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Lead in Urban Soils: A Real or Perceived Concern for Urban Agriculture?

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Abstract

Urban agriculture is growing in cities across the United States. It has the potential to provide multiple benefits, including increased food security. Concerns about soil contamination in urban areas can be an impediment to urban agriculture. Lead is the most common contaminant in urban areas. In this paper, direct (soil ingestion via outdoor and indoor exposure) and indirect (consumption of food grown in Pb-contaminated soils) exposure pathways are reviewed. It is highly unlikely that urban agriculture will increase incidences of elevated blood Pb for children in urban areas. This is due to the high likelihood that agriculture will improve soils in urban areas, resulting in reduced bioavailability of soil Pb and reduced fugitive dust. Plant uptake of Pb is also typically very low. The exceptions are low-growing leafy crops where soil-splash particle contamination is more likely and expanded hypocotyl root vegetables (e.g., carrot). However, even with higher bioaccumulation factors, it is not clear that the Pb in root vegetables or any other crops will be absorbed after eating. Studies have shown limited absorption of Pb when ingested with food. Best management practices to assure minimal potential for exposure are also common practices in urban gardens. These include the use of residuals-based composts and soil amendments and attention to keeping soil out of homes. This review suggests that benefits associated with urban agriculture far outweigh any risks posed by elevated soil Pb.

Core Ideas

- Urban agriculture offers a wide range of public health and ecosystem benefits.
- Urban soil contamination is perceived to be a risk to urban agriculture.
- Urban agriculture is not likely to pose any additional health risks associated with soil Pb.
- Best urban farming practices are also best practices to limit any risk associated with soil Pb.

A range in estimates puts the population of food-insecure individuals in the United States at 49 million to 93 million people (Meter, 2015; Tagtow, 2015). This includes 8.3 million children. The latter estimate is based on the number of school children qualifying for free or reduced-price lunch in schools. In contrast, surveys have consistently shown that the prevalence of children in urban areas with elevated blood Pb has been decreasing over time (ATSDR, 2007; Jones et al., 2009; Scott and Nguyen, 2011; Wheeler and Brown, 2013). The most recent survey, conducted between 2007 and 2010, put the number of children with elevated blood Pb level (BLL) (>5 μg dL^{-1}) at 535,000. This latter number represents a decrease of close to 9% from a similar survey conducted between 1999 and 2002 when the level of concern was also higher (>10 μg dL^{-1}). Increased BLLs are also associated with income level, with higher BLLs seen in families with lower incomes (Wheeler and Brown, 2013). This suggests a potential population overlap between food insecurity and elevated BLL in urban areas. Urban agriculture is recognized as a potential way to alleviate food insecurity. However, there are concerns that growing food in urban areas will result in increased exposure to Pb, a ubiquitous contaminant in urban soils. This review summarizes some of the benefits that have been associated with urban agriculture. Information on the extent of Pb contamination in urban soils, uptake of Pb by garden vegetables, absorption of Pb into the blood through soil and plant ingestion, and the relative risks associated with these pathways are presented. Best management practices to limit exposure to Pb-contaminated soils in the context of urban agriculture are summarized. The review is not intended to suggest that elevated blood Pb in children in urban areas is not a concern; it is meant to provide information on whether growing food in urban soils has the potential to increase exposure to and hazards from elevated soil Pb and to provide guidance to minimize the Pb exposure potential.

Benefits Associated with Urban Agriculture

Agriculture in or near urban areas is experiencing a resurgence in the United States. Historically most of the cities in the United States were established in close proximity to fertile soils so that locally grown foodstuffs would be readily available

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Abbreviations: BLL, blood lead level; IEUBK, Integrated Exposure Uptake Biokinetic.

to urban residents. With the advent of rail transport, centers of food production moved outside the urban centers. During World War II, government encouragement of Victory Gardens led to an increase in food production in urban areas. There were a total of 20 million gardens, equivalent to one garden for every seven people. These produced 40% of the fresh produce consumed at the time (Meter, 2015). The current urban agriculture movement, although encouraged by the garden in the White House, has not received the same level of national support (Obama, 2012). Despite that, there has been a dramatic and diverse increase in interest in urban agriculture extending from curbside plots to commercial farms.

The increase in urban food production has been associated with a wide range of benefits. From a public health perspective, urban agriculture has been linked to improved nutrition, higher levels of physical activity, benefits associated with exposure to nature, and increased food security (Davis et al., 2011; Park et al., 2011; Carney et al., 2012, Alaimo et al., 2015, Gonzalez et al., 2015; Smith, 2015). Social benefits, including improved understanding of natural processes and increased social capitol, have also been documented (Okvat and Zautra, 2011; Carney et al., 2012; Pencke, 2015). In addition to direct benefits for people, urban agriculture has the potential to provide a range of other ecosystem services. These include providing habitat, pollination, waste treatment, nutrient recycling, water supply, and climate regulation (Brown, 2015).

In this review, we focus on three of these services in greater depth: waste treatment, nutrient cycling, and climate regulation (Costanza et al., 1997). Urban areas produce a range of residuals that have potential value as soil amendments. These include yard waste and food scraps from the solid waste stream and municipal biosolids produced during centralized wastewater treatment. Each individual generates approximately 20 kg biosolids and 45 kg yard and food scraps per year (King et al., 2011). Food scraps constitute approximately 50% of the total organics in municipal solid waste (36.4 million wet Mg yr^{-1}), of which 4.8% is recovered (USEPA, 2015). A similar volume of yard waste is generated; however, the recovery rate is much higher (57.7%) (USEPA, 2015). The fraction of the 6.9 million dry tons of municipal biosolids that is beneficially used is estimated at 50%, with the remainder landfilled, incinerated, or used as landfill cover material (NEBRA, 2007). Diverting these materials from landfills and treating them to produce soil conditioners suitable for general use results in significant greenhouse gas savings (Table 1). These savings are due to fugitive emissions avoidance, soil carbon sequestration from amendment addition, and fertilizer avoidance (Brown et al., 2008, 2010, 2011; USEPA, 2015). The emissions avoidance for landfill diversion of biosolids has been estimated at close to 3 Mg CO_2e for each dry ton of biosolids beneficially utilized on land (Brown et al., 2010). The newly revised Waste Reduction Model has estimated the diversion credits for food scraps at 0.71 Mg CO_2e per wet ton of food scraps (USEPA, 2015). Each kilogram of N fertilizer produced using the Haber Bosch process requires the equivalent of 4 kg of CO_2 to manufacture (Brown et al., 2010). Although the energy required to produce 1 kg of P fertilizer is less (~2 kg CO_2), concerns over limited P reserves have also highlighted the importance of recycling this nutrient (Amundson et al., 2015; Brown et al., 2010; Matassa et al., 2015)

Research has also shown the benefits to soils from the addition of residuals-derived high-carbon soil amendments (Brown and Cotton, 2011; Brown et al., 2011; McIvor et al., 2012; Cogger et al., 2013a,b). These include reduced bulk density, increased infiltration rate and water-holding capacity, higher net productivity, and long-term increase in phytoavailable nutrients.

In many cases, practitioners of urban agriculture rely on residuals-derived composts and soil amendments to enhance soils and provide sufficient fertility for food production. In limited cases, these amendments are provided directly to community gardens by municipalities (e.g., City of Tacoma, 2015). In other cases, community garden programs also operate composting operations, accepting and/or collecting food scraps from neighbors and commercial sources (e.g., Growing Power, 2015). Urban agriculture offers a significant opportunity for local use of residuals-derived soil amendments. Local demand and use of these materials would provide the ecosystem benefits detailed above.

Lead in Urban Soils

Lead occurs naturally in soils. Uncontaminated surface soils in the United States have about 22 mg kg^{-1} mean background soil Pb concentration (Smith et al., 2013). Background concentration of Pb in urban soil is about 150 mg kg^{-1} or higher, with some soils having total Pb in excess of 1000 mg kg^{-1} (Mielke et al., 1983; Datko-Williams et al., 2014; Minca et al., 2013). Lead is the most common contaminant in urban soil (Attanayake et al., 2014). Lead concentrations in urban soils are often highly variable over short distances (Fig. 1). In some cases, predictive factors, including age of housing, proximity to a roof drip line, and distance from a well-traveled road, can be used to predict soils with a higher likelihood of elevated soil Pb (Schwarz, 2012, 2013).

Lead Exposure Pathways

People can be exposed to soil contaminants via several pathways. These fall into two general categories: direct and indirect exposure. Examples of direct exposure pathways are soil/dust ingestion, inhalation, and dermal absorption. Soil ingestion, as

Table 1. Greenhouse gas benefits of organic waste diversion. Benefits are reported as tons of CO_2 equivalent per dry ton of material.

Source	Material	Landfill diversion	Treatment emissions	Soil C sequestration	Fertilizer offset
		Mg CO_2 equivalent Mg material			
Brown et al., 2010	municipal biosolids	−3		−0.25	−0.11 to −0.32
USEPA Warm Model	food scraps	−2.84	0.05	−0.24	
	yard waste	−0.19	0.07	−0.24	
Brown et al., 2011	municipal biosolids			−0.04 to −1.6	
	compost			−0.22 to-1.98	

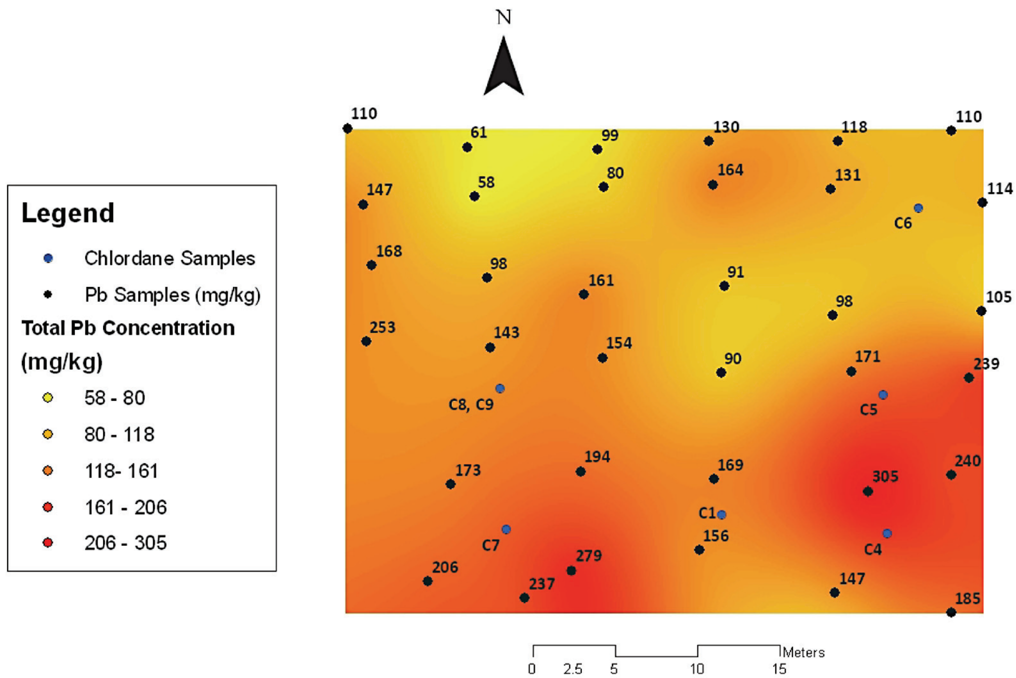

Fig. 1. Concentration of soil Pb in an urban lot in Kansas City, MO. Concentrations were measured using a hand-held X-ray fluorescence analyzer on surface soil samples.

dust within a home or outdoors, is considered to be the main exposure pathway for soil Pb (Lanphear and Roghmann, 1997; Lanphear et al., 2003; Hettiarachchi and Pierzynski, 2004; Scheckel et al., 2013; Henry et al., 2015). Indoor dust sources are much more closely related to elevated BLL than are exterior soil Pb levels (Lanphear et al., 1998). The main indirect exposure pathway of concern is the transfer of soil contaminants to humans via consumption of food crops grown in contaminated sites. There is little evidence that urban agriculture produces Pb-rich respirable particle size dusts, and dermal uptake of Pb from soil is nil.

For direct and indirect exposure pathways, the hazards associated with elevated soil Pb depend on multiple factors. The relationship between total soil Pb and the portion that can be absorbed varies based on Pb mineral form, soil properties, and exposure pathway (Ryan et al., 2004). Chronic Pb toxicity, the concern for urban children, involves multiple exposures over time.

Direct Exposure to Lead

Elevated Pb in urban soils already provides a basis for human exposure (Fig. 2). For urban agriculture to increase the potential for Pb exposure, the act of growing and/or consuming food grown in urban soils has to result in added exposure to bioavailable Pb. In addition, the benefits associated with urban agriculture from a nutritional health and development perspective must be less than the additional hazards.

The prevalence of elevated blood Pb in children is higher in urban areas than in suburban or rural communities (Laidlaw and Filippelli, 2008; Stewart et al., 2014). In older urban areas, legacy contamination of soils by leaded paint and gasoline as well as indoor leaded paint may contribute to exposure. Soil contamination can be a concern through direct contact with soils and associated hand-to-mouth play, through ingestion of Pb-contaminated foods grown in the soil, or through dust that enters homes (Fig. 2). Studies have attempted to isolate the importance of individual factors to determine the most cost-effective remedial options. For example, in a three-city study, soil replacement significantly reduced children's blood Pb levels only in one of the cities where soil Pb was generally about 2000 mg kg^{-1} (Aschengrau et al., 1994). Reductions in blood Pb of 2.25 to 2.7 $\mu g\ dL^{-1}$ were observed overall, with the greatest reductions seen for children whose beginning blood Pb measures were 15 to 22 $\mu g\ dL^{-1}$. Interior Pb sources, predominantly from fine particles of paint dust, contribute more strongly to elevated BLL than exterior soil sources.

In most of these cases, water, paint, and indoor dust were also sources of Pb contamination (Aschengrau et al., 1994). Aerial suspension of contaminated soils has been associated with elevated blood Pb in children with the highest blood Pb observed during summer months when dust is highest, but Pb-rich airborne dust does contribute to house dust Pb accumulation (Laidlaw and Filippelli, 2008). This confirms work that had identified Pb-contaminated household dust loadings as the primary source of Pb exposure for children in urban areas (Laidlaw and Taylor, 2011; Lanphear and Roghmann, 1997; Lanphear et al., 1998).

A follow-up study to Aschengrau et al. (1994) looked at the cost:benefit ratio of different interventions for blood Pb abatement and found soil removal to be extremely costly with only moderate demonstrated benefits (Glotzer et al., 1997). Remediation of only select parcels within an urban area is unlikely to eliminate all sources of contaminated dust. This may explain the moderate benefits associated with localized soil removal and replacement. Some authors consider factors that could be associated with participation in urban agriculture to determine if there is a relationship to increased soil Pb. For example, Aschengrau et al. (1994) included "eats food outdoors" and the "number of

Fig. 2. Risk pathways for Pb in urban soils. Pathways for all urban areas are shown. The potential impact of urban agriculture including use of soil amendments is also modeled. Photos by Kate Kurtz and Don Comstock.

hours played in the yard per week" as part of their survey. Neither was found to be a significant predictor of blood Pb.

A recent study examined the relationship between total and bioaccessible soil Pb and elevated blood Pb for children in Toledo, OH (Stewart et al., 2014). Of the 81 soils sampled, 8.6% had total Pb equal to or greater than the USEPA level of concern (400 mg kg^{-1}). The authors then used the Integrated Exposure Uptake Biokinetic (IEUBK) model's predicted BLLs in combination with expert knowledge and an index model including weighted linear combination to produce a more refined and potentially accurate model of exposure (USEPA, 1994). The IEUBK model has traditionally been used to predict Pb exposure to children from elevated soil Pb. With this refined approach, the authors concluded that 28.4% of the sites were predicted to have elevated BLLs, far in excess of that predicted by total soil Pb or the IEUBK models alone. Although blood Pb was not measured as part of the study, the authors note that 16.6% of children tested in Toledo had blood Pb above 5 μg dL^{-1}. A range of other factors were also modeled in an attempt to predict the potential for elevated blood Pb. Of the factors found to be related, the most significant—age of housing, road density, and percent impervious surfaces—can be linked to increased Pb-rich dust within a home (Aschengrau et al., 1994; Lanphear and Roghmann, 1997; Lanphear et al., 1998; Laidlaw and Filippelli, 2008). Also significant, but of less importance, were home value, household income, and soil type. Two of these—home value and household income—can also be related to food insecurity

(Olson, 1999). Food insecurity is related to negative academic performance, social skills, and psychological well-being, consequences that are associated with elevated blood Pb (Alaimo et al., 2001; DTSC, 2004). Whether engaging in urban agriculture would increase the potential for exposure depends on children's time spent in the garden, accessibility to soil within the garden, and whether time in the garden results in increased household Pb-contaminated dust.

Indirect Exposure to Lead–Plant Uptake

Although certain contaminants (e.g., Cd) have a high potential to be absorbed by plants (Chaney, 2015), plant absorption of Pb is relatively low, often showing no significant relationship to enriched soil Pb (Table 2). Despite this, concerns about the perceived human health risk of gardening on urban soils due to possible or real crop contamination continue to hinder the revitalization of underutilized urban lots by deterring potential gardeners. Research has repeatedly shown that concentrations of Pb in vegetables harvested at urban sites are low (Table 2).

Lead is generally highly insoluble in soils and is not chemically similar to other elements that are required plant nutrients. However, in the urban gardening context, this exposure pathway is often considered to be a potential concern. Phytoavailability of trace elements like Pb depends on several factors, such as solubility/speciation of the trace elements in soil, plant nutrient status in soil (especially phosphate) (Sterrett et al., 1996), characteristics/physiology of plant species/cultivars (Huang and Cunningham, 1996; Price and Hettiarachchi, 2012), and heat/moisture stress (Merry et al., 1986). Speciation of Pb in urban soils depends on sources of soil contamination and other site-specific soil characteristics and the reaction of Pb entering soil to forms with low phyto- and bio-availability. Recent studies have shown that Pb in contaminated urban garden soils (concentrations ranging from <300 to 2586 mg kg^{-1} Pb) mainly existed in the carbonate fraction complexed with organic matter or adsorbed to iron oxides (Attanayake et al., 2014; Attanayake et al., 2015; Cheng et al., 2011). Lead entering soils from Pb-based paints or gasoline will generally have high bioavailability. Adding organic matter amendments and phosphorus fertilizers to the soil over time can

Table 2. Vegetable uptake of Pb from peer-reviewed literature. Some studies report specific paired values for soil Pb and plant Pb; others report ranges in measured values.

Source	Crop	Soil	Total soil Pb	Plant Pb concentration†	Bioconcentration factor
			mg kg^{-1}		
Attanayake et al., 2015‡	collard greens	Indianapolis urban garden, sandy loam soils, control, and compost-amended soils	261–461	0.5–2.5	0.0014–0.0072
	tomato		231–507	0.4–2.3	0.0009–0.0076
	carrot		210–1402	1.1–5.2	0.012–0.0091
Attanayake et al., 2014§	swiss chard	Kansas City urban garden, silt loam soil, control and compost amended	81–348	0.29–0.71	0.002–0.005,
	tomato		97–189	0.06–0.09	0.004–0.008
	carrot		109–388	1.37–1.41	0.011–0.012
Defoe et al., 2014¶	lettuce	Seattle urban garden, sandy loam soil, control, and compost added	535–1605	3.95–13.92	0.005–0.01
	tomato		480–1510	0.86–2.3	0.01–0.002
	carrot		648–1528	28.6–38.4	0.027–0.051
Defoe et al., 2014#	lettuce	Tacoma urban garden, loamy sand, control and compost added	105–312	0.37–2.9	0.02–0.02
	tomato		88–262	0.56–1.2	0.03–0.012
	carrot		115–271	12–18	0.104–0.141
McBride et al., 2014	fruit	urban gardens in New York City and Buffalo, NY	17.5–3580	0.018 mean (range, 0.0023–0.21), 46% nondetects	
	leafy			0.099 mean (range, 0.01–0.59), 7% nondetects	
	herb			0.44 mean (0.085–2.1 range), 0% nondetects	
	root			0.2 mean (0.014–1.9 range), 9% nondetects	
Intawongse and Dean, 2008	lettuce	compost soil spiked with salts	control, medium, and high	0.49, 0.44, 0.12††	
	spinach			0.74, 0.44, 0.68	
	carrot			0.06, 0.06, 0.20	
	radish			0.12, 0.47, 0.37	
Finster et al., 2004	bean, bell pepper, corn, cucumber, squash, tomato, zucchini	urban gardens in Chicago	169–3470	plant Pb all below detection limit of 10 mg kg^{-1}	
Sterrett et al., 1996	lettuce	urban soil Baltimore	12–5210	2.22–21.7	0.19–0.004

† Plant Pb is reported on a dry weight basis.

‡ Laboratory-cleaned samples; mean values of 2011 and 2012 data.

§ Laboratory -cleaned samples; mean values of 2010 data

¶ Laboratory -cleaned samples; mean values of 2011 and 2012 data.

Laboratory -cleaned samples; mean values of 2011 and 2012 data.

†† For control, medium, and high Pb, respectively.

reduce total and bioavailable Pb. For example, a highly contaminated garden soil in a mining village situated in Derbyshire, UK (71,400 mg kg^{-1} Pb) was found to contain substantial amounts of Pb phosphate and pyromorphite [$Pb_5(PO_4)_3Cl$], both with relatively very low solubility (Cotter-Howells and Thornton, 1991). Much of the focus on reducing the hazards associated with direct ingestion of Pb-contaminated soils has focused on altering the mineral form of Pb to pyromorphite (Ma et al., 1995; Cotter-Howells and Caporn, 1996; Ryan et al., 2004; Scheckel et al., 2013). The addition of P to soils has also shown reductions in plant Pb uptake in Pb-contaminated soils (Laperche et al., 1997; Hettiarachchi and Pierzynski, 2004; Ryan et al., 2004; Scheckel and Ryan, 2004; Attanayake et al., 2014). Low solubility of Pb in most soils limits movement to plant roots; however, precipitation of Pb with P in plant roots can also limit translocation from roots to tops (Laperche et al., 1997; Cotter-Howells et al., 1999).

Availability of adequate amounts of nutrients in the soil improves plant growth and leads to higher biomass production. Higher biomass yield dilutes the absorbed potentially toxic elements in the plants (Ekvall and Greger, 2003; Attanayake et al., 2014). It has been found that increasing plant nutrients (N, P, and K) in Pb-contaminated urban soil reduced Pb concentrations in lettuce (Sterrett et al., 1996). Similarly, low concentration of Pb, Cd, and Hg were found in water spinach grown in high-nutrient medium compared with that of water spinach grown in low-nutrient medium (Gothberg et al., 2004).

In general, plant concentrations of Pb are very low, even when grown on highly contaminated sites. There are two exceptions to this generalization. These include a select subset of plants and the potential for soil to adhere to the edible portion of plant tissue. Some plant species and cultivars show higher potential to absorb and accumulate potentially toxic elements from the soil (Davies and White, 1981; Alexander et al., 2006; Liu et al., 2010; Price and Hettiarachchi, 2012). The expanded hypocotyl root vegetables (carrot, radish, redbeet, turnip, etc.) accumulate Pb in their core. The core in these plants is actually xylem tissue through which Pb has passed and has partially become trapped (see Codling et al., 2015). Chaney et al. (2010) examined localization of Pb in carrot xylem using extended X-ray absorption fine structure and showed that nearly all the Pb in peeled carrots was in the core/xylem tissue. In contrast, potato is phloem fed and does not have xylem running thru the potato, so potatoes remain very low in Pb even when grown in Pb-rich soils. Of the range of crops studied, root crops such as carrots had higher Pb concentrations in edible tissue than leafy or fruit crops (Finster et al., 2004; Attanayake et al., 2014; Defoe et al., 2014; Codling et al., 2015). Lead concentrations in the edible portion of carrots, even when elevated in comparison to other plant species, do not increase linearly with increases in soil Pb (Fig. 3). A review of the literature showed that carrot Pb concentrations ranged from >1 to 61 mg kg^{-1}, with corresponding soil Pb concentrations of >0.01 to 2117 mg kg^{-1} (Fig. 3). This would be a concern only if the garden-harvested roots comprise a significant portion of a diet and if the Pb in the crops is absorbed in the stomach. Previous work suggests that this is unlikely to be a significant source of Pb for the vast majority of individuals (e.g., James et al., 1985).

Vegetables grown in urban soils can also increase exposure to soil Pb via contaminated dust (fine soil particles) deposited on

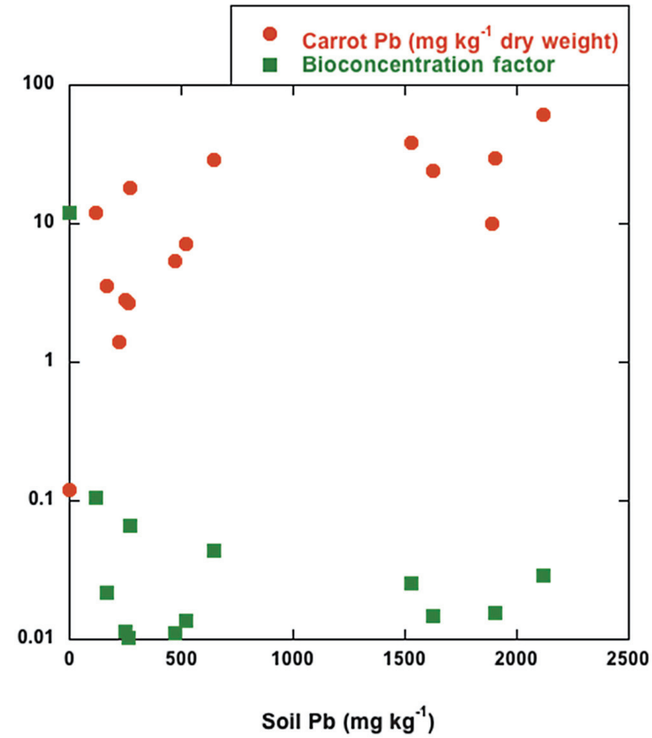

Fig. 3. Carrot Pb concentrations (mg kg^{-1} dry weight) and bioconcentration factors in response to total soil Pb (mg kg^{-1}). Data used for this table are from Codling et al. (2015), Defoe et al. (2014), Attanayake et al. (2014, 2015), Finster et al. (2004), and Hettiarachchi (unpublished data, 2015).

and imbedded in the cuticular surfaces of the produce. A recent study showed high correlation with Pb in leaf tissue and elevated Al for plants grown in a Pb-contaminated soil as evidence of soil contamination (McBride et al., 2013). For example, low-growing leafy vegetables and herbs can become contaminated by adhering soil particles that become bound in the leaf waxy cuticle (Cary et al., 1994). In fact, research has shown that inadequate or lack of washing of plant materials can lead to overestimation of Pb accumulation in crops (Attanayake et al., 2014; Defoe et al., 2014; McBride et al., 2013). This suggests that previous reports of Pb uptake by garden vegetables may be the result of soil contamination of samples, which can be estimated by analysis of soil elements that are weakly absorbed by plants (i.e., Al, Ti, or Zr or Y) (e.g., McBride et al., 2013). Washing crops before eating reduces the potential for transferring Pb in soil to humans (Attanayake et al., 2014; Defoe et al., 2014). Traditional rinsing with water washes off most soil particles.

Lead in the Diet

The amount of Pb in diets has been monitored by the FDA over time (Adams, 1991; Bolger et al., 1991). After removal of Pb from gasoline by about 1980 and removal of Pb from food cans by about 1990, the FDA estimated that 16% of the total Pb in a 2 yr old's diet comes from food, with 75% from dust and 1% from soil. For women of child-bearing age, this percentage shifts to 43% from food, 31% from dust, and an insignificant quantity from soil. The FDA collected and tested a market basket of foodstuffs from groceries across the United States at different times of the year annually for several decades and noted a marked decrease in total dietary Pb as a result of the elimination of Pb solder in cans. Total dietary Pb for teenagers decreased from 38 μg d^{-1} in 1979 to near the detection limit (3.2 μg d^{-1}) in 1990 with the change in US canning technologies (Bolger et al., 1991). Further efforts to decrease intake of Pb have included elimination of Pb in glazes, nutritional supplements, and leaded crystal (Bolger et al., 1996). More recent studies looked at plant uptake of Pb from different contaminated soils to quantify bioconcentration factors from soils to washed foods (Attanayake et al., 2014; Augustsson et al., 2015; Defoe et al., 2014; Intawongse and Dean, 2006). Low bioconcentration factors were seen for Pb, indicating that growing foodstuffs on high-Pb soils did not change exposure potential (Table 2).

In addition to total Pb consumed, it is important to consider the quantity of Pb that is absorbed into the blood. The bioavailable fraction of total soil Pb has been measured using an extraction method that mimics absorption in an empty stomach (Henry et al., 2015). This acidic environment is meant to maximize dissolution and subsequent absorption of Pb. When Pb is ingested along with foods, the pH in the stomach is increased, as is the solid:solution ratio. Intawongse and Dean (2006, 2008) tested the availability of metals in vegetables grown in Pb salt–spiked potting composts using a version of this extract by adding 1 g of vegetables to 15 mL of the gastric solution used in the extract. Although lower than the standard extract ratio of 1:100 soil to solution, this vegetable:solution ratio is not characteristic of a full stomach. Despite this, Pb concentrations in plant tissue did not reflect increases in soil concentrations. Although a portion of the Pb in the plant tissue (~50%) did come into solution during the extraction process, these results are likely not reflective of Pb adsorption with food at realistic vegetable:gastric solution ratios. Studies have shown absorption of 40 to 80% of soluble Pb isotope when ingested by adults with distilled water during fasting (Heard et al., 1983; James et al., 1985). Adding other nutrients to the test solution with Pb inhibited uptake of Pb (Heard and Chamberlain, 1982; Heard et al., 1983). Lead uptake further decreased to 2 to 7% when Pb was ingested with light breakfast meals (Heard et al., 1983; James et al., 1985). Phytate in foods will also reduce the amount of Pb that is absorbed when eating foodstuffs with measurable concentrations of Pb (James et al., 1985). The USEPA estimated that a 0.16 μg d^{-1} increase in blood Pb per μg Pb ingested would be observed for children (Carrington and Bolger, 1992; USEPA, 1986). This absorption efficiency was estimated to decrease to 0.04 μg dL^{-1} per μg Pb ingested for adults. These results (low plant uptake in combination with low solubility when eaten as part of foods due to the presence of phytate, Ca, phosphate, and fiber in crops) suggest that eating plants grown in urban soils, including soils with elevated Pb, would not provide a significant risk pathway.

Best Management Practices to Reduce Potential for Soil Lead Transfer to Humans in Urban Gardens

The use of compost is one of the most common practices used by gardeners who grow food in urban soils. Research has shown that the immediate beneficial effect of amending soils with compost is to dilute overall soil contaminant concentrations significantly (Attanayake et al., 2014; Attanayake et al., 2015; Defoe et al., 2014). Concerns have been raised regarding the long-term effectiveness of compost amendments because composts may decompose over time (Henry et al., 2015). However, most urban gardeners add compost to soils annually; over time, these additions help to significantly lower Pb concentration and phyto- and bio-availability in soils. Compost addition also increases plant biomass production, helping to further reduce food-chain transfer of contaminants via dilution of Pb concentration in plants. This is mainly through improving soil fertility parameters such as plant nutrient concentrations in soil, soil structure, and water-holding capacity. Compost amendments may also help to reduce bioaccessible Pb (Table 3). Here bioaccessibility refers to the portion of total soil Pb that may be absorbed when soil is accidently ingested. The use of compost or other organic amendments on bioaccessibility of Pb in soils seems to have mixed effects (Sauvé et al., 1998; Vega et al., 2009; Brown et al., 2003; Brown et al., 2012; Fleming et al., 2013; Attanayake et al., 2014; Defoe et al., 2014; Attanayake et al., 2015). Differential responses to organic amendments are not surprising because speciation and bioavailability of Pb in soils amended with organic matter depends on the composition and maturity of the organic matter and site-specific soil chemistry. Moreover, reductions in bioaccessibility for some soils are unclear or insignificant (Table 3), most likely because of the inherent low soil Pb bioaccessibility in tested urban soils (Attanayake et al., 2014; Attanayake et al., 2015). In addition, a high concentration of available P in organic amendments can induce formation of Pb phosphate with low solubility in the amended soils or during the in vitro bioaccessible Pb extraction procedure, reducing the potential for transfer of Pb from contaminated urban soils to humans (Zia et al., 2011; Attanayake et al., 2014; Juhasz et al., 2014).

Besides amending soils to reduce soil Pb phyto- and bioavailability, one should examine the potential garden area for sources of Pb contamination. Soil near painted building surfaces of older homes (built before 1980) are often more highly contaminated than soils in the middle of a yard. Further, if an exterior Pb-painted wall is adjacent to gardens or raised beds, falling paint dust can recontaminate soils in a few years (Clark et al., 2008). Similarly, soils near heavily trafficked roadways showed localized Pb contamination.

Urban agriculture offers a wide range of environmental and public health benefits. Based on a survey of the available literature, it is highly likely that increased exposure to soil Pb and associated health effects to children as a result of urban agriculture are minimal. Well-tended soils result in less fugitive dust and higher plant cover than neglected soils. The use of composts dilutes total soil Pb and may decrease bioaccessible Pb. Plant uptake of Pb is minimal, with the exception of certain root crops. Moreover, absorption of plant Pb is likely limited by competing nutrients and increased stomach pH, and growing the few crops that require additional attention (low-growing leafy and expanded hypocotyl root vegetables) in raised beds with clean soil/compost can minimize that concern.

If Pb is still a concern, there are many options to eliminate risk. A list of best management practices is shown in Table 4. Selection of suitable crop types or cultivars could also be used to minimize soil–plant–human transfer of soil Pb. Research has clearly shown that Pb uptake in root crops > leafy crops > fruiting, legume, and grain crops. Other preventive measures to ensure safe gardening include actions to minimize the direct ingestion risk of contaminated soils. Main precautions are washing crops thoroughly before consumption to remove adhering soil particles, washing hands thoroughly after gardening, using a mulch to cover bare soil, keeping soil moist during dry and windy conditions to prevent dust generation, making sure no soil gets tracked into the house on shoes and/or clothing, and supervising children in the garden. Although there is no precisely defined limit for total soil Pb for urban agriculture, research indicates that use of best management practices can allow for urban growers to realize the benefits of food cultivation with minimal risk.

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Table 3. Observed reductions in bioaccessible Pb with the use of compost or biosolids soil amendments. Total bioaccessible Pb is the total soil metal × the percent bioaccessible.

Study	Soil	Treatment	Total soil Pb	Bioaccessible Pb†	Total bioaccessible Pb
			mg kg^{-1}	%	mg kg^{-1}
Brown et al., 2003	Baltimore garden soil	control	2135	78	1670
		biosolids compost (10%)	1768	71	1250
		high-Fe biosolids compost (10%)	2576	34	884
Brown et al., 2004	smelter-contaminated, Missouri	control	2892	46	1340
		high-Fe + lime biosolids compost (10%)	2617	18	470
Brown et al., 2007	smelter-contaminated soil, Oklahoma	control	623	84	523
		biosolids compost	623	49	305
Farfel et al., 2005	Baltimore garden				
	near home	control	2534	65	1655
		high-Fe biosolids compost (10%)	1064	56	595
	midyard	control	913	68	620
		high-Fe biosolids compost (10%)	1106	69	764
Brown et al., 2012‡	Pb-arsenate–contaminated orchard soil, Washington	control	1705	48	818
		biosolids compost	1201	48	576
		high-Fe biosolids compost		35	
Fleming et al., 2013§	Pb-arsenate–contaminated orchard soil, New York	control	66–892	1.99–4.73	
		yard waste compost	22–667	0.77–2.23	
Attanayake et al., 2014	Pb-contaminated urban garden soils, Kansas City	nonamended	252¶	5.6¶	14.1¶
		leafy compost amended	190¶	3.9¶	7.4¶
		nonamended	251#	5.1#	12.8#
		leafy compost amended	218#	3.9#	8.5#
Defoe et al., 2014	Pb-contaminated urban garden soils, Tacoma, WA	nonamended	157–213	11–15	23.5
		TAGRO + dolomite amended in 2010	191–248	8.5–11	21.1
		TAGRO + dolomite repeated amendment in 2011	180–210	6–7	12.6
Defoe et al., 2014	Pb-contaminated urban garden soils, Seattle, WA	nonamended;	1190	27.5	324
		compost + dolomite amended in 2011	817	20.2	163
		compost + dolomite repeated amendment in 2012	679	14.0	117

† Bioaccessible Pb was measured using different versions of an extract to simulate availability under fasting gastric conditions with solution pH ranging from 2 to 2.5. Fraction used for extraction: <2 or <0.25 mm.

‡ Sample taken 7 to 664 d after compost addition.

§ Used a Modified Morgan extraction.

¶ Sample taken 16 d after compost addition.

Sample taken 105 d after compost addition.

Table 4. Suggested best management practices to limit any risk posed by soil Pb in urban agriculture. These recommendations are meant to provide common sense guidance.

When to follow			
Always			
	Wash fruits and vegetables before eating.		
	Garden away from the drip line of the roof in older homes (pre-1980).		
	Use regulated composts or biosolids based soil products to improve soil tilth and productivity.		
	Thoroughly wash hands after working in the soil.		
	Take off or rinse shoes used to garden to avoid tracking dirt into the home.		
If a child under 5 yr old regularly eats fruits and vegetables grown in your garden			
	Most conservative		
	Garden in raised beds filled with tested soils.		
		Composts or soil products made using municipal biosolids will be tested for total Pb, As, and other contaminants.	
		Composts made from food and yard scraps meeting the US Compost Council STA standards will be tested for Pb, As, and other contaminants.	
		Clean fill, commercial topsoils, and other composts are not required to be tested. Use these materials only after they have been tested by a soil testing laboratory for total Pb.	
	Less conservative		
	If you grow directly in the soil		
		Amend soil with composts as directed above.	
		Or add high rates of P fertilizers	
		Avoid feeding children carrots from the garden on a regular basis.	
		Fruit crops where there is little to no potential for soil splash are not a concern.	
		Test your soil for total and/or bioaccessible Pb before gardening.	
			The Mehlich III soil extract is a commonly used test for soil fertility. Lead concentrations in the Mehlich III test are often 50% lower than measures of total Pb.
			If the total soil Pb is >900, you may want to avoid feeding children produce with a high potential for soil contamination (greens and tubers are two examples).
	Least conservative		
		Amend soil with composts as directed above.	
		Or add high rates of P fertilizers	
If a child under 5 yr accompanies you to the garden			
Always	Wash his or her hands after they leave the garden and/or before eating.		
	Most conservative		
	Garden in raised beds as specified above.		
	Make sure soil in between beds has a thick mulch cover or a dense plant cover.		
	Less conservative		
	Have soil that the child has access to tested for total and/or available Pb. If the total soil Pb is >400 you may want to limit trips to the garden with him/her to a few times per month.		
	Bring your child to the garden with a full stomach.		
If only older children and/or adults participate in gardening and eat foodstuffs from the garden			
	There is little indication that growing or eating food from urban gardens will result in high Pb exposure.		
	If Pb exposure is still a concern, follow the practices specified above to the degree that you are comfortable with.		

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