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RESEARCH ARTICLE

Biogeochemical characterization of municipal compost to support urban agriculture and limit childhood lead exposure from resuspended urban soils

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Chronic low-level lead exposure among low-income minority children is an urgent environmental justice issue. Addressing this ubiquitous urban public health crisis requires a new transdisciplinary paradigm. The primary goals of this work are to inform best practices for urban gardeners working in lead contaminated soils and to reimagine urban organic waste management schemes to produce compost, which when covering or mixed with urban soil, could minimize lead exposure. We investigate bulk and bioaccessible lead from five types of compost used in urban gardens in Boston, MA. We categorized them by feedstock and measured bulk elemental concentrations and physical characteristics. Our results show that different feedstocks exhibit unique geochemical fingerprints. While bulk lead concentrations in compost are a fraction of what is typical for urban soils, the bioaccessible lead fraction in compost is greater than the default parameters for the Integrated Exposure Uptake Biokinetic (IEUBK) model. The lack of geochemical differences across feedstocks for lead sorption to carbon indicates a similar sorption mechanism for all compost. This suggests that municipal compost would be suitable for capping lead contaminated urban soils. Risk assessment models should consider lead bioaccessibility, to prevent the underprediction of exposure risk, and should include compost along with soils as urban matrices. Based on the observed bioaccessibility in our compost samples, 170 mg/kg total lead in compost will yield the same bioaccessible lead as the IEUBK model predicts for the 400 mg/kg EPA soil lead benchmark. Local logistical challenges remain for interdisciplinary teams of city planners, exposure scientists, and urban agricultural communities to design organic waste collection practices to produce compost that will support urban agriculture and primary lead exposure prevention.

Keywords: urban agriculture; compost; lead; bioaccessible; soils

1. Introduction

In cities across the US, the primary variable correlated with childhood lead blood levels is not exposure to leaded paint, but exposure to re-suspended lead contaminated soil dust (Laidlaw et al., 2005; Laidlaw et al., 2016; Laidlaw et al., 2017; Laidlaw and Filipelli, 2008; Zahran et al., 2013). This newly emerging urban lead exposure paradigm significantly alters the landscape of lead exposure prevention programs, placing the emphasis on addressing legacy lead sources in soils rather than leaded paint. The ubiquitous and non-point source nature of this exposure pathway necessitates a focus on primary prevention (Laidlaw et al., 2016; Lanphear et al., 2016; Needlemen 2004; Zhang et al., 2013) and primordial prevention (Leech et al., 2016) as the most viable strategies for reducing blood lead levels (BLLs) in urban children. Since the bioavailable fraction of lead in urban soils ultimately governs its public health burden, effective remediation schemes must reduce exposure to bioavailable lead fractions (Henry et al., 2015). In 2012 the CDC lowered the BLL benchmark from 10 μg/dL to 5 μg/dL, which substantially increased cases of childhood lead poisoning as defined by the reference value (Handler and Brabander, 2012). Since urban soil is a major source of Pb exposure (Mielke et al., 2016) that is not given the concerted attention required to solve the problem (Laidlaw et al., 2017), creating remediation schemes is an imperative. There is no safe level of exposure to lead (Lanphear et al., 2016), and lead exposure is an environmental justice issue that has both historically caused and currently contributes to racial inequalities (Leech et al., 2016; Sampson and Winter, 2016).

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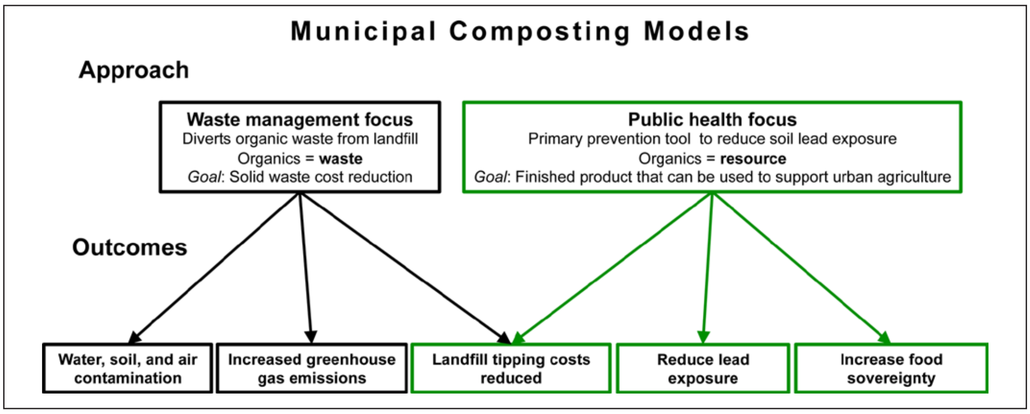

Figure 1: Proposed public health framework for managing urban carbon waste streams. A new paradigm envisions geochemically characterized organics as a resource that can reduce landfill costs, foster urban agriculture, and decrease soil lead exposure. DOI: https://doi.org/10.1525/elementa.238.f1

Capping lead contaminated urban soil with clean fill prevents contaminated soil from being resuspended as dust, thus reducing exposure through ingestion and inhalation of this resuspended soil dust, especially in summer months (Beniston and Lal, 2012; Filipelli and Laidlaw, 2010; Mielke et al., 2006; Mielke et al., 2011; Mielke et al., 2013; Wortman and Lovell, 2013). This approach is effective and financially feasible when a readily available, locally sourced fill is applied to exposed soils at the neighborhood scale (Filippelli et al., 2015). Mielke et al. (2011) implemented a pilot project in New Orleans in which clean alluvial sediments applied to playground surfaces reduced exposure to lead contaminated soils, an intervention that reduced soil lead levels by 92%.

Municipally sourced compost could cap lead contaminated soils in cities, rendering the lead inaccessible, and could also contribute to fostering urban agriculture. This public health motivation does not currently inform organic waste management decisions: current municipal composting facilities, when they exist, primarily serve the function of reducing landfill tipping costs to municipalities. This work proposes a new model in which the production and use of compost in urban centers could 1) reduce childhood lead exposure and 2) increase food sovereignty in environmental justice neighborhoods where the majority of residents are low income people of color living with disproportionate environmental pollution (Agyeman et al., 2002; Alkon and Mares, 2012) (**Figure 1**). To explore the viability of this model and ensure that using urban compost does not add a new exposure pathway for lead, we examine the geochemical characteristics and lead bioaccessibility, an *in-vitro* proxy for bioavailability, of composts from different waste streams and used by community organizations for urban gardening in Boston, MA.

To characterize common constituents of urban compost, we 1) measured bulk physical and chemical characteristics of typical compost source streams, 2) conducted a metal inventory analysis and geochemically fingerprinted final compost products, and 3) determined the bioaccessibility of lead in our samples. This research aims to identify common municipal compost source streams that are high in organic carbon and low in total and bioaccessible lead, with the goal of informing the design of compost collection and processing schemes that will permit widespread use of compost in preventing lead exposure associated with re-suspended urban soils while also supporting the growing urban agriculture movement.

2. Methods

2.1 Urban carbon source streams

Sixty-one compost samples were obtained from a) the Boston, MA municipal composting site and the Deer Island Wastewater Treatment Plant (Boston Harbor, MA); b) Boston area nurseries and garden centers; c) raised bed gardens and compost piles in Roxbury and Dorchester, MA; and d) household backyard compost piles. Additional heavy metal concentrations of 19 biosolids from wastewater treatment plants from across the Northeast were obtained from the EPA Targeted National Sewage Sludge Survey (U.S. EPA, 2009). **Table 1** describes the source streams of the samples, which were sorted into the following five categories based on feedstock: Municipal/Residential, Compost/Loam Mix, Commercial Food Sourced, Household Food Sourced, and Biosolids.

The first category, Municipal/Residential, needs to be distinguished from municipal solid waste (MSW) compost, a widely studied material (Baldantoni et al., 2010; Businelli, 1996; Chaney et al., 2000; de Miguel et al., 1998; Deportes et al., 1995; Epstein et al., 1992). Unlike MSW compost, in which organic waste is extracted from a mixed waste stream (including plastics and metals) and then separately composted, this compost is collected at the household level and then processed as a separate waste stream. A historically important feedstock for this category is street sweepings, a potential source of Pb. The yard waste in this matrix comes from neighborhoods in Boston, where yards contain high soil Pb concentrations averaging 900 mg/g (Clark et al., 2008), and where houses with Pb paint are still prevalent.

Compost/Loam Mixes in this study are all produced by companies and sold to farmers and gardeners. Compost sourced from leaves is mixed with loam, composed of 40% clay, 40% silt and 20% sand. Commercial food sourced composts are also created as an agricultural and

Table 1: Compost matrices and feedstocks.[a] DOI: https://doi.org/10.1525/elementa.238.t1

Matrix (S, N, A)	Feedstocks
Biosolids **(B)** (20, 19, 25)	wastewater treatment solids
Municipal Compost **(M)** (2, 44, 138)	Residential yard waste Park waste Street sweepings Marine waste Zoo waste
Loam Compost Mix **(L)** (4, 13, 45)	Yard trimmings Wood waste Agricultural waste Cardboard Food waste USDA sandy loam Mature leaf compost Sand Screened soil
Commercial Food Sourced Compost **(C)** (3, 12, 37)	Leaves Grocery store waste Ground up brush Horse manure/bedding Compostable paper products University dining hall waste Biosolids Brewers yeast Wood waste Treatment plant residuals
Household Food Sourced Compost **(H)** (6, 6, 18)	Household food scraps Wood chips Yard trimmings Coffee grounds

[a] Compost samples in this study were categorized into five matrices and grouped by similar feedstocks. For each matrix, the three numbers given indicate, respectively, the number of sites (S), samples (N), and aliquots (A).

garden product. Companies sell the service of accepting organic waste from food service providers seeking a food waste diversion alternative from incineration or landfilling. Commercial food sourced composts contain the broadest range of feedstocks and may also contain biosolids.

Household food sourced compost samples represent the small backyard pile composting style, where roughly 1 m^3 sized piles contain food scraps and yard waste from one home.

Biosolids are composed of precipitated solids at wastewater treatment plants. Two samples were obtained from the Deer Island treatment plant in Boston, MA. Northeast biosolids contain the Pb concentrations of wastewater treatment plants in the Northeast region of the United States, from the Environmental Protection Agency's 2009 Targeted National Sewage Sludge Survey Overview Report (U.S. EPA, 2009).

2.2 Analytical methods

Samples were dried at 35°C for 48 hours and ground to a fine powder with a mortar and pestle. Large debris (i.e., twigs, rocks) were removed from samples by hand. Three 4 g aliquots of powder samples were prepared in X-ray fluorescence (XRF) analytical cups and sealed with 4 μm Teflon windows (3526 Ultralene, Spex Sample Prep, Metuchen, NJ, USA).

The samples were analyzed on a SPECTRO XEPOS polarized energy dispersive X-ray fluorescence instrument (PED-XRF, Spectro, Kleve, Germany) using the Turboquant method. National Institute of Standards and Technology Standard Reference Material 2709a (San Joaquin Soil, Gaithersburg, MD, USA) was measured 72 times during the course of analyses to monitor the accuracy and precision of analytical measurements. The accepted Pb concentration for NIST 2709a is 17.3 μg/g, and measured Pb in this study averaged 17.3 ± 1.4 μg/g.

The pH of bulk samples was measured in triplicate using a 2:1 distilled water: soil ratio with a temperature compensating pH electrode. Loss on ignition (LOI) was determined as a proxy for organic matter content (Heiri et al., 2001). Aliquots of 0.2 g were burned for 8 hours at 500°C, and change in mass after burning was recorded. Samples were measured in triplicate.

Since feeding studies to measure Pb bioavailability are time and resource intensive and present ethical considerations, they are not recommended for widespread testing. Instead, *in-vitro* bioaccessibility tests that measure trace element solubility in simulated gastric or lung fluid can provide a reasonable proxy since they are correlated with *in-vivo* studies (Juhasz et al., 2013). Select compost samples (0.1 g) were digested in simulated human gastric fluid to model the bioaccessibility of lead in compost, using the EPA Standard Operating Procedure for an *in-vitro* bioaccessibility assay for lead in soil (U.S. EPA, 2012). Compost samples were digested in 0.4 M glycine solution adjusted to pH 1.5 with HCl. Before adding samples, solutions were preheated to 37°C. Acid-washed bottles containing 10 mL of acid and 0.1 g compost were placed on a rocker for one hour at 37°C. Samples were then transferred into a syringe fitted with a Luer-Lok attachment and filtered through a 0.45 μm cellulose acetate disk filter. Filtered solutions were analyzed for Pb using Optima 7200 DV inductively coupled plasma optical emission spectroscopy (ICP-OES, Perkin-Elmer, Waltham, MA, USA). Principal components analysis of the data set was performed using JMP Pro v9 (see supplemental information).

3. Results and discussion

Pb, a potent neurotoxin, causes irreversible damage at BLLs below 5 μg/dL, including lowered IQ and decreased academic achievement (Canfield et al., 2003; Lanphear et al., 2000; Zhang et al., 2013) and increased rates of attention deficit disorders, depression and anxiety (Bouchard et al., 2009), and violent behaviors (Mielke and Zahran, 2012; Needleman, 2004). There is no safe level of exposure to Pb (Bellinger, 2011). Therefore, a detailed inventory analysis of potential Pb sources in the feedstocks of municipal compost is required to ensure that none are added to already contaminated soils in environmental justice neighborhoods. Recent research indicates that total Pb concentrations do not necessarily predict bioaccessible lead concentrations in a soil sample.

Table 2: Bulk physiochemical properties and major and trace element compositions of compost samples by matrix.[a] DOI: https://doi.org/10.1525/elementa.238.t2

Matrix	Bulk physiochemical properties mean, IQR (range)			Major element composition (Wt%) mean, IQR (range)			Trace element concentration (µg/g) mean, IQR (range)		
	pH	**% LOI**	**Density (g/cm^3)**	**Si**	**Al**	**Ca**	**Pb**	**Ti**	**Zn**
biosolids (B)	6.00	63.1	0.93	4.77	1.3	3.39	112	898	984
municipal compost (M)	6.53, 0.24 (4.91, 7.53)	48.4, 8.32 (24.6, 75.1)	0.54	11.4, 3.69 (4.10, 26.5)	1.92, 0.58 (0.57, 3.66)	3.14, 0.67 (0.83, 4.31)	241, 21.8 (88.9, 440)	1620, 676 (867, 3708)	310, 58.8 (100, 469)
loam compost mix (L)	7.03, 0.31 (4.88, 7.90)	23.2, 3.0 (10.9, 88.9)	1.68	18.8, 2.13 (2.79, 22.9)	4.72, 0.66 (0.41, 6.47)	1.87, 0.50 (1.04, 2.56)	95.2, 13.8 (2.68, 205)	3220, 189 (437, 4447)	138, 10.3 (33.1, 246)
commercial food sourced compost (C)	6.91, 0.21 (5.28, 7.56)	52.2, 5.86 (32.6, 74.2)	0.89	8.53, 1.01 (3.60, 14.3)	1.86, 0.15 (0.51, 3.43)	5.41, 3.31 (1.44, 11.9)	102, 18.9 (3.80, 470)	1370, 233 (728, 2239)	209, 30.1 (42.5, 992)
household food sourced compost (H)	7.13, 0.18 (6.42, 8.99)	63.4, 23.7 (60.3)	0.99	7.50, 1.72 (0.10, 13.7)	1.66, 0.31 (0.07, 2.84)	2.46, 1.62 (0.54, 5.39)	118, 44.9 (1.00, 174)	1150, 334 (38.9, 1787)	288, 160 (47.2, 537)

[a] The mean, interquartile range (IQR), and range of bulk physiochemical properties and major element and trace element concentrations are given for each compost matrix. The upper and lower limits of the range are reported in parentheses. Percent loss on ignition (LOI) is used as a proxy for organic matter content. For biosolids, given the small sample size (n = 2), only mean values are reported.

Thus, Pb bioaccessibility values and not just total Pb concentrations will determine the efficacy of using urban sourced waste carbon as a capping material in neighborhoods with Pb contaminated soils.

3.1 Bulk properties of urban carbon matrices

The range, mean and interquartile range (IQR) of pH, loss on ignition, density, major elemental composition (Si, Al, Ca) and trace elemental composition (Pb, Ti, Zn) for each source stream are shown in **Table 2**. The global mean pH for all samples was 6.74 and mean by source stream ranged from 6.00 (biosolid) to 7.13 (household food sourced compost), representing a range difference greater than an order of magnitude. 75% of municipal compost samples were slightly acidic (6.1–6.5) or neutral (6.6–7.3) while 90% of loam compost mix samples were neutral or slightly alkaline (7.4–7.8). The range within each source stream varied greatly for pH, showing that pH may not be matrix specific. The global mean for all samples for loss on ignition (LOI) was 45.8% and mean LOI by source stream ranged from 23.2% (loam compost mix) to 63.4% (household food sourced). This difference is expected, given the addition of mineral rich loam to loam compost mixes and the lack of an inorganic soil mineral fraction in food-based composts (see **Table 1**). LOI within a single source stream also illustrates high deviations on a percent basis around the means, further highlighting that compost overall is a highly heterogeneous matrix. Loam compost mix had the highest representative density (1.68 g/cm^3) and municipal compost had the lowest (0.54 g/cm^3). This is also expected given the higher mineral content of loam compost mix samples and the light, porous texture of municipal compost samples. The wide range of feedstock materials across and within source streams can help explain the large variation in all bulk properties.

Density, pH, and organic matter content influence both total metal inventories and the speciation of lead in soils and compost. For example, Szymanski et al. (2005) show that during the decomposition process, metal inventories on a mass/volume ratio increase as organic matter is reduced and density increases. As pH decreases in compost and compost/soil matrices, aqueous lead concentrations in solution with the matrix increase (Sauve et al., 2000). A large fraction of labile lead in compost and compost/soil mixtures is bound to organic matter (Sauve et al., 1998; Szymanski et al., 2005). Chemical parameters in compost, especially pH, must be understood to elucidate the mechanisms of sorption and mobility of lead (Basta et al., 2005).

3.2 Major element geochemistry

The major elemental compositions seen in **Table 2** and **Figure 2** illustrate some predictable trends, given the differences in feedstocks within and between source streams. The high concentrations of Si and Al in loam-rich compost mixes are expected given the known addition of mineral-rich loam in this matrix. Food-based composts have the lowest concentrations of elements associated with mineral fractions (**Table 2**). The high mean Ca concentration for commercial food-based compost may be explained by the addition of lime or Ca-rich amendments, a common practice. A large dynamic range in the concentrations of major elements, especially Si, highlights the characteristic heterogeneity of compost (**Table 2, Figure 2a**). Within compost matrices, biosolids showed the most homogeneity, while household food sourced and

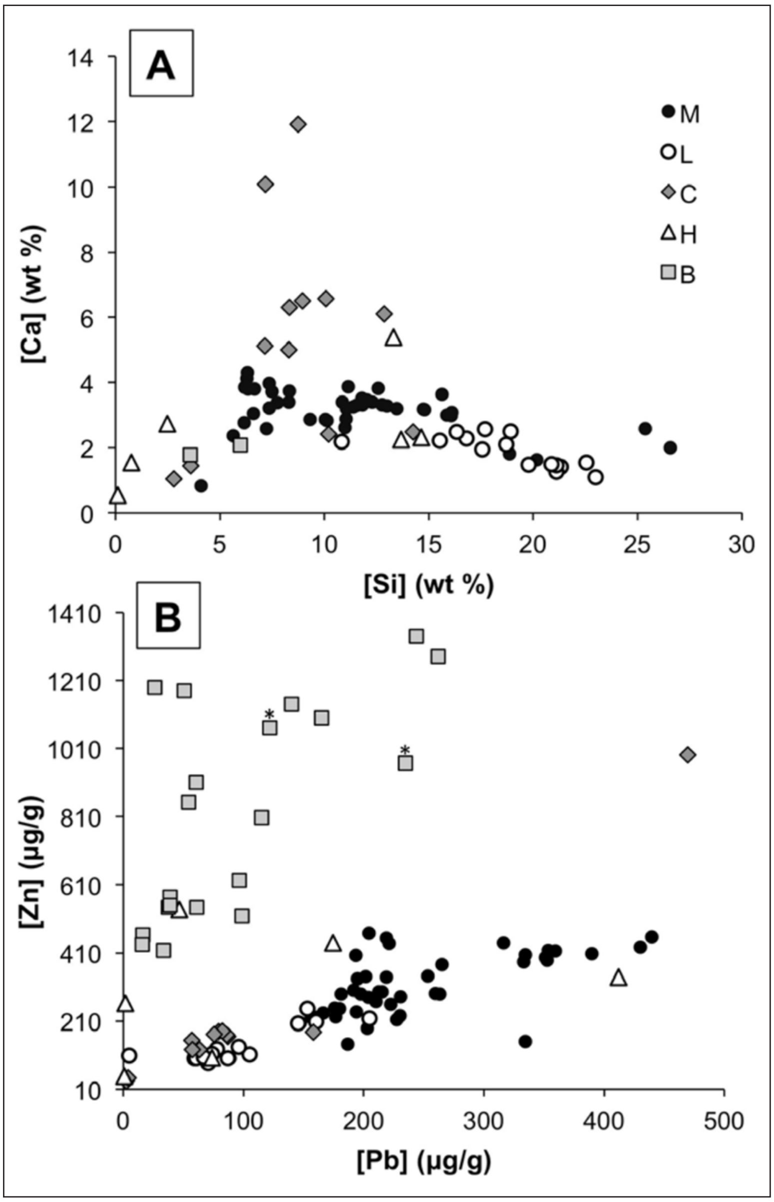

Figure 2: Major and trace element distributions in compost feedstocks. Figure 2a illustrates the geochemical variation in calcium and silica, the major element constituents in these matrices. Each source stream has a unique major element signature. Figure 2b shows that Pb and Zn are correlated within these source streams with the biosolid matrix displaying a unique and characteristically higher Zn signature. (Note, samples marked with asterisks are Boston biosolid data points from this study while the rest of the biosolid data is from Northeast EPA TNSSS data (2009). DOI: https://doi.org/10.1525/elementa.238.f2

municipal source streams showed the highest IQR around the mean (**Table 2** and **Figure 2b**).

Si and Ca play a significant role in mass balance for these materials (**Figure 2a**). Despite heterogeneity within source streams, a unique data cluster characterizes each feedstock. High Si and low Ca content characterize loam compost mixes, while lower Si and high Ca concentrations characterize commercial food sourced composts. Household food sourced composts have the lowest Si content. Municipal compost samples cluster between commercial food sourced compost and loam compost mixes. The distinct clustering of source streams in **Figure 2a** shows that source stream controls bulk chemical properties, and each source stream shows a unique geochemical fingerprint.

3.3 Trace element geochemistry

While major element geochemistry is useful in identifying the source streams for the feedstock, trace element inventories and ratios are useful in evaluating potential point and non-point sources of toxic elements. Municipal compost samples have the highest mean Pb concentration at 241 mg/kg, a concentration 1.6 times higher than the German Pb compost benchmark of 150 mg/kg (**Figure 2b**) (Brinton, 2000; Hogg et al., 2002). The global mean of the entire dataset exceeds the current German

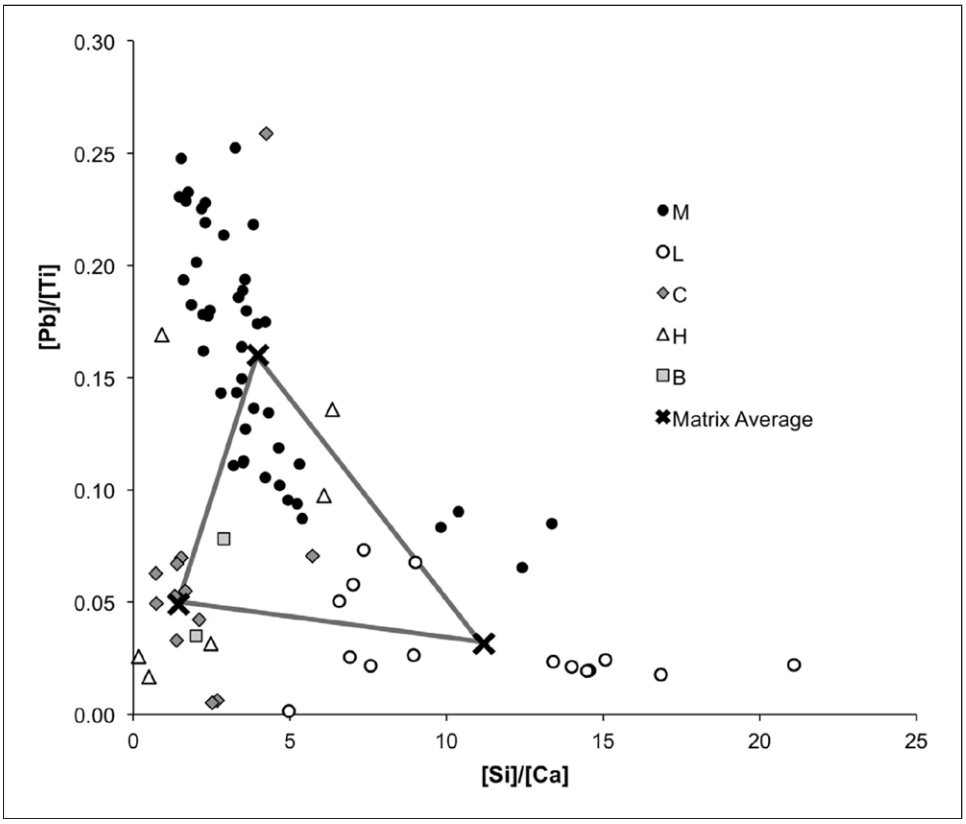

Figure 3: Ratio plot of major and trace elements in compost feedstocks. Feedstocks signatures have distinct geochemical fingerprints. The average value is plotted for three geochemical matrices: loam, municipal, and commercial food. The variability in the geochemical signature in backyard sourced materials is not well characterized by an average value. DOI: https://doi.org/10.1525/elementa.238.f3

benchmark for Pb in compost, which we use in lieu of a US benchmark specifically for compost. Compost that has a significant fraction of food sourced carbon has the lowest Pb concentrations followed by loam compost mixes. The mean Pb concentration for municipal compost is two times higher than the mean for all food waste composts. Higher Pb concentrations in municipal compost may be attributed to yard waste collection in neighborhoods with Pb contaminated soil in the city of Boston. Contaminated soil particles associated with yard waste would then accumulate during the composting process and result in higher Pb concentrations in this source stream. On a percent basis, Zn concentrations across matrices vary less than Pb, with the notable exception of higher Zn concentrations observed in biosolids.

Figure 2b shows the correlation between Pb and Zn in for all compost source streams. Correlations between Pb and other metals can yield insight into both the source of metal contamination and the mode of transport. In urban soils, a correlation between Pb and Zn has been suggested to be linked with traffic patterns and the combustion of leaded gasoline (Mielke et al., 1983; Zhang et al., 2012) while associations between Pb and Ti have been linked with Pb-based paint contamination (Clark et al., 2006). Within the municipally sourced matrix, the Pb/Ti ratio systematically varies, nearly linearly, when plotted against the major element ratio (Si/Ca). This correlation is not observed for the other compost matrices, suggesting that only the municipally sourced compost includes a fraction of urban soil, which contains paint-based lead. The steeper slope correlation between Zn and Pb for biosolids represents a unique source and transport relationship. High Zn concentrations have been previously reported in biosolids (Berti and Jacobs, 1996).

Using a combination of major and trace elements, it is possible to fingerprint the components of each source stream and make first order distinctions between different source and transport models for metals entering compost.

3.4 Fingerprinting matrices

Element-element ratio plots are useful tools for identifying potential end members in complex mixtures and source appropriation modeling. The element-element ratio plot in **Figure 3** highlights that when mass balance is removed, the clustering of samples by source stream is preserved in dimensionless space, further substantiating their unique geochemical properties. Three distinct clusters are seen for municipal, loam compost mixes, and commercial food based composts. This clustering by source stream for municipal, loam compost, and commercial food samples as shown in **Figure 3** is preserved in Principal Components Analysis, a multivariate statistical tool that transforms the total variance within a dataset into a two-dimensional space (Figure S1).

This combined analytical/modeling approach could be developed and calibrated on a city-by-city basis so that predictive models would permit composting facilities to estimate and track the relative proportions of the carbon waste streams entering and leaving their facilities, helping to ensure quality control benchmarks. This approach could be optimized to minimize either total metal inventories or bioaccessible metal pools and would permit a wider range of end uses for food production. All of these elements could be sufficiently quantified "in the field" using field portable X-ray fluorescence instrumentation. Rapid *in situ* screening protocols are preferable for material with inherent large-scale heterogeneity.

3.5 Bioaccessibility of Pb in compost

As shown in **Figure 4**, a positive linear relationship is found between total Pb concentrations and bioaccessible Pb fractions in compost, with an r^2 of 0.98 for all samples. Bioaccessible Pb as measured by the U.S. EPA *in vitro* Bioaccessiblility Assay in this study ranges from 34 to 339 mg/kg, with a mean concentration of 161 mg/kg (**Figure 4**). On average the municipally sourced compost samples have five times more bioaccessible lead. The linear trend between bioaccessible and total Pb suggests that despite differences in bulk geochemical characteristics across compost types (including bulk pH, see **Table 2**), the geochemical mechanisms associated with lead solubility are similar within this matrix.

The difference between Pb bioaccessibility in urban compost feedstocks in the United States has not been systematically studied. Previous research has extensively characterized municipal solid waste (MSW) composts (Baldantoni et al., 2010; Businelli et al., 1996; Chaney et al., 2000; de Miguel et al., 1998; Deportes et al., 1995; Epstein et al., 1992; Paradelo et al., 2011; Smith, 2009; Szymanski et al., 2005). In this matrix, the formation of organo-metallic complexes have resulted in reduced Pb bioavailability in compost and compost-amended soil. The bioavailability of Pb in biosolid-amended urban soils has also been extensively studied and Pb bioavailability has reduced with amendments (Brown et al., 2003, 2004, 2015).

While previous studies show promising reductions in lead bioaccessibility in compost-amended urban soils (Attanayake et al., 2015), both the range of feedstocks used and the end uses in this study can be significantly different: in community and backyard urban gardens, compost can make up to 50–100% of the growth media in raised bed gardens. These variations along with the likelihood of multiple sources of lead (including lead based paint, combustion of leaded gasoline, smelters, and lead acid battery recycling) require detailed geochemical characterization to understand the relationship between source of lead and sorption behavior.

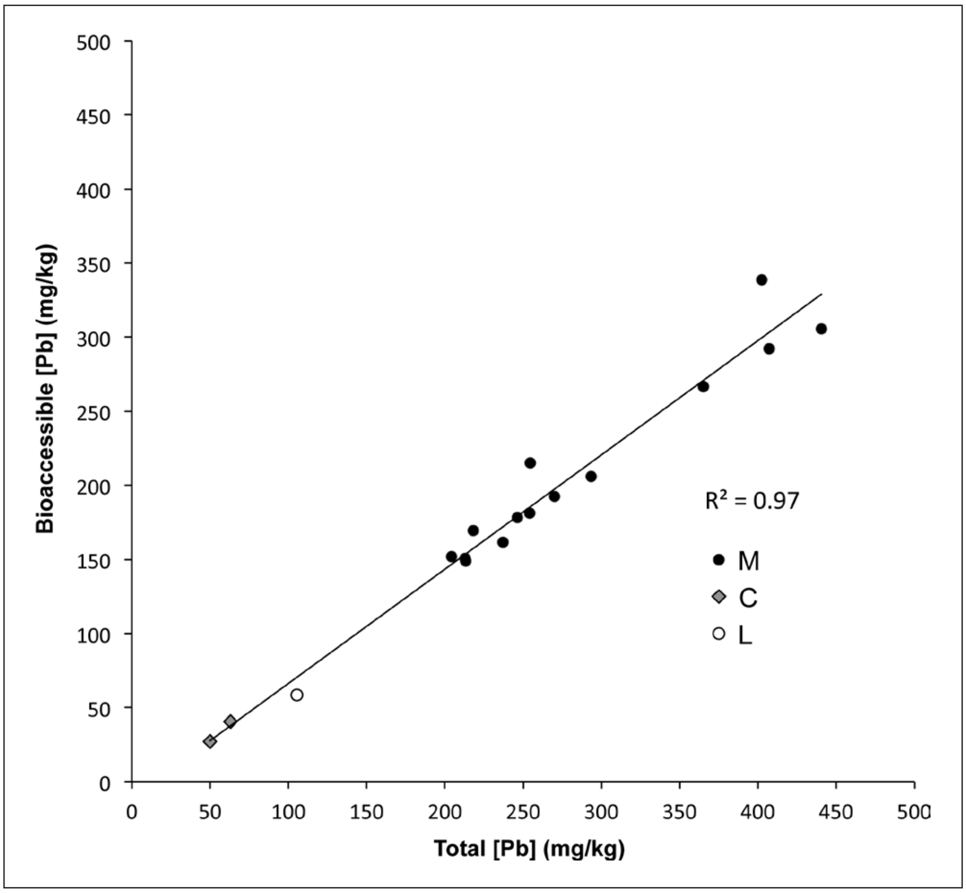

Figure 4: Lead bioaccessibility of compost and loam samples. This figure illustrates a linear relationship between total lead concentration and bioaccessible lead across all matrices, with municipally sourced compost consistently having the highest soluble lead fraction. DOI: https://doi.org/10.1525/elementa.238.f4

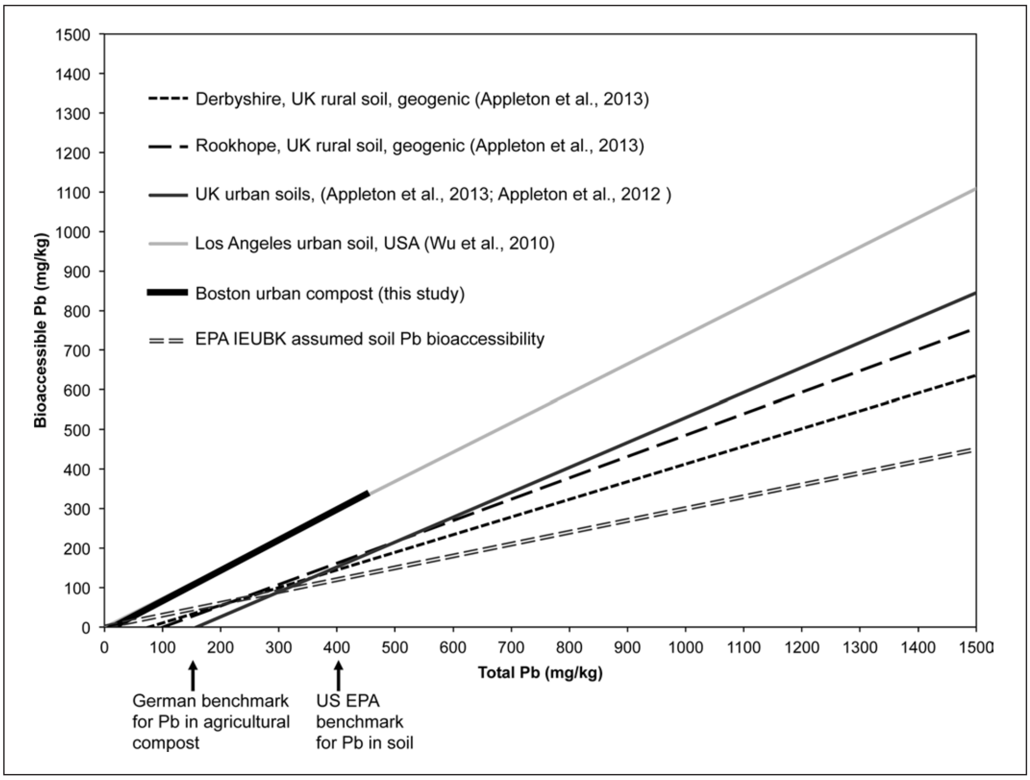

Figure 5: Bioaccessibility of geogenic and anthropogenically sourced lead in urban soils and compost. The U.S. EPA soil and German compost benchmarks are noted on the total lead concentration axis (mg/kg). Urban matrices have steeper slopes, indicating a higher fraction of bioaccessible lead for a given total lead concentration. Length of each line represents a linear regression over the range of reported Pb concentrations. Measured bioaccessibility exceeds EPA-IEUBK model defaults for all matrices at total lead concentrations greater than the U.S. EPA soil benchmark of 400 mg/kg. DOI: https://doi.org/10.1525/elementa.238.f5

The correlation between bioaccessible and total Pb (**Figure 4**) can be explained by either a mass balance control from a dominant source of Pb or Pb sorption mechanisms in compost. To evaluate which factor is driving the observed solubility, future Pb bioaccessibility analyses should focus on a wider range of urban carbon matrices including garden soils and raised bed fills and be coupled with lead isotope analysis to further fingerprint potential sources.

3.6 Pb bioaccessibility in the built environment

Recent literature revealing that the seasonality of children's blood lead levels in urban centers is largely associated with resuspended urban soils (Laidlaw et al., 2005; Laidlaw et al., 2008; Laidlaw et al., 2016; Laidlaw et al., 2017; Mielke et al., 2016; Zahran et al., 2013) precipitates an urgent need to include bioaccessible soil lead characterization in risk evaluations. A few studies from the urban-rural gradient have attempted to systematically measure the fraction of soil lead that is soluble in simulated gastric fluid assays (Appleton et al., 2012, 2013; Wu et al., 2010). **Figure 5** plots total lead concentrations in soil and compost matrices (mg/kg) versus bioaccessible lead (mg/kg). Linear regressions are presented over the concentration ranges reported. Compost matrices all exhibited lower bulk and bioaccessible lead than the highly variable soils from the UK, where the dominant source of lead was geogenic. We observe that bioaccessible Pb concentrations in compost are below 336 mg/kg, while bioaccessible Pb in geogenically sourced leaded soils observed by Appleton et al. (2013) ranges from 51 – 8565 mg/kg.

The regression line slopes, which represent the average percent bioaccessible Pb for each matrix, are steeper in urban regions than in rural regions (**Figure 5**). Furthermore, urban soils/compost slopes are similar across a wide range of geographic settings (Boston, MA, USA; Los Angeles, CA, USA; UK), suggesting that anthropogenic biogeochemical cycling of lead in urban environments increases bioaccessible lead. It is possible that in this setting, biogeochemical cycling of allochthonous (anthropogenic) lead results in its redistribution from mineral lattice positions on soil particles to sorption sites in organic matter. Additional research is needed to evaluate all the geochemical controls on gastric soluble lead in urban soils and compost. Quantification of the roles of nature (the source of lead), nurture (the matrix in which the lead resides), and transport mechanisms in governing the health risks associated with exposure to these matrices would further our understanding of how this matrix contributes to elevated BLLs.

The steeper urban slopes in **Figure 5** (in comparison to rural slopes) have important implications for public health: lower total concentrations result in higher gastric soluble lead in urban compost in Boston, MA (this study) and urban soils in Los Angeles, CA (Wu et al., 2010), as compared to rural soils with similar total lead concentrations. For example, at the EPA benchmark concentration (400 mg/kg), the bioaccessible lead fraction in compost samples from this study is 2.5 times greater than the Integrated Exposure Uptake Biokinetic (IEUBK) model default input parameter, while at the German compost benchmark (150 mg/kg), the IEUBK model would under predict risk by 2.2 times. Based on the observed bioaccessibility in our compost samples, 170 mg/kg total lead in compost will yield the same bioaccessible lead as the IEUBK model predicts for the 400 mg/kg EPA benchmark (**Figure 5**). We suggest a benchmark for Pb in urban compost in the range of 150–200 mg/kg, similar to the German standard.

3.7 Implications for environmental justice, lead primary prevention, and urban agriculture

In addition to being a primary exposure pathway in urban centers, soil lead disproportionately affects low income communities and communities of color (Aelion et al., 2013; Bellinger and Bellinger, 2006; Campanella and Mielke, 2008; Filipelli et al., 2015; Filipelli and Laidlaw, 2010). Racial disparities exist in the magnitude of toxic exposure, with the burden of exposure falling on minorities (Sampson and Winter, 2016). Furthermore, residents face restricted access to fresh, healthy food, recreational facilities, and healthcare, which constitute a serious health burden that only amplifies the negative health outcomes of lead exposure. Business disinvestment, redlining, and other forms of systemic discrimination have left many low-income urban neighborhoods without access to basic goods and services, forcing residents to leave their community to purchase food, clothes, and other amenities. The absence of a local economy limits job opportunities and perpetuates poverty (Alkon et al., 2013). Poor health and low nutritional status, including irregular food intake, high fat intake, and calcium and iron deficiency, increase the toxicity of lead in the body (Mahaffey, 1990, 1995). Since low-income urban populations that face the highest risk for lead exposure also have the highest risk for these nutritional status characteristics, these issues must be understood as interrelated and driven by systems of social, environmental, and economic injustice (Bellinger, 2008; Mahaffey, 1995).

The urban farming movement addresses these injustices in urban food systems. In addition to increasing access to fresh, healthy food, urban community gardens provide opportunities for youth empowerment, political organizing, and cultural preservation, all of which help create strong, supportive social networks that catalyze bottom-up neighborhood revitalization (Ober Allen et al., 2008; Okvat and Zautra, 2011; Saldivar-Tanaka and Krasny, 2004; Subica et al., 2016). The challenge, then, is to enable urban agriculture and its widespread benefits without perpetuating the injustice of urban gardeners having only highly lead-contaminated urban soil as an available growing media (Brown et al., 2016; Clark et al., 2006; Clark et al., 2008; Kessler, 2013; Kim et al., 2014; Säumel et al., 2012; Wortman and Lovell, 2013). In the urban gardening context, more than 80% of exposure is attributed to soil ingestion and inhalation (Clark et al., 2008), increasing the importance of capping this source of lead.

3.8 A new conceptual model for organic waste management

The current waste management paradigm in the United States treats organic material as a waste stream rather than a valuable resource. We challenge this way of thinking about urban organic carbon and propose a new public health model for waste management systems that considers the environmental and health benefits of source-separated urban carbon composting (**Figure 6**). In our model, geochemically informed collection and processing schemes minimize the incorporation of high Pb inputs, allowing municipally sourced compost to be safely used for capping lead contaminated soils and supporting urban agriculture (**Figure 6**). The results presented in this study can be used to inform geohealth-based benchmarks for a range of urban compost applications, especially food production. These results could be used to inform and

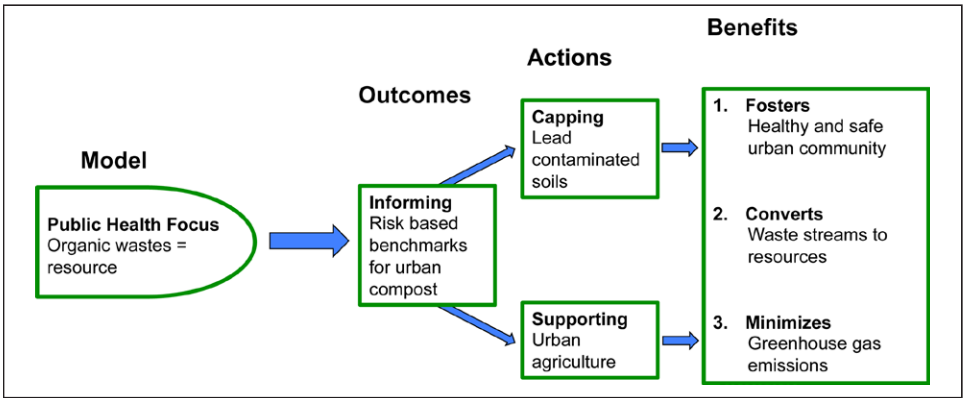

Figure 6: Outcomes and benefits of a public health focused model for managing urban organic waste streams. By adopting a geochemically informed source stream management scheme, the motivation for composting urban food and yard waste can be shifted merely from waste reduction to generating a locally sourced resource to reduce lead exposure and promote food sovereignty. DOI: https://doi.org/10.1525/elementa.238.f6

develop a predictive model for compost application and combined with predictive models for soil lead levels in urban areas (Schwarz, 2016).

This new conceptual model is widely implementable. The basic components of low bioaccessible lead waste streams (e.g., commercial and residential food waste) are common components of the carbon flux of cities and play a role in the metabolism of urban ecosystems, an understudied but important quantification of energy and resource use fluxes in urban environments (Kennedy et al., 2007). In addition to the community and health benefits of adopting this paradigm shift in waste management, the carbon contribution of cities is lowered by reducing the climate impacts of traditional waste disposal and increasing the organic matter content of urban soils (Jones and Healey, 2010). In the economic and environmental analysis of various organic waste management strategies by Sonesson, et al. (2000), composting is an environmentally friendly and cost-effective waste management strategy when compared to anaerobic digestion and incineration. Interdisciplinary teams in the United States working toward integrating waste management practice changes into primordial lead prevention need not reinvent the wheel and can create models based on the standards and practices implemented in European organic waste management (Hogg et al., 2002).

4. Summary and conclusions

On a global scale, the burden of cardiovascular disease and mild mental retardation from lead exposure falls highest on low- and middle-income countries (LMICs), contributing 1% of the global disease burden (Fewtrell et al., 2004) and placing an economic burden on LMICs equal to 1.2% of the total global GDP (Attina and Trasande, 2013). Additionally, urban agriculture in developing countries is gaining attention and relevance as the global population becomes increasingly urbanized (Orsini et al., 2013). Despite extensive evidence pointing to its significance, the contribution of soil lead to the public health crisis of low-level childhood lead poisoning remains on the sidelines. In the emerging public media narrative on drinking water lead contamination in cities like Flint, MI, USA, soil lead contribution to total lead exposure has not been recognized (Laidlaw et al., 2016). Clearly, low-cost and widely implementable intervention schemes are needed to reduce routine exposure to urban soils for both the general public and urban farmers.

This work addresses the challenge faced by urban farmers of enabling urban agriculture and its widespread benefits without perpetuating the injustice of using lead-contaminated urban soil as an available growing media. The results of our geochemical study of urban composts reveal that different feedstocks for compost create geochemically distinct materials. Depending on the feedstocks and production, some compost has lower total lead than others, with municipal compost containing the highest Pb concentrations. Despite the differences in total concentration, lead is similarly bound in all compost feedstocks, and percent bioaccessibility is consistently low across feedstocks. This suggests that all composts, even municipal compost (with Pb total concentrations around the EPA soil benchmark of 400 mg/kg), are suitable for urban agriculture and capping lead-contaminated urban soils, an urgent public health need (Laidlaw et al., 2017; Mielke et al., 2016).

We use bioaccessible Pb instead of total lead to assess risk for lead exposure and show that the IEUBK model underpredicts the risk associated with urban soils and compost. Regulatory frameworks for assessing Pb exposure risk from urban soils and compost are lacking and should take bioaccessible, not total, Pb into account Zia et al., 2011. This approach (the combined analytical/modeling) could be optimized to minimize either total metal inventories or bioaccessible metal pools and would permit a wider range of end uses of compost for food production. Systems for successful compost production in Europe can be taken as models for US cities to implement lead safe waste management and compost production.

We propose that compost use in soil remediation in urban gardens be situated within the context of primordial and primary prevention efforts as described by Leech, et al. (2016) and Mielke, et al. (2013, 2016). A paradigm shift in urban organic waste management would be required to produce safe compost to cap high Pb soil at the neighborhood scale. Such a shift will be a key component to low-cost primary prevention for chronic low-level childhood lead poisoning and to creating just and sustainable urban food systems in the United States and globally.

Data accessibility statement

Major dataset including total and bioaccessible element concentrations has been submitted to the Wellesley College Digital Scholarship and Archive Repository located at: http://repository.wellesley.edu/.

Supplemental files

The supplemental files for this article can be found as follows:

- **Figure S1.** Principal components analysis plot for all geochemical variables in compost/loam samples. Geochemical clustering of feedstocks is preserved even when entire chemical analysis is modeled. Total variability preserved is 70.5%. DOI: https://doi.org/10.1525/elementa.238.s1
- **Table S1.** Bioaccessible soil lead regression equations. DOI: https://doi.org/10.1525/elementa.238.s2

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Competing interests

The authors have no competing interests to declare.

Author contributions

- Contributed to conception and design: MGF, RMS, DJB
- Contributed to acquisition of data: MGF, RMS, DJB
- Contributed to analysis and interpretation of data: MGF, RMS, DJB
- Drafted and/or revised the article: MGF, RMS, DJB
- Approved the submitted version for publication: MGF, RMS, DJB

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