Key Points:
- Resuspendable soil fractions containing legacy Pb are a significant source of bioaccessible Pb in urban soils decades after deposition.
- Legacy Pb sources (gasoline and paint) are both bioaccessible, and the labile fraction of Pb is isotopically similar to total Pb digests.
- Locally sourced compost reduces fine soil particle resuspension, lowers the soluble pool of Pb in the growing matrix, and adds carbon.

Supporting Information:
- Supporting Information S1.

1. Introduction
Legacy anthropogenic soil lead (Pb) poses a major health risk for inner city residents across the country, and this risk is heightened for urban gardeners who are regularly exposed to open soil and consume food that may have remnant soil dust on the surface (Cheng et al., 2015; Clark et al., 2008; Filippelli et al., 2005; Mielke, Covington, et al., 2011). There is no safe level of Pb exposure, and even a small dose can cause serious intellectual deficits and increase the likelihood of depression, anxiety, and other detriments (Bellinger et al., 1991; Lanphear et al., 2005; Bouchard et al., 2009; World Health Organization, 2014). Pb poisoning is particularly harmful for children, and the impacts of childhood exposure are felt throughout an individual’s life since Pb can accumulate in bone and permanent cognitive deficits can lower socioeconomic mobility in adulthood (Reuben et al., 2017).

Urban agriculture plays a key role in the food justice movement, providing fresh produce and a range of social benefits. Soil Pb contamination is most prominent in low-income communities of color, where urban agriculture is often common practice (Aelion et al., 2012; Bernard & McGeehin, 2003; Campanella & Mielke, 2008; Filippelli & Laidlaw, 2010; Leech et al., 2016; McClintock, 2012). Patterns of race-based discrimination in housing, financing, education, and incarceration have left these communities with limited access to basic living necessities, including affordable fresh food (Alexander, 2012; Alkon et al., 2013; Berlak, 2001). Urban agriculture provides quality food as well as opportunities for youth empowerment, community organizing, and cultural preservation. These are powerful tools in any community, and even more so in neighborhoods struggling to overcome environmental, economic, and racial injustice (Ober Allen et al., 2008; Okvat & Zautra, 2011; Saldivar-Tanaka & Krasny, 2003; Subica et al., 2015). For cities to ensure safe urban farming, addressing urban soil Pb is essential.

Various remediation strategies have been proposed to reduce Pb exposure in urban gardens (Kessler, 2013; Mitchell et al., 2014). Planting crops in raised beds filled with low-Pb compost or diluting contaminated soil with compost are two popular and accessible methods for gardeners to reduce Pb exposure (Clark et al., 2006). Cities are beginning to utilize their large organic waste streams by recycling them into low-Pb
compost, which is a promising alternative source of high-quality growing material (City Soil, 2016; Fitzstevens et al., 2017; SF Rec & Parks, 2016). Soil management strategies like these can reduce risk of Pb exposure by lowering garden soil Pb concentrations below the neighborhood average (Clarke et al., 2015), but to truly practice safe and sustainable urban agriculture the garden Pb concentrations must be low enough to prevent negative health outcomes.

The Pb health burden is ultimately governed by the fraction of Pb absorbed into the bloodstream, or bioavailable Pb, rather than total Pb in the soil. Since Pb bioavailability in urban soils can vary significantly (Zia et al., 2011), recent studies are framing soil exposure risk in terms of bioavailable Pb instead of the total soil Pb (Cheng et al., 2015; Clarke et al., 2015; Fitzstevens et al., 2017; Henry et al., 2015). We measure in vitro bioaccessible Pb, or the Pb that is soluble in simulated gastric fluid, as a time and resource efficient proxy for in vivo bioavailable Pb (Zia et al., 2011).

Zahran et al. found that Detroit children’s elevated blood lead levels (BLLs) are linked with seasonal trends of suspended soil dust, implicating wind transportable surface soil as the primary driver of bioavailable Pb (Laidlaw et al., 2012, 2016; Zahran et al., 2013). This observation calls for a closer examination of the Pb exposure risk associated with fine soil particles that are mobile in the summer months. Urban gardeners face frequent exposure to these particles, which easily stick to skin, crop surfaces, and can recontaminate clean gardens and raised beds by wind transport and soil splash during rain storms (Clark et al., 2008; Kissel et al., 1996).

Since gardeners are regularly exposed to Pb while working with a range of growing materials, their Pb exposure is unique compared to most urban dwellers. To better understand Pb exposure in an urban agricultural setting, we investigate how bioaccessible Pb changes as a function of growth medium, grain size, and Pb source. First, we characterize the geochemical distinctions in urban growing materials collected in Roxbury, MA, ranging from unamended soil to compost. We then examine the variables controlling Pb bioaccessibility and mobility of fine-grained, transportable particles. We use Pb isotopes to fingerprint Pb source mixtures across growing mediums and compare Pb bioaccessibility of leaded paint and gasoline. Ultimately, this analysis contributes to developing best management practices for gardening in contaminated soil.

2. Materials and Methods

2.1. Sample Collection and Categorization

We collected a range of growing material samples from the Dudley triangle in Roxbury and Dorchester, MA, Boston, neighborhoods where residents widely practice urban agriculture and seek soil remediation strategies. Dudley demographics reflect national trends for communities with high soil Pb levels: most residents are people of color and over half of residents earn less than $25,000 per year (Dudley Street Neighborhood Initiative, 2014). Sample collection in this neighborhood was conducted in partnership with The Food Project, a Boston-based nonprofit organization promoting the practice of urban agriculture for youth and community empowerment. In addition to collecting discrete samples for laboratory analysis discussed in this paper, we also performed in situ soil tests for residents and community gardens. Partnering with The Food Project throughout this study helps inform localized remediation decisions for urban gardeners and formulate new research questions (Sharp, 2016).

Samples represent a realistic range of what Dudley urban farmers use to grow food. Though each sample is unique due to urban environment heterogeneity, they can be grouped into four categories. Composts are the nutrient-rich product of accelerated degradation of organic matter, primarily food, yard, and park waste (Fitzstevens et al., 2017). We collected samples from compost piles at Roxbury gardens after they had been brought from the production site. We collected raised bed fills from raised beds, above-ground gardens which are initially filled with a low-Pb alternative to urban soil (typically compost) and have been used to grow crops (The Food Project, 2012). Garden soils are from plots without raised beds where compost is usually mixed with the original soil. We collected unamended urban soil samples from uncultivated areas near garden plots where there was no evidence of soil management.

2.2. Sample Processing and Sieving

All samples were dried at 30°C to a constant mass, then sieved to <2 mm. Bulk samples were ground in a Spex CertiPrep 8000 M mixermill prior to analysis. Four samples (two unamended soils, one raised bed fill,
and one compost) were sieved postdrying using Chemplex Nylon mesh screens into the following grain size fractions: 2 mm–250 μm (termed >250), 250 μm–149 μm, 149 μm–74 μm, 74 μm–37 μm, and <37 μm. Only the 2 mm–250 μm fractions were ground prior to analysis.

2.3. Primary Geochemical Characterization

We measured trace element concentrations using energy-dispersive X-ray fluorescence (SPECTRO-XEPOS). Ground samples were analyzed in Premier Lab Supply XRF analytical cups sealed with 4 μm Teflon windows. Three aliquots were prepared for each bulk sample, and one for each sieved grain size fraction. All samples were analyzed in triplicate. Percent carbon was measured using a CHNS Element Analyzer (Elementar Vario Micro MICRO Cube) in three aliquots for each bulk sample. pH was measured in solution (1 g sample and 2 mL were analyzed in triplicate. Percent carbon was measured using a CHNS Element Analyzer (Elementar Vario Micro MICRO Cube) in three aliquots for each bulk sample. pH was measured in solution (1 g sample and 2 mL H2O) for all bulk samples using a Thermo Electron pH meter. Triplicate pH analyses of three aliquots were analyzed for each sample.

Scanning electron microscopy (JEOL 6610LV VP-SEM-EDS) backsscatter electron (BSE) images provide a more in-depth fine-grain analysis and textural characterization of compost and unamended soil. Samples were prepared for SEM imaging by sieving to <37 μm.

To aid in the characterization of the high Pb matrix components, we experimented with density fractionation to determine if the Pb was preferentially associated with the denser particles of the <37 μm grain sized material. Two <37 μm samples (an unamended soil and raised bed fill) were poured onto a Sodium Polytungstate (density = 2.89 g/cm3) solution, and the dense particles were allowed to settle. Trace element concentrations of the carbon-rich “floats” were analyzed using the SPECTRO-XEPOS. We estimate the Pb concentration of the mineral-rich “sinks” to compare with the carbon-rich “floats” using mass balance since low sample volume prevented XRF analysis. The final masses of the floats and sinks used to estimate the sinks’ Pb concentration were 1.49 g and 0.05 g, respectively (Figure S2 in the supporting information).

2.4. In vitro Bioaccessibility Assays

We performed a slightly modified Environmental Protection Agency (EPA) In-vitro Bioaccessibility Assay for nine bulk ground samples and three sieved samples (U.S. Environmental Protection Agency (USEPA), 2012). As described in section 2.2, sieved samples consist of five grain size fractions for each sample, of which only the >250 μm fraction was ground. Bulk samples were ground to ensure a representative bioaccessibility measurement since grain size and texture are considerably varied and only a small sample mass was used in the bioaccessibility assay. We were able to evaluate the impact of grinding samples prior to partial digest by using an inventory analysis approach that calculated a bulk bioaccessible Pb from two sieved (nonground) samples. We observed that these weighted summed average bioaccessible Pb values were comparable with those measured on ground bulk samples. We used a sample-fluid ratio consistent with the EPA method but reduced sample mass to accommodate limited sample material.

We performed a partial digest of 0.1 g of sample in 10 mL of simulated gastric fluid at 37°C for 1 h. Simulated gastric fluid is a solution of 0.4 M glycine solution adjusted to pH 1.5 with HCl and heated to 37°C before being mixed with samples in acid-washed vials. Post leaching, samples were filtered through a 0.45 μm cellulose acetate disk filter. We analyzed the extraction fluid using Optima 7200 DV inductively coupled plasma (ICP) optical emission spectroscopy (Perkin-Elmer).

2.5. Pb Radiogenic Isotope Analysis

Bioaccessible Pb extraction solutions containing bioaccessible Pb from 13 discrete samples were analyzed to determine concentrations of 206Pb, 207Pb, and 208Pb using a VG Plasma Quad ExCell ICP-MS at The Boston University Department of Earth and Environment. Solutions were 1000 times diluted with nitric acid prior to analysis.

We compared sample ratios of 207Pb/206Pb and 208Pb/206Pb to known ratios for Pb paint and gasoline to determine relative contribution of these legacy sources along a mixing line. Established 207Pb/206Pb and 208Pb/206Pb end-member ratios plotted in Figure 4 were measured in Boston and published by Rabinowitz in a report to the EPA. Rabinowitz (1986) measured isotopic signatures of 13 samples of Pb-based paint and 12 samples of nonresidential soil, which capture the signature of leaded gasoline fallout. Using the average 207Pb/206Pb ratio for paint and gasoline fallout, we estimate percent contribution of Pb paint in each sample using the mass balance equation published by Clark et al. (2006).
3. Results

3.1. Geochemical Characterization of Urban Growing Materials

We found several geochemical differences between unamended soil and compost, which, as the components of garden soils and raised bed fills, constitute end-members of the growing material spectrum examined in this study. Aligning with Fitzstevens et al. (2017), composts have significantly lower Pb concentrations than soils. All samples of growth media containing compost (compost, raised bed fill, and garden soil samples) have significantly lower Pb concentrations than 950 μg/g, the neighborhood average soil Pb in Roxbury (Clark et al., 2006).

Scanning electron microscopy (SEM) backscatter electron (BSE) imaging of unamended soil shows bright grains with cleavage surfaces, indicating high mineral content and the presence of heavier elements such as silicon and iron in the finest grains of unamended soil (Figure S1a). Alternately, compost BSE imaging shows darker, less uniform particles, indicating high organic matter and lighter elements typical in compost (Figure S1b). The compost also has considerably more carbon and a higher pH compared to the soil, factors that may limit Pb solubility (Farrell et al., 2010; Sauvé et al., 1998).

The BSE images highlight the range of grains within the <37 μm grain size fraction for both samples. Fine grains are more mobile in the environment: grains <150 μm particles are transportable by sticking to hands, <100 μm particles are transportable by wind, <10 μm particles are respirable, and <2 μm can stick to skin even after washing (Kissel et al., 1996; de Miguel et al., 1997; Ljung et al., 2006; U.S. Environmental Protection Agency (USEPA), 2015). BSE imaging shows that within the <37 μm fine grain size category,
both soil and compost contain \(<10 \mu m\) and \(<2 \mu m\) grains rich in heavy elements. Future studies quantifying these particulates on a percentage basis will improve understanding of Pb exposure risk associated with these materials.

### 3.2. Pb Bioaccessibility

Total Pb concentration is directly proportional and tightly correlated with bioaccessible Pb for all growing materials. Compost shows the most variation away from this trend (Figure 1).

Compost consistently contains lower bioaccessible Pb and higher percent carbon than other growing materials (Figure 2a). Percent carbon is inversely proportional to and well correlated \((R^2 = 0.6)\) with Pb bioaccessibility, or the percentage of total Pb that is bioaccessible (Figure 2b). This observation shows that percent carbon, in addition to total Pb, plays a role in controlling bioaccessible Pb, which is likely due to increased sorption of aqueous Pb to sites in organic matter (Brown et al., 2003; Sauvé et al., 1998). However, while urban soils contain less carbon than composts, all samples in this study appear to have sufficient organic matter sites for Pb sorption, which is why percent carbon has a relatively muted impact on bioaccessible Pb compared to total Pb.

**Figure 2.** The relationship between carbon content and (a) bioaccessible Pb and (b) Pb bioaccessibility across 2015 samples of growing materials. High carbon samples have lower bioaccessible Pb and slightly lower Pb bioaccessibility \((R^2 = 0.6)\). Compost samples have the highest %C of the growing materials studied. Only bulk samples are included in this analysis.
3.3. Pb Across Grain Size Fractions

Smaller grain size fractions of all materials have higher concentrations of Pb since the small particles’ high surface area-volume ratio maximizes Pb sorption (Cheng et al., 2015; Clark et al., 2008). Soils have the widest range in Pb concentrations across grain sizes (Figure 3a). The Pb concentration in the <37 μm soil grains is four times that of the >250 μm soil grains. Comparatively, the Pb concentration in the <37 μm compost grains is only twice as high as the >250 μm compost grains. Since bioaccessible Pb is directly proportional to total Pb, this trend is the same for bioaccessible Pb.

Consistent with Clark et al., transportable grains (<150 μm) represent a greater fraction of total mass in soil than in compost (Figure 3b) (2008). Further, because of the steeper Pb concentration gradient across soil grain sizes (Figure 3a), the transportable grains contribute more to total Pb in soil than in compost (Figure 3c). Since bioaccessible Pb is directly proportional to total Pb across growing materials, the grain size contributions to bioaccessible Pb (Figure 3d) are comparable to their contributions to total Pb for the soil, raised bed fill, and compost. However, the fine grain fractions’ contributions to bioaccessible Pb do...
increase slightly compared to their contributions to total Pb. This increase can be attributed to slightly higher Pb bioaccessibility in the fine grains compared to larger grains. Pb bioaccessibility in the \(<37 \mu m\) fractions of unamended soil, raised bed fill, and compost is 75%, 64%, and 61%, while Pb bioaccessibility in the \(>250 \mu m\) fractions is 69%, 53%, and 49%, respectively.

### 3.4. Isotopic Signatures of Growing Materials, Bioaccessible Pb, and Grain Sizes

Ratios of $^{207}$Pb/$^{206}$Pb and $^{208}$Pb/$^{206}$Pb in bioaccessible soil and compost Pb are well described by a two end-member mixing line bound by Pb isotope signatures of leaded gasoline fallout in roadside soil and Pb paint measured in Boston, MA, by Rabinowitz (1986), which implicates gasoline and paint as the dominant sources of urban soil Pb in Boston (Burnett et al., 2007; Clark et al., 2006; Rabinowitz, 1986). The soils, garden soils, and raised bed fills in this study fall within the same range of $^{207}$Pb/$^{206}$Pb and $^{208}$Pb/$^{206}$Pb, indicating common inputs of gasoline and paint. Composts, however, are isotopically distinct and plot significantly closer to the Pb gasoline end-member (Figure 4). Calculating the percent paint sourced Pb for each growing material reflects this difference. On average, only 23% of the bioaccessible Pb in compost comes from paint, compared to 43% from paint in raised beds/garden soils and unamended soils (Table S2 in the supporting information).

Isotopic signatures vary between compost types: Boston municipal compost, which is produced close to the city and sourced primarily from yard waste, resembles the isotopic signatures of garden soils, raised beds, and soils. Meanwhile, the commercial compost, which was also produced close to the city but sourced primarily from food waste, falls closer to the Pb gasoline end-member isotopic composition. The sample of suburban yard waste compost has the same isotopic signature as fallout from Pb gasoline (Figure 4).

Clark et al. measured total Pb isotopic signatures of Roxbury garden soils, which serve as a valuable comparison to the samples in this study and are included for reference in Table S2 (Clark et al., 2006). They measured isotopic signatures of total Pb following a total digest of the samples, while in this study we measured the bioaccessible Pb isotopic signature in simulated gastric fluid following the in vitro bioaccessibility assay.
Garden soil samples from both studies have nearly identical isotopic signatures, indicating that bioaccessible Pb and total Pb contain the same Pb source mixture.

Pb isotopic ratios are not associated with grain size. The < 37 μm grain fingerprints fall in the same isotopic range as the bulk samples plotted on Figure 4 and show no trend toward either end-member. This result shows that neither paint nor gasoline particulates are preferentially concentrated in the transportable fractions (Figure 4 and Table S2).

4. Discussion

4.1. Drivers of Pb Bioaccessibility

We found that total and bioaccessible Pb are highly correlated across all growing materials despite the geochemical distinctions between soil and compost. Other studies have also found a linear relationship between total and bioaccessible Pb, though the slope of the regression line varies by study location (Fitzstevens et al., 2017). Fitzstevens et al. suggest that the observed differences in Pb bioaccessibility between cities are due to Pb origin: bioaccessibility of geogenic Pb in UK soils is lower than that of anthropogenic Pb in Boston compost and Los Angeles soils (Appleton et al., 2013; Wu et al., 2010).

Building on the multicity analysis by Fitzstevens et al., we attribute the similarity in Pb bioaccessibility observed in this study to environment and source specific Pb characteristics. The consistent Pb isotopic signatures across Dudley soils, garden soils, and raised beds indicate consistency in Pb source mixture (Duzgoren-Aydin & Weiss, 2008). These growing materials experienced the same localized contamination patterns in Dudley, and this shared history is reflected in the predictable linear trend between total and bioaccessible Pb (Figure 1).

While the linear relationship between total and bioaccessible Pb provides a useful first-order approach for quantifying regional (urban versus rural) Pb bioaccessibility (Fitzstevens et al., 2017), there are other known matrix controls that play a role in modulating Pb solubility. Amending soils with municipal solid waste, iron, and manganese oxides and with phosphate have all been shown to reduce the labile fraction of Pb in soils (Brown et al., 2003; Cao et al., 2002; Hettiarachchi & Pierzynski, 2004; Scheckel et al., 2003). We found Pb bioaccessibility to be 19% lower in composts than in unamended soils (Table 1). We attribute this difference in part to the higher carbon content in compost, which could result in increased complexation of Pb to organic matter and reduce Pb solubility in compost compared to soil. This finding suggests that working to increase organic carbon content in gardens and yards would reduce Pb bioaccessibility.

The lower Pb bioaccessibility in compost is likely also impacted by the quality and type of organic matter present in each material. Additional research is needed to both characterize and differentiate the pools of organic matter in urban growing materials beyond an inventory of percent carbon. In many unamended urban soil settings organic carbon concentrations are lower than in the matrices studied here, and Pb-organic matter sorption dynamics may have a stronger impact on Pb bioaccessibility.

| Material characteristic | Compost mean (SD) | Unamended soil mean (SD) | Significance |
|-------------------------|------------------|--------------------------|-------------|
| Total Pb (μg/g)         | 265 (70)         | 2,450 (1,170)            | Compost reduces concentrations of total and bioaccessible Pb by an order of magnitude (Figure 1). |
| Bioaccessible Pb (μg/g) | 144 (55)         | 1,780 (889)              | Compost reduces Pb solubility in gastric fluid by 19%. |
| %Pb bioaccessibility    | 53% (9)          | 72% (2)                  | Compost contains 14% more carbon, which may increase available sites for Pb to form insoluble complexes and improves cultivation conditions by increasing organic matter content (Figure 2). |
| %C                      | 21% (3)          | 7% (1)                   | Compost contains a smaller fraction of transportable grains, and the Pb concentration in that fraction is smaller than in soil, resulting in 23% less transportable Pb in compost (Figure 3). |
| %Transportable Pb       | 11%              | 34%                      | Note. Only samples for which we measured all categories of material characteristics are included in this table. For discrete samples, soil n = 2 and compost n = 3, though 5 grain size fractions of each material are included in addition to bulk for each material. |
4.2. Fingerprinting Pb Source

The isotopic signature of compost is distinct from unamended soils and garden soils due to significant production differences (Figure 4). Rather than the slow in situ weathering of parent material and organic matter, which characterizes the formation of urban soils, composts are produced on a shorter time scale from organic waste (Fitzstevens et al., 2017). The varying isotopic signatures between compost types reflect differences in their feedstocks. The Pb isotopic signature of city compost is close to those of soil and garden soil because more of the starting materials (e.g., urban yard waste) experienced the same contamination trends as yards and gardens. Other compost samples have lower Pb concentrations that are primarily from gasoline emissions rather than paint since their feedstocks (e.g., food and nonurban yard waste) were not exposed to the urban Pb contamination of the inner city.

Sieved isotope data show that Pb paint and Pb gasoline are present in all grain size fractions (Table S2). This result is expected for the fine particles associated with leaded gasoline fallout, but it is not typical for Pb paint, which usually enters the soil as paint chips from decaying houses and weathers over time. A closer examination of Dudley neighborhood history could explain the presence of the Pb paint isotopic signature in the fine grain size fractions. Throughout the 1970s and 1980s, intense disinvestment, redlining, and discrimination against Dudley’s increased population of people of color—primarily Black people, Cape Verdean immigrants, and Latinos—left residents with a declining local economy and deteriorating infrastructure, among other social and environmental challenges. During these decades, arson was incredibly common as absent property owners in Dudley burned buildings primarily to sever ties with the neighborhood by displacing residents. In 1981, Roxbury’s Highland Park neighborhood had the highest arson rates in the nation; by the late 1980s there were over 850 vacant lots in Dudley, most of which had been vacated through arson (Medoff & Sklar, 1994). This widespread burning deposited large amounts of fine incinerated Pb paint particulates into the soil.

The preliminary work in this study combining SEM analysis and density separation confirms the presence of fine, dense, high Pb particles that we attribute to Dudley’s history of arson. BSE imaging for the $< 37 \mu m$ unamended soil shows extremely fine ($< 10 \mu m$) angular grains composed of high atomic mass elements. Density separation shows that the fine, mineral-rich grains of soil and raised bed fill were highly concentrated with Pb: by our estimate, they contain more than an order of magnitude higher Pb than the carbon-rich floating fraction (Figure S2). We propose that these particles are likely the remnants of incinerated Pb paint, and their prevalence in the $< 37 \mu m$ fraction heightens the known health and recontamination risks associated with fine-grained urban soil dust.

We found that bioaccessible Pb has the same isotopic signature as total Pb, indicating that in Dudley, soil Pb from paint and gasoline are similarly soluble in gastric fluid (Table S2). These observations may be attributable to Dudley’s arson history, since the Pb in fine particles of incinerated paint is potentially more bioaccessible than larger Pb paint chips. In cities without a history of arson it is possible that Pb bioaccessibility would be different for paint and gasoline sourced Pb, which would result in different isotopic signatures between total and bioaccessible Pb.

4.3. Benefits of Compost Use in Urban Agriculture

Previous studies have shown that compost dilutes total soil Pb concentrations (Attanayake et al., 2015; Clark et al., 2008; Clarke et al., 2015; Fitzstevens et al., 2017). Since total Pb is directly proportional to bioaccessible Pb and compost binds Pb more effectively than soil, compost application also reduces urban gardeners’ exposure to bioaccessible Pb through dilution and limiting Pb solubility (Table 1).

The grain size analysis in this study shows that compost lowers the prevalence of fine, transportable particles that Zahran et al. found to be the primary Pb exposure pathway in the urban environment (Zahran et al., 2013). Compost has a high moisture holding capacity that can limit particle resuspension into the air (Farrell et al., 2010; Gould, 2015). Taken together, these qualities considerably limit the transport of bioaccessible Pb in the urban environment and therefore urban gardener Pb exposure.

Compost use is easily integrated into the practice of urban gardening because its high organic matter content improves the health of depleted urban soils. Compost can be produced at the regional scale by redirecting organic waste from landfills to separate processing facilities, a common practice in most European cities. Improved city-level organic waste management would make compost available and affordable for urban
communities while reducing greenhouse gas emissions associated with waste disposed of in landfills (Brown et al., 2016; Fitzstevens et al., 2017; Jones & Healey, 2010).

4.4. Recontamination and the Need for Neighborhood-Scale Remediation

Recontamination of remediated areas by wind transportable particles is still a major challenge in communities with high soil Pb contamination (Clark et al., 2008; Zahran et al., 2013). Fine particles are not only high in Pb and transportable by wind but also have higher Pb bioaccessibility compared to the larger grained fractions (Figure 3). This finding helps explain the seasonality in children’s BLLs observed by Laidlaw and Filippelli and amplifies the risk associated with these particles (Laidlaw & Filippelli, 2008; Zahran et al., 2013).

To mitigate the recontamination risk, gardeners must annually reapply compost to their raised beds and plots, which can be prohibitively costly and time-intensive for low-income residents. Capping contaminated soil with clean fill at the neighborhood scale has been shown to lower BLLs and prevent soil recontamination, though these plans are often limited by cost and material availability (Filippelli et al., 2015; Hynes et al., 2001; Laidlaw et al., 2017; Mielke et al., 2016).

Municipal compost, clean sediment, or a mix of these materials have been proposed as local, affordable materials that cities can use for regional remediation (Egendorf et al., 2015; Fitzstevens et al., 2017; Mielke et al., 2006; Mielke, Laidlaw, & Gonzales, 2011). These plans require a monetary investment from the city, but their implementation costs pale in comparison to the social and economic costs of delayed remediation. Costs associated with healthcare, criminal justice, and human capital loss due to Pb poisoning have been estimated to exceed 10 times the cost of cleaning up Pb contaminated neighborhoods (Drum, 2013; Mielke & Zahran, 2012; Nevin, 2007; Nevin et al., 2008; Zahran et al., 2011).

5. Conclusions

In this study we investigate the factors controlling bioaccessible Pb in Boston growing materials. Total and bioaccessible Pb are linearly related, indicating that total Pb is a primary driver of bioaccessible Pb. Other studies have also found a linear relationship between total and bioaccessible Pb, though the slope of this trend varies across cities, which implicates Pb source as a key driver of bioaccessibility. Pb source and bioaccessibility are consistent across Dudley unamended soils, gardens, and raised beds, which reflect their shared inputs of Pb over time and the impact of neighborhood history on present Pb reservoirs. Further research on the relationship between total Pb, bioaccessible Pb, and Pb source in other cities will continue to explain the role of Pb source in governing Pb bioaccessibility in urban soils and composts.

Compost is a beneficial material for lowering Pb exposure in urban gardens. Since compost contains less bioaccessible Pb than unamended soils, applying it as a soil cap or amendment in gardens dilutes the bioaccessible Pb concentration in the soil. Further, results from this study suggest that carbon-rich materials like compost may bind Pb more effectively than soils, likely due to insoluble Pb complexes formed with organic matter that reduce the fraction of Pb available for uptake in the human body. Fine grains constitute a smaller fraction of compost than soil, which is highly beneficial for Pb exposure reduction since the fine grain size fractions contain elevated concentrations of bioaccessible Pb. These findings provide further geochemical evidence to support using compost as an alternative growing medium in urban agriculture and as an amendment tool for Pb contaminated lots.

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