discussion

3.1 Metal concentration differences/similarities between homeowners and renters

For Pb, there were not any significant differences ($p \leq 0.05$) between environmental media and rental status except for dust wipes (Fig. S1) and soil when ignoring the N/A (no response given) category (Fig. 2). Rental property soil is higher in Pb (median = 65.0 mg/kg) than homeowner property soil (median = 45.4 mg/kg). For Cu, there are no significant differences between environmental media except for soil as well (Fig. S2 and Fig. 2). The rental property soil (median = 22.0 mg/kg) was significantly ($p = 0.04$) higher in Cu than homeowner property soil (median = 19.0 mg/kg). Zinc concentrations revealed significant differences ($p \leq 0.05$) in all environmental media except vacuum dust when including N/A housing owner status (Fig. S3), but of note contained significantly ($p = 0.036$) greater Zn in rental property soil (median = 134.0 mg/kg) versus homeowner property soil (median = 100.0 mg/kg) (Fig. 2).

Overall, soil was consistently higher in Cu, Zn, and Pb in rental properties versus owner-occupied homes (Fig. 2). This has also been found for multiple heavy metal(loid)s in Santa Ana, CA soils *(Masri* et al *2021)*, and may be due to a variety of factors such as renters being less able to perform any maintenance or remediation directly on their property (i.e., opposition from landlords), like mulching to cover old contaminated soil or replacing fixtures that have peeling/degrading Pb paint *(Masri* et al *2020)*. While a possible covariate may be that renters are more likely to live in older housing with more metal pollution sources, our data thus far does not show any significant differences between rental status and housing age (Fig. S4). The relationship between higher soil metal concentrations and rental status reflects a pertinent environmental justice issue, as oftentimes rental status is associated with lower-income and higher proportions of minority groups such as Latinos and African-Americans as opposed to homeowners (e.g., *McCabe 2018, Masri* et al *2021, 2020)*. Thus, at least in cities such as Santa Ana and Indianapolis, renters are more likely to be exposed to elevated levels of heavy metals in soil, and renters, in general, are likely less well-equipped to deal with any adverse health outcomes of exposure due to socioeconomic disadvantages.

Interestingly, Zn reflected significant differences based on rental status in most environmental media, unlike Cu or Pb (Fig. S3). This is difficult to interpret, as Zn can come from many anthropogenic sources, such as tire wear, roofing/siding, paint, metal appliance coatings, etc. (e.g., *Davis* et al *2001)*. While dust wipe samples are only semi-quantitative and cannot be used to draw meaningful conclusions, the slightly higher median Zn concentrations in homeowner paint samples relative to renter paint samples (Fig. S3) may reflect a tendency of different paint pigments richer in Zn to be more heavily utilized in Indianapolis homes versus apartment rental units. However, more samples and detailed housing info would be needed to discern this, particularly because median Pb concentrations in homeowner paint is also slightly higher than renter paint samples, even though renter soil samples are significantly higher in Pb and Zn (Fig. 2). Thus, housing conditions may play a pivotal role in potential heavy metal exposure and risk (transfer of Pb & Zn from paint to soil and/or dust), or additional covariates may be at work such as rental units being more likely to exist near high traffic roadways where large volumes of Pb and Zn automobile pollution have been released both in the past and present.

Importantly, rental status and homeownership characteristics may vary greatly depending on city or region. For example, in Philadelphia, PA, due to historic affordable housing policies, there was an abundance of low-income housing built prior to 1980, with current high home ownership rates corresponding to low median household income *(Caballero-Gómez* et al *2022)*. Thus, in Philadelphia, homeownership is a greater risk factor for elevated blood lead levels (BLLs) than renting a home *(Caballero-Gómez* et al *2022*, *O'Shea* et al *2021)*, which may hold true for other areas with similar past affordable housing policies. Well worth noting is also a third housing category often not accounted for when examining Pb risk factors—that is homeowners under contract, or rent to own (RTO) properties. In our initial work thus far in Marion County, this seems to affect the Latino population in particular, and moving forward will be an imperative additional housing category to consider in questionnaires. RTO properties may be more susceptible to Pb pollution in certain areas if those properties tend to be older and occupied by low-income individuals lacking the ability to easily do renovations.

3.2 Metal concentration relationships with housing age

Older housing age has been well established to be significantly correlated with higher metal concentrations in soils and dusts, particularly Pb and Zn (e.g., *Dietrich* et al *2022, Yesilonis* et al *2008)*. Our results support this notion for Pb and Zn in soils, but not as much for Cu (Figs. 3 & 4). While Cu concentrations in soil are slightly negatively correlated with housing age and statistically significant (ρ = -0.19, p = 0.0013), it is much less of a correlation than Pb (ρ = -0.68, p < 2.2e-16) or Zn (ρ = -0.47, p < 2.2e-16). This may be due to less household sourced Cu that is dependent on housing age, unlike Pb and Zn, which were both oftentimes in Pb paint and more common with older homes (e.g., *Hunt 2016, Dietrich* et al *2022)*.

While there was some variability in soil sampling location by household (Table S1), we simplified sampling categories to dripline, streetside, and yard to generalize any trends based on location (Fig. 4). While trends are generally similar across locations in a yard, there are two important items to note: 1) For Zn and Pb, the strongest correlation between housing age and soil concentration is at the dripline, even if only slightly, likely because driplines are in closest proximity to the home—the likely predominant source of Pb and Zn pollution, 2) For Cu, the most significant relationship between soil and housing age is at the streetside (ρ = -0.28, p = 0.006), which may be because older homes tend to be near older roadways with more historic vehicular Cu pollution from brakes/tire wear. Lastly, it is essential to consider the possible transport of pollutants from roadways to the household dripline, which has been documented to occur in the area *(Dietrich* et al *Under Review)* and can influence interpretations of household pollutant sourcing.

In household dust, vacuum dust Pb has the strongest negative correlation with housing age and is highly significant (ρ = -0.59, p = 1e-04), while dust wipe Pb is slightly less correlated with housing age (ρ = -0.33, p = 1.7e-05) (Fig. 5). This supports broader U.S. housing age and vacuum dust data from throughout the U.S. *(Dietrich* et al *2022)*, indicative that older homes are more likely to contain elevated Pb in dust, likely from housepaint and/or outside soil. The less significant correlation between dust wipes and housing age is likely due to the larger general variability of dust wipe data, both from an analytical and sampling perspective. For example, vacuum dust is more of a general housing composite sample, while dust wipes are from specific locations where residents were instructed to wipe. Additionally, the heterogenous nature of wipe surfaces and variability in dust accumulation on the wipe influences XRF readings more so than composite, sieved vacuum dust samples. Thus, we recommend vacuum dust samples as a more accurate screening tool for general household dust Pb hazard.

The only other relationship between housing age and environmental media that has a $|\rho| > 0.3$ and p-value ≤ 0.05 is for Pb concentrations in paint (ρ = -0.37, p = 9.6e-05) (Fig. 3).

The Pb paint and housing age correlation makes sense, as homes built prior to 1978 in the U.S. are more likely to contain Pb paint.

3.3. Nuance between household environmental media

There are clearly several environmental media that express more pronounced relationships between housing age, rental vs. homeowner status, and metal concentration. Specifically, soils are significantly elevated in Cu, Zn, and Pb for renters versus homeowners (Fig. 2); soil Pb and Zn are very significantly correlated with older housing age at all sampling locations, particularly at the dripline (Fig. 4); and vacuum dust Pb is very significantly correlated with older housing age as well (Fig. 5).

These are all environmental media that can be analyzed quantitatively via XRF and serve as repositories for both legacy and modern heavy metal pollution. While household environmental media such as paint and water can be useful for helping determine a holistic picture of heavy metal hazards within a home, water and paint sampling by community scientists can be highly variable depending on location within the home, time of sampling, how they sample, and how much they sample. What is conducive about vacuum dust and yard soil sampling is that both can be easily completed by community scientists and that they both serve as excellent general indicators of composite heavy metal risk on a property. Thus, sampling of both can serve as a robust primary prevention tool to help residents become aware of any heavy metal hazards on their property and provide the catalysis for more detailed screening/remediation if necessary.

3.4 Relationships between paired soil, dust, and paint data

Paired average dust wipe, vacuum dust, paint, and average soil sample metal concentrations across all households revealed several important statistically significant ($p \leq 0.05$) or insignificant ($p > 0.05$) relationships between sample media (Fig. 6). Of note are significant positive correlations between indoor vacuum dust Pb and both interior and exterior paint Pb concentrations (ρ = 0.40-0.47, $p \leq 0.001$). This supports the notion that Pb paint is contributing to household dust Pb *(Dietrich* et al *2022)*, although average dust wipe Pb concentration was not significantly correlated with exterior or interior paint Pb (Fig. 6). However, average dust wipe Pb was positively correlated with average soil Pb ($\rho = 0.40$, $p \leq 0.001$), like Pb in vacuum dust ($\rho = 0.50$, $p \leq 0.01$) (Fig. 6). This supports data from Australian homes, where paired soil and vacuum dust data revealed moderate positive correlations between front yard soil and indoor vacuum dust ($\rho = 0.53$, $p < 0.05$), even though there was variability between the exchange of metals outdoors-indoors (*Gillings* et al *2022)*.

A significant positive correlation between Pb in the soil and exterior paint Pb ($\rho = 0.38$, $p \leq 0.01$) in our Indianapolis samples also suggests exterior paint as a large contributor to Pb in Indianapolis soils, although obviously not the only source (i.e., past leaded gasoline).

Several other important trends with Pb are the bimodality of the vacuum dust Pb concentration distribution (Fig. 6). This is unique, as Pb dust concentrations tend to be lognormal, as shown in a recent international dataset of vacuum dust Pb concentrations *(Isley* et al *2022;* their supplementary Fig. 4.1). Possible explanations for this bimodality include a smaller population size (n = 46) in our dataset, spatial effects based on relation to the city center (higher Pb tends to be associated with the Indianapolis urban center; *Filippelli* et al *2018),* or the fact that interior and exterior paint Pb concentrations display some bimodality as well and are a likely source of some of the Pb in the vacuum dust based on significant positive correlations (Fig. 6).

Interior paint Pb and exterior paint Pb are significantly positively correlated ($\rho = 0.46$, $p \leq 0.001$), as are interior and exterior paint Zn ($\rho = 0.33$, $p \leq 0.001$), reflecting that there are some similarities between paint layers inside and outside the home, but there is still a large amount of variance not accounted for. This is important from a risk assessment perspective, as elevated Pb paint outside a home may mean there is likely to be elevated Pb paint inside a home. Furthermore, Zn and Pb in both exterior and interior paint are significantly positively correlated with one another (ρ = 0.45-0.64, $p \leq 0.001$), indicative of both elements commonly being used in the same paint pigment and supporting strong positive correlations in soil ($\rho = 0.79$, $p \leq 0.001$) (Fig. 6).

For Cu and Zn, average concentrations in the soil are not significantly correlated with any paired dust or paint sample concentrations of the same element, indicating that indoor Zn and Cu concentrations are likely predominantly sourced from indoors and not outdoor soil. However, there are some slight positive correlations between exterior paint Zn and Cu and vacuum dust Zn and Cu concentrations (Fig. 6), indicating the potential for at least some outdoor to indoor metal transport.

3.5 Future aims and recommendations for metal pollution screening, prevention, and remediation

Moving forward, our work will expand holistic Pb screening to more locations, with particular emphasis on low-income minority populations who are the most likely to be exposed to heavy metal pollution. As our work expands, we will gain a broader suite of data to assess the relationships between race, income, housing age, homeownership status, and heavy metal concentrations in all household environmental media. As more demographic, household, and heavy metal data is gathered, more informed decisions about targeted intervention can be made, such as focusing on housing blocks with greater proportions of rental properties and older homes. However, as noted, while there are general characteristics that tend to be related to heavy metal exposure risks, such as housing age and rental status, there may be regional differences based on local policy like the example we mentioned in Philadelphia. Thus, it is recommended that community science endeavors like those utilized here be implemented in all cities throughout the U.S. and abroad, so that researchers and policymakers alike can make targeted decisions about how to most effectively address heavy metal pollution.

4. Conclusions

Through a Pb screening program sponsored by the U.S. Department of Housing and Urban Development, we were able to both inform community members about possible Pb exposure hazards and action steps they can take, as well as gain more detailed information on general trends related to heavy metal pollution. Preliminary data suggests that rental-occupied homes are significantly more likely to contain elevated Pb, Cu, and Zn in their soils as opposed to owner-occupied homes in Marion County, Indiana; Pb and Zn in soil are strongly negatively correlated with housing age; indoor vacuum dust Pb is significantly negatively correlated with housing age; and relationships between paired soil, paint, and dust samples at the household level are nuanced, although there are some clear associations such as positive correlations between Pb in soil and Pb in indoor dust. Renters and those in older homes in Indianapolis appear more likely to be exposed to elevated levels of heavy metals. Additional sampling and surveying of household socioeconomic data is needed both in Indianapolis and elsewhere to better understand and address environmental justice issues with metal pollution.

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7. **Ethical statement**

The authors declare no conflicts of interest.

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Figures

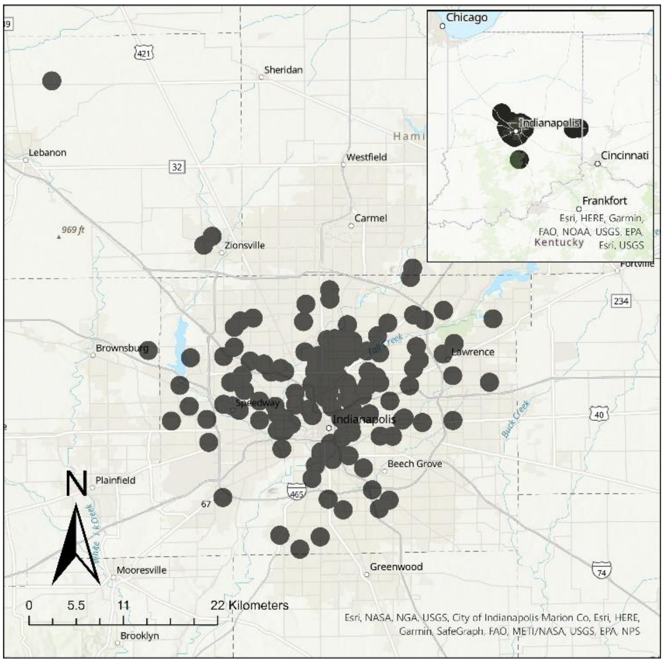

Fig. 1: Sampling locations within the greater Indianapolis, IN area. Note, not all participants provided a housing location and the symbols are enlarged and the maps zoomed out to protect privacy.

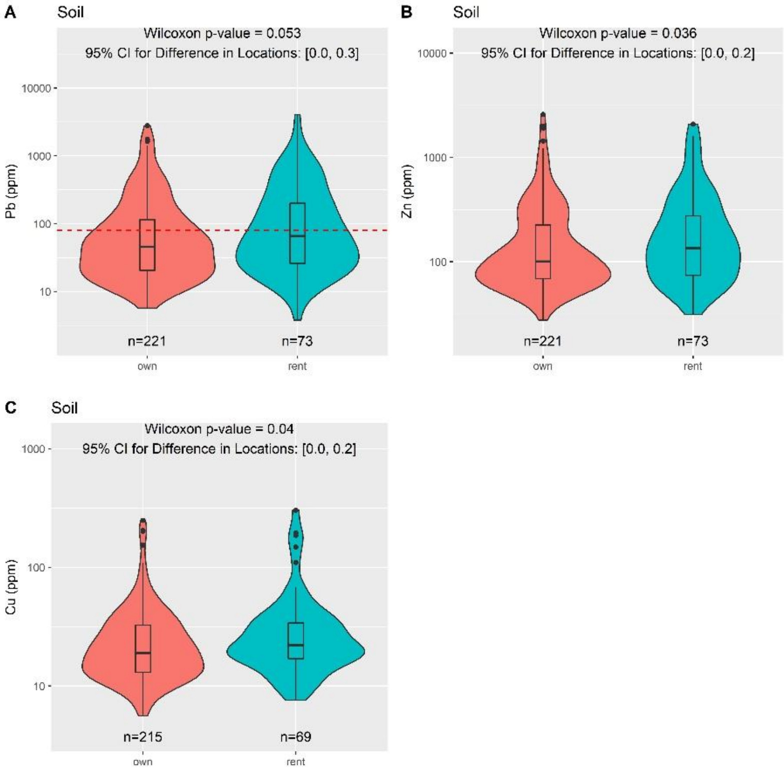

Fig. 2: Embedded boxplots within violin plots displaying the distributions of metal concentrations in soil (ppm or mg/kg) for (a) Pb, (b) Zn, and (c) Cu. The boxes represent the interquartile range (IQR) of 25th–75th percentiles of data, the horizontal line is the median, and the whiskers represent 1.5 times the IQR. Nonparametric Wilcoxon signed rank tests with p-values of log10 transformed metal concentrations between renter and owner are also provided. The y-axes are transformed on a log10 scale, and the dashed red line represents California's safe screening soil Pb level of 80 ppm.

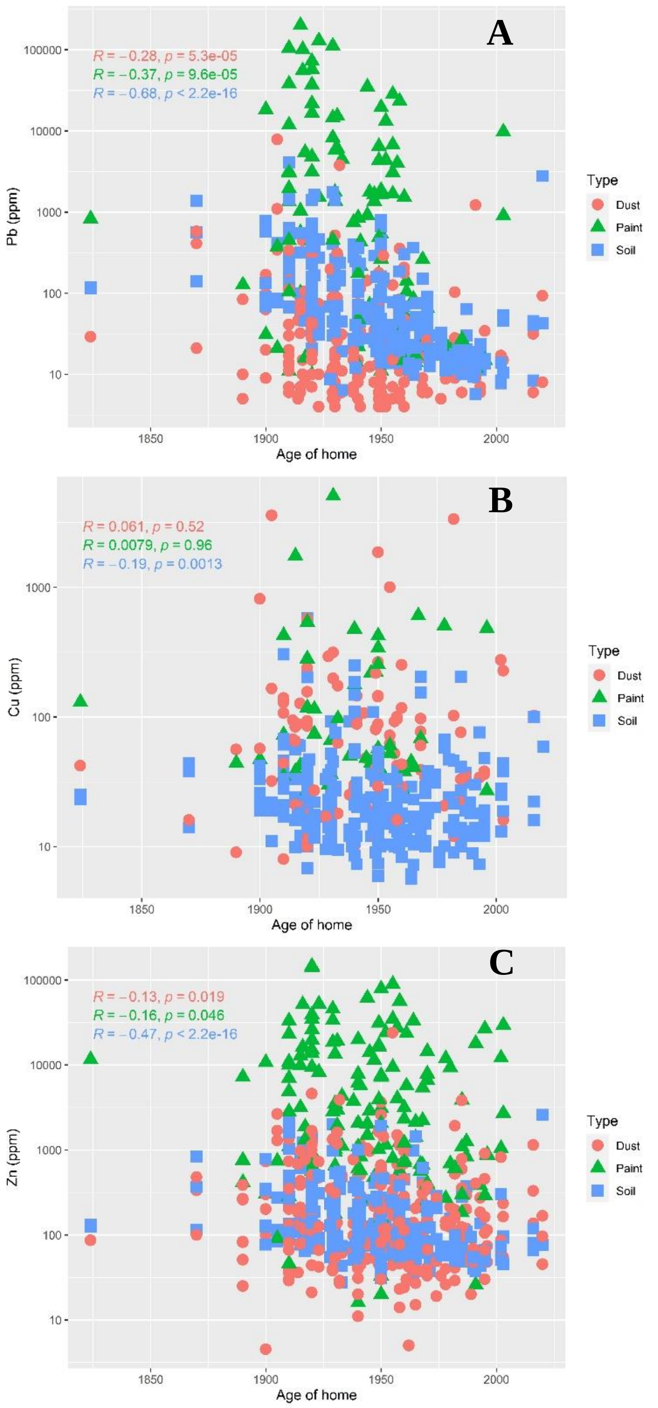

Fig. 3: Bivariate scatterplots between age of the home and (a) Pb, (b) Cu, and (c) Zn. Sampling point color and shapes are by sampling media type, with the matching colored non-parametric Spearman ρ correlation coefficient (R) and associated p-value. Y-axes values are log-transformed.

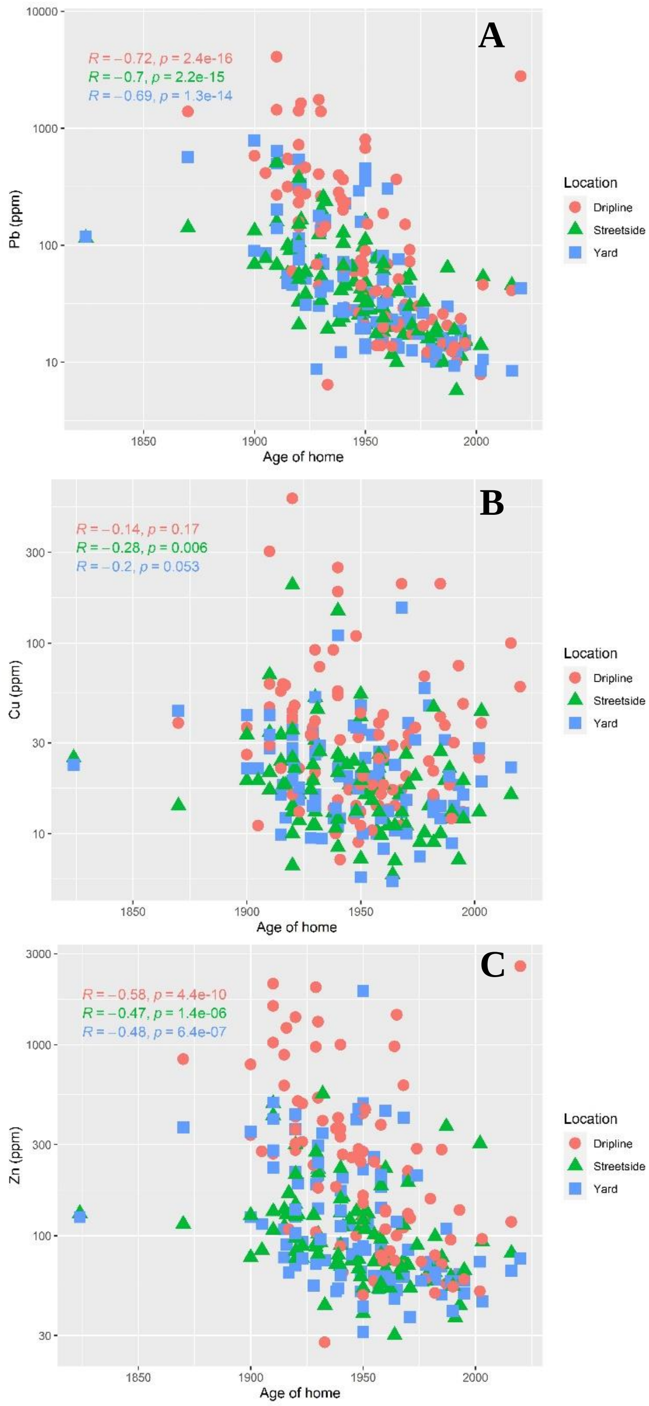

Fig. 4: Bivariate scatterplots between age of the home and (a) Pb, (b) Cu, and (c) Zn in soil. Sampling point color and shapes are by approximate sampling location, with the matching colored non-parametric Spearman ρ correlation coefficient (R) and associated p-value. Y-axes values are log-transformed.

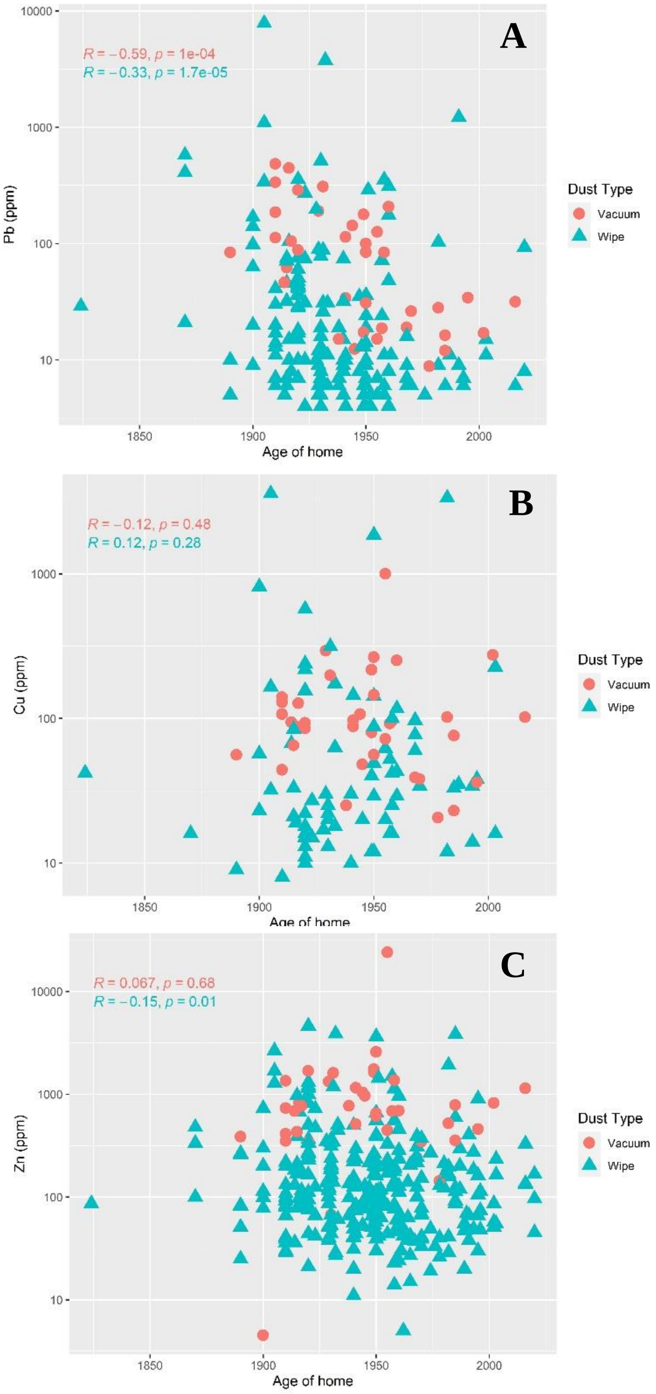

Fig. 5: Bivariate scatterplots between age of the home and (a) Pb, (b) Cu, and (c) Zn in dust. Sampling point color and shapes are by type of dust sample, with the matching colored non-parametric Spearman ρ correlation coefficient (R) and associated p-value. Y-axes values are log-transformed.

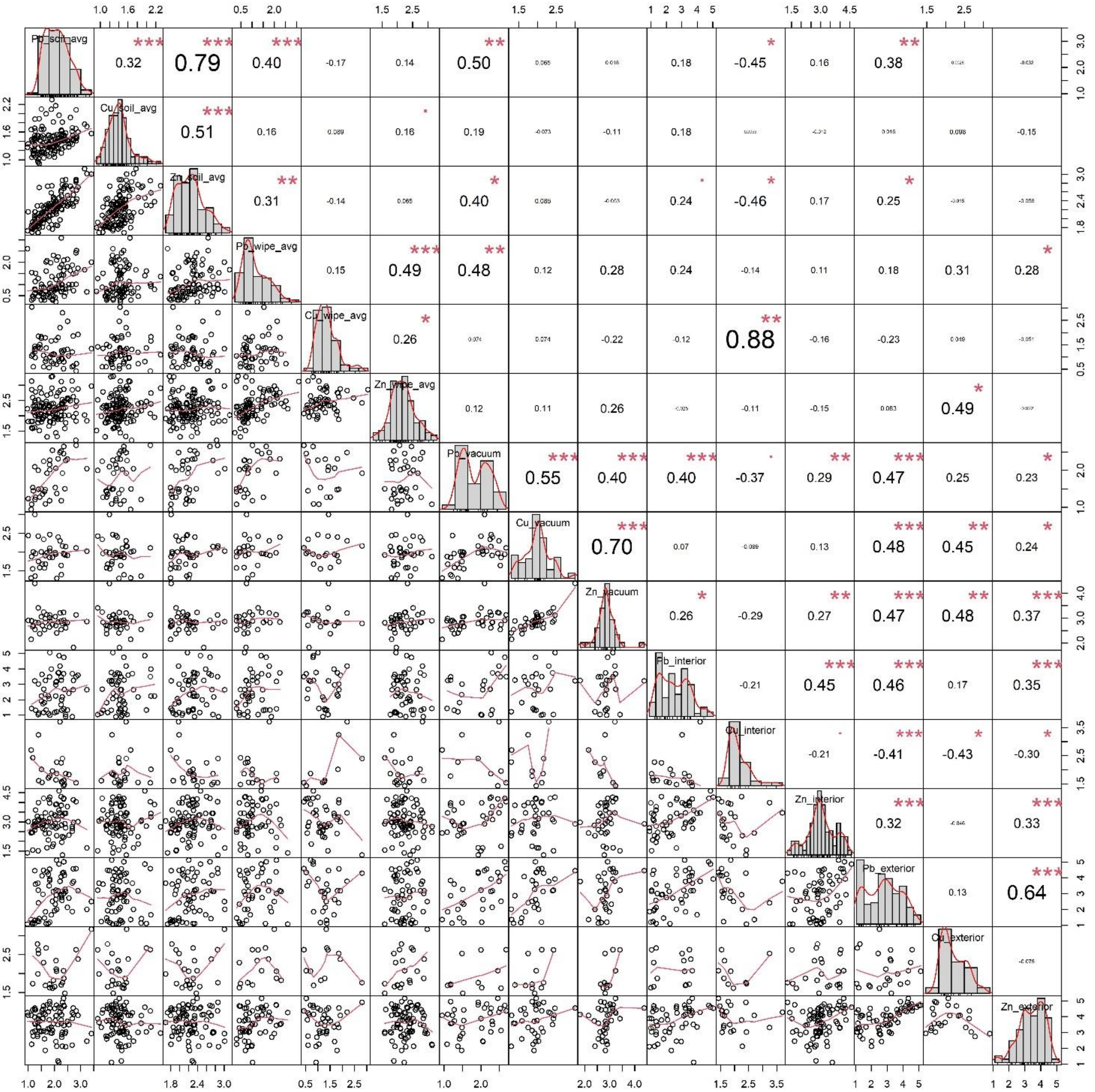

Fig. 6: Spearman correlation matrix of paired vacuum dust and average soil, average dust wipe, and exterior and interior paint Pb, Zn, and Cu concentrations (mg/kg). All data is log-transformed, and bivariate scatterplots and histograms with population density distribution curves are also presented for each variable. Stars indicate the level of significance [p-values (0.001, 0.01, 0.05, 0.1) <=> symbols (" *** ", " ** ", " * ", " . ")].