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Field Evaluations on Soil Plant Transfer of Lead from an Urban Garden Soil

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Abstract

Lead (Pb) is one of the most common contaminants in urban soils. Gardening in contaminated soils can result in Pb transfer from soil to humans through vegetable consumption and unintentional direct soil ingestion. A field experiment was conducted in 2009 and 2010 in a community urban garden with soil total Pb concentration of 60 to 300 mg kg^{-1}. The objectives of this study were to evaluate soil-plant transfer of Pb, the effects of incorporation of a leaf compost as a means of reducing Pb concentrations in vegetables and the bioaccessibility of soil Pb, and the effects of vegetable cleaning techniques on the Pb concentrations in the edible portions of vegetables. The amount of compost added was 28 kg m^{-2}. The tested plants were Swiss chard, tomato, sweet potato, and carrots. The vegetable cleaning techniques were kitchen cleaning, laboratory cleaning, and peeling. Compost addition diluted soil total Pb concentration by 29–52%. Lead concentrations of the edible portions of vegetables, except carrot, were below the maximum allowable limits of Pb established by FAO and WHO. Swiss chard and tomatoes subjected to kitchen cleaning had higher Pb concentrations than laboratory-cleaned plants. Cleaning methods did not affect Pb concentrations in carrots. Bioaccessible Pb in the compost-added soils was 20–30% less than that of the no-compost soils; compost addition reduced the potential of transferring soil Pb to humans via vegetable consumption and direct soil ingestion. Thorough cleaning of vegetables further reduced the potential of transferring soil Pb to humans.

Keywords: urban soil, lead, soil-plant transfer, bioaccessibility

Introduction

Use of vacant lands in urban and suburban areas for vegetable production is growing. About 15% of the world’s food is produced in urban areas (USDA, 2012). Urban agriculture has the ability to provide a substantial proportion of local food demand, because most of the produce is used for household consumption and the rest is sold in local markets. This helps alleviate the issue of food deserts in urban areas, at least seasonally. Many of these urban gardens are subdivided into small plots that are managed by individuals, families, or small groups. Community gardening improves social cohesion and the awareness of ecosystem (Hynes and Genevieve, 2004).

Urban lands often were previously used residential, industrial, and commercial activities. Using urban lands for food production is challenging, because the quality of urban soil is poor for growing plants; and urban soils generally have a high bulk density, low nutrient and organic C content, and low biological activity (Jim, 1998). Mielke et al. (1983) reported that urban soils may contain higher concentrations of potentially toxic trace elements based on a study done in metropolitan Baltimore. These trace elements can originate from lead-based paint; burning of fossil fuels, including leaded gasoline (before the 1970s); and lead-arsenate pesticides (Klein, 1972; Carey et al., 1980; Turer et al., 2001; Zhai et al; 2003). The possibility of urban soils containing potentially toxic trace elements is a perceived obstacle to developing urban gardens. Lead is one of the most common potentially toxic trace metals in urban soils. Elevated Pb in the environment can increase blood Pb levels in children (Lanphear and Roghmann, 1997). About 310,000 U.S. children between the ages of 1 and 5 years are believed to have blood Pb levels at or greater than 10 $\mu g\ dL^{-1}$ (ATSDR, 2007), which was the blood Pb level of concern recommended by the United States Center for Disease Control and Prevention (CDC). If the blood Pb concentrations of many children are above the level of concern, community-wide primary lead poisoning prevention activities should be implemented. In 2012, CDC reduced the definition of elevated blood Pb in children from 10 $\mu g\ dL^{-1}$ to 5 $\mu g\ dL^{-1}$based on CDC's Advisory Committee on Childhood Lead Poisoning Prevention recommendations (ACCLPP, 2012).

Soil Pb can transfer to humans through soil ingestion, consumption of Pb-contaminated foods, and inhalation of Pb-containing soil particles. The amount of Pb that can transfer through inhalation is minute compared with the other two pathways (Davies et al., 1990); of those, soil ingestion is the most significant (Lanphear and Roghmann, 1997). Plant absorption and accumulation of soil Pb is lower than other potentially toxic trace elements such as Cd and Se, mainly because of comparatively low concentrations of free Pb (Pb^{+2}) in the soil solution. When Pb is absorbed by plant roots, it can precipitate as Pb-phosphate forms in root cells and in xylem because of high P concentration and moderate pH in the root cells. In P-deficient soils, Pb precipitation in the root cells is limited and Pb is transferred to shoots efficiently. Under such conditions, plants may show high Pb absorption (Foy et al. 1978), so natural translocation limits may be more important than uptake limits from the acidified rhizosphere. Consumption of vegetables grown in Pb-contaminated soils may cause adverse health effects, but very little literature supports this idea. Especially in urban areas, plants may be superficially contaminated by the atmospheric deposition of Pb-containing particulates from contaminated soils or other atmospheric emissions. Combustion of leaded gasoline releases Pb-containing particulates into the atmosphere, and those particulates may deposit on plants that are grown close to major roads. Although leaded gasoline has been banned in many developed countries, it is still used in developing countries. Nabulo et al. (2006) found higher Pb concentrations in vegetables grown along major highways in Kampala City, Uganda; furthermore, they observed a significant difference in Pb concentrations in unwashed and washed leafy vegetables grown in urban gardens (Nabulo et al., 2010). They analyzed Pb concentrations of 15 leafy vegetables in several urban gardens that had Pb concentrations ranging from 9 to 770 mg kg^{-1} near Kampala City, Uganda. Washed leafy vegetables had 35% lower Pb concentration than unwashed vegetables.

Bioavailability means the portion of a substance or element in a soil that is available for absorption into living organisms, such as humans, animals, or plants. Bioavailability of soil Pb cannot be explained solely by the total Pb concentration; rather, it largely depends on speciation of Pb in soil (Davis et al., 1992; Ge et al., 2000) and other site-specific soil chemistry (Hettiarachchi and Pierzynski, 2004). Soil pH, soil organic matter content (Sauve et al., 1998), total Pb concentration, and soluble P concentration (Hettiarachchi et al., 2000) collectively affect soil Pb speciation. Speciation of soil Pb can be altered by changing soil chemical properties through adding amendments to soils. Phosphorous fertilizers, Mn oxides, and organic matter (e.g., compost, straw, and manure) have been tested for their ability to reduce the bioavailability of Pb in soils. Adding P fertilizer increases soil-available P and results in the formation of Pb pyromorphite-like minerals, thereby immobilizing soil Pb (Ma et al., 1995; Hettiarachchi et al., 2000; Brown et al., 2003).

Speciation and bioavailability of Pb in soils amended with organic matter depends on the composition of the organic matter and soil chemistry. High Fe and Mn concentrations in biosolids reduce bioavailability of soil Pb (Brown et al., 2003). Increase of organic matter content and cation exchange capacity of soils as a result of compost application increase Pb sorption capacity of soil (Vega et al., 2009). In contrast, application of leaf compost increased soil Pb solubility at soil pH range of 6.5 to 8 by promoting formation and dissolution of organic-Pb complexes (Sauve et al., 1998). In the above context, soil- and amendment-specific studies are essential to evaluate soil Pb bioavailability.

In addition to the direct effects of organic matter application on speciation of soil Pb, organic matter also provides plant nutrients to soil and improve soil physical properties such as bulk density and water holding capacity (Chaoui et al., 2003; Gallardo-Lara and Nogales, 1987; Khaleel et al., 1981). This improves plant growth and leads to high biomass content. High biomass content itself dilutes any absorbed potentially toxic elements in the plants

(Ekvall and Greger, 2003). Increased plant nutrients (N, P, and K) in Pb-contaminated urban soil have been found to reduce Pb concentration in lettuce (Sterrett et al., 1996). Similarly, low concentrations of Pb, Cd, and Hg were found in water spinach grown in a high-nutrient medium compared with water spinach grown in a low-nutrient medium (Gothberg et al., 2004).

Regardless of the effects of organic matter amendment on Pb bioavailability, the addition of locally available compost is a common practice among community gardeners, because it improves the workability of soil and plant growth; therefore, study of the ability of locally available compost to reduce bioavailability of Pb in urban soils would provide useful and important information to urban gardening communities. Although the acceptable blood Pb concentration level in children continues to decrease due to the subtle health effects of elevated blood Pb concentrations, only a limited number of studies focused on uptake of soil Pb by plants (Sterrett et al., 1996; Cui et al., 2004) and how that uptake transfers Pb to humans, and very little attention has been given to the importance of cleaning of vegetables grown in urban areas as an effective way to minimize soil Pb transfer to humans through vegetable consumption.

We conducted a field experiment in an urban community garden located on a formerly residential brownfield site with soil contaminated by Pb to assess vegetable crop uptake of Pb, effectiveness of compost addition on Pb concentrations in vegetables, and the effects of vegetable-cleaning methods on Pb concentrations. The risk of Pb transfer via direct ingestion of garden soil also was evaluated using *in-vitro* bioaccessibility measurements.

Materials and Methods

A field study was performed in an urban community garden located in the Washington Wheatley neighborhood in Kansas City, Missouri. The garden is 42 m × 37 m, and the site was formerly occupied by four houses. The houses were demolished in the late 1970s. We suspect the source of soil Pb concentration is past use of leaded paint on the houses, although the use of leaded gasoline until 1971 and burning coal for heat also may have contributed. First, the site soils were screened approximately every 3 m using a XL3T Niton handheld x-ray fluorescence (XRF) analyzer (Thermo Scientific, Billerica, MA) to detect the concentrations of potentially toxic trace elements. The initial XRF screening revealed that the site soils had elevated Pb concentrations; however, other potentially toxic trace element concentrations were not elevated. Spatial distribution of total Pb in the site soils was heterogeneous (Figure 1). Concentration of soil Pb ranged from 60 mg kg^{-1} to 300 mg kg^{-1}. Two field test studies were conducted in 2009 and 2010. In 2009, the test plots were located in an area closer to the average urban background concentrations of Pb (77 to 157 mg kg^{-1}) (USEPA, 2013), whereas in 2010, test plots were installed in an area with 186 to 388 mg kg^{-1} of Pb in the soils with the objective of gathering the maximum possible Pb uptake by the vegetables grown in the site soils.

Field study

Soil pH in urban garden soils that have elevated Pb should be maintained at a neutral level to minimize Pb solubility (Sterrett et al., 1996). Because soil pH was neutral (Table 1), this soil did not require pH adjustment or addition of lime. Mehlich-III P was high (Table 1), so no P fertilizer addition was recommended for this site. After excluding lime and P as our treatments, we selected locally available leaf compost (Missouri Organic, Kansas City, MO), which is commonly used by the gardeners in this area, as our field treatment. Some selected chemical properties of the compost are listed in Table 1.

In 2009, the experiment plot area was 2.4 m × 3.7 m, and in 2010 it was 5.2 m × 8.8 m. The plot area was demarcated from the rest of the garden using 20-cm-high plastic plot dividers such that 15 cm of the dividers remained aboveground. Compost was added at 28 kg m^{-2} and mixed with the top 15 cm of soil, representing a compost:soil ratio of approximately 1:3 (v/v). Control plots with no compost were maintained. A leafy vegetable, a fruiting vegetable, and a tuber/root vegetable were grown to assess Pb uptake of vegetables in the presence and absence of compost treatment. In 2009, Swiss chard (*Beta vulgaris;* variety: Gator Perpetual Spinach), tomatoes (*Solanum lycopersicum;* variety: Biltmore) and sweet potatoes (*Ipomoea batata;* variety: Beauregard) were grown. In 2010, Swiss chard (variety: Burpee's Rhubarb Chard), tomatoes (variety: San Marzano) and carrots (*Daucus carota*; variety: Danvers #126) were grown. Three blocks were prepared for each vegetable in 2009. The number of blocks was increased to four in 2010. Planting/sowing was done 16 days after incorporation of compost in both years. The recommended variety-specific spacing was maintained for all crops. At the end of the growing season, the edible portions of the plants were harvested as each plant type reached maturity. Representative soil samples were collected prior to adding compost, at planting, and at harvesting from each plot.

Soil chemical properties (available N, P, and K; electrical conductivity; soil pH, soil organic matter content; total Pb and easily extractable Pb)

Soil samples were analyzed for available N, P, and K; pH; electrical conductivity (EC); and organic C concentration. Available N (ammonia and nitrate) of soils was extracted by 1 M KCl (Mulvaney, 1996). Available K was extracted by 1 M NH_4CH_3COOH (pH=7.0) (Helmke and Spark, 1996). Available P was extracted by Mehlich-III (Mehlich, 1984) and analyzed calorimetrically using a flow injection analyzer (Lachat Instruments, Loveland, CO). The Walkley-Black procedure was used to determine organic C content in soils (Nelson and Sommers, 1996). Soil pH was determined using a 1:10 soil:deionized water mixture and a pH meter with an 'Accumet' pH/ATC Electrode and Accumet AP 115 meter (Fisher

Scientific, Pittsburgh, PA). Soil-soluble salts were extracted using a 1:2 (v/v) soil:water extraction (Sonneveld and Van den Ende, 1971). EC of the extraction was measured with a Seven Easy conductivity meter S30 and Inlab 731 electrode (Mettler-Toledo Inc., Columbus, OH). Dissolved organic carbon (DOC) concentrations were also determined in the 1:2 (v/v) soil:water extractions using a total organic carbon analyzer that purged inorganic carbon of the extractions using 1 M HCl (Shimadzu, Columbia, MD).

Soil total Pb and other trace element concentrations (Cr, As, Ni, Cd, Co, Cu, and Zn) were determined by EPA method SW846-3051A (USEPA, 2007b). To determine total trace element concentrations, 10 mL of trace metal–grade concentrated HNO_3 was added to 0.5 g of soil and digested in a microwave digestion unit (MARSXpress, CEM Corporation, Matthews, NC). The temperature of the soil-acid mixture in the microwave digestion unit was increased to 165^oC in 5.5 min in the first stage of the temperature program. In the second stage, temperature was further increased to 175^oC in 4.5 min and the mixture was held at 175^oC for 5 min. A standard reference soil (NIST 2711a-Montana II) was digested along with every batch of test samples as a quality assurance/quality control (QA/QC) sample to evaluate digestion and analytical procedures. After filtering using the Whatman No. 42 filter papers, the solutions were analyzed for Pb using an inductively coupled plasma optical emission spectrophotometer (ICP-OES; Varian Inc., Foster City, CA).

Easily soluble, extractable Pb in the soils was extracted using 0.01M $Sr(NO_3)_2$. The soil:0.01M $Sr(NO_3)_2$ solution ratio was 20g:40mL. After shaking the suspension for 1 hour, it was filtered using 0.45-µm syringe filters. Resulting solutions were digested using the EPA SW846-3015A method (USEPA, 2007a) in the microwave digestion unit. This digestion minimized the matrix suppression of Pb absorbance in the Graphite Furnace Atomic Absorption Spectrometry (GF-AAS; Varian Inc., Foster City, CA) and equalized the matrix effects in the extractions of soils with and without added compost. The matrix suppression for the Pb absorbance in the GF-AAS was high in the compost-added soils compared with the soils without added compost. To overcome this issue, 1 mL of concentrated nitric acid was added to 9 mL of the filtered solution and the temperature was increased to 160°C in 10 min, then to 170°C in the next 10 min. The solution was again filtered using Whatman No. 42 filter paper and analyzed for Pb using GF-AAS.

Cleaning methods for vegetables

Produce in the 2010 study was divided into two portions and subjected to two cleaning procedures: laboratory cleaning and kitchen-style cleaning. Laboratory cleaning was done by rinsing the produce with tap water, deionized (DI) water, 5 g kg^{-1} sodium lauryl sulfate ($CH_3(CH_2)_{10}CH_2OSO_3Na$) solution, and again with DI water. This method was developed to remove all adhering soil dust particles from produce surfaces. Kitchen-style cleaning was done using only tap water to mimic the washing procedure of vegetables in a home kitchen. During kitchen cleaning, we removed all visible soil particles from the produce. In addition to these two methods, a portion of the lab-cleaned carrots was also peeled.

Plant digestion

Cleaned plant samples were chopped using a stainless steel knife, then dried at 70°C for 4 to 5 days. Dried plant materials were ground using a Willey Mini Mill-Arthur Thomas–type grinder (Thomas Scientific, Swedesboro, NJ). The sieve size was 250 µm (60 mesh).

Plant samples were handled in a biosafety cabinet, class II type A2 (Esco Technologies Inc., St. Louis, MO), to avoid contamination by airborne dust in the laboratory. Ten milliliters of trace metal-grade concentrated HNO_3 were added to 0.5 g of ground plant material and digested in a microwave digestion unit. The temperature of plant-acid mixture in the microwave digestion unit was increased to 200°C in 15 min, and the mixture was held at

200^{o}C for another 15 min. All the plant samples were digested in duplicates. In each batch of digestion, two samples of standard reference plant material (NIST 1515-Apple leaves) and two blanks (concentrated HNO_3 only) were included as QA/QC. Solutions were filtered using Whatman No. 42 filter papers and analyzed for Pb using GF-AAS. Different modifiers and temperature programs were used to enhance the signals (absorbance) of Pb in GF-AAS. The modifier used for analyzing Pb in Swiss chard and sweet potatoes was 1mg mL^{-1} $NH_4H_2PO_4$ and 2% (w/v) H_3PO_4 for tomatoes and carrots. Recoveries of spiked digested solutions with known concentrations of Pb were used as a guide to method development in GF-AAS. The recoveries of spiked samples were 93% for Swiss chard, 98% for tomatoes and sweet potatoes, and 103% for carrots.

Simplified Physiologically Based Extraction Test (Simplified PBET)

Ruby et al. (1996) suggested that PBET can be used in site-specific studies to assess exposure of humans to Pb (and As) in soils. This *in-vitro* method extracts the bioaccessible Pb of Pb-contaminated soils in the human digestive system. Bioaccessible Pb levels were determined in the soil samples collected from tomato-growing plots at planting and at harvesting using the PBET procedure developed by Ruby et al. (1996) and simplified by Brown and Chaney (1997). We employed this method for two particle size fractions, < 250 μm and < 2 mm (whole soil). The < 250 μm size fraction represents the soil fraction that adheres to hand of a child and is recommended (USEPA, 2012); however, some scientists argue that larger soil particles can be ingested and may have a significant impact on Pb bioaccessibility (USEPA, 2007c). Furthermore, a complete characterization of soil fractions may be more consistent across sites (USEPA, 2007c). Based on these arguments, we also performed simplified PBET using < 2 mm soil fraction to estimate the bioaccessibility of the whole soil.

The gastric solution was prepared by mixing 1.25 g of pepsin, 500 mg of sodium L-malate, 500 mg of sodium citrate dihydrate, 500 µL of trace metal–grade acetic acid, and 420 µL of L(+)-lactic acid with 1 L of deionized water. The solution was acidified (pH was about 2.00) with trace metal–grade concentrated HCl prior to adding the solution to the soil. One gram of soil and 100 mL of gastric solution were added to a 250-mL polypropylene bottle. The gastric solution was heated to 37°C before adding it to the soil. The extraction was done at two initial pH values of the soil–gastric solution mixture, 1.5±0.02 and 2.5±0.02. pH 1.5 represents fasting gastric pH, and pH 2.5 represents the intermediate stomach state between fasting and fed conditions (Ruby et al., 1996). The pH adjustment of the soil–gastric solution mixture was done by adding varying volumes of trace metal–grade concentrated HCl. The soil–gastric solution mixture was shaken at 37°C at 100 rpm for 1 hour, then the samples were filtered using 0.45 µm syringe filters. A standard reference material (NIST 2711a-Montana II soil) was subjected to this test at both pH 1.5 and 2.5 with each batch of extraction (A batch consisted of 20 samples). Two blanks were also included in each extraction batch. Analysis of extractions for Pb was done by GF-AAS. The signal of the GF-AAS was enhanced by using 2% (w/v) H_3PO_4 as a modifier. Recovery of the spiked extraction with known concentration of Pb was 99%.

Statistical analysis

SAS 9.2 statistical software was used (SAS Institute, 2010). The Pb concentrations of vegetables and bioaccessible Pb concentrations were transformed to log base 10 to achieve normal distribution prior to statistical analysis. One-way analysis of variance (ANOVA) using PROC GLM was performed to analyze the effect of compost addition on Pb concentrations in vegetables. Separate analyses were done for each vegetable. The design was a split-plot design with completely randomized block arrangement with three (in 2009) or four (in 2010) blocks: the main plot factor was compost (compost added and no compost), and the subplot factor was the cleaning techniques used. The effects of compost addition on bioaccessible Pb and % bioaccessible Pb (i.e., [bioaccessible Pb concentration in mg kg^{-1}/ total soil Pb in mg kg^{-1}]*100) were analyzed using PROC GLM. Differences between bioaccessible Pb, determined at 16 days (at planting time) and 105 days (at harvest time of tomatoes) after compost treatment were analyzed using a paired t-test by PROC TTEST procedure.

Results and Discussion

Compost addition changed soil chemical properties

As expected concentrations of plant nutrients in compost-added soils were significantly higher than in soils that did not receive compost (Table 1). During the growing season, available N, Mehlich III-P, and available K concentrations reduced in compost-added soils. In soils that did not receive compost, concentrations of available N, Mehlich III-P,and available K did not decrease throughout the growing season. Soil pH in compost-added and no-compost-added soils was in the neutral range; furthermore, as one would expect, compost addition improved the concentration of soil organic carbon and cation exchange capacity (Table 1).

We observed high biomass production in compost-added soils. For example, in 2010 the average fresh Swiss chard harvest in compost-added plots weighed 1.61 kg m^{-2} (standard error 0.19), whereas in the plots that did not receive compost it was 0.58 kg m^{-2} (standard error 0.12). We also observed that plants in compost-added plots grew faster, were healthier, and produced higher biomass contents than the plants in plots that did not receive compost. It is not the intention of this paper to discuss soil fertility aspects in detail; however, due to possible effects of poor nutrient status on plant Pb uptake (this was discussed later in the paper), we were interested in the soil fertility status of the soil.

Dilution of soil matrix after compost addition significantly reduced total Pb concentrations in soils, and this effect was immediate. After adding compost, initial soil total Pb concentrations were reduced by 29–52% (data not shown). In contrast, easily soluble Pb concentration, as estimated by 0.01M $Sr(NO_3)_2$ extraction, was high in compost-added soils compared with no-compost soils (Table 5). Increased extractable Pb concentration in compost-added soils related to increased DOC concentration in the soils upon compost addition (Table 1). Dissolved organic matter degrades over time and makes the dissolved Pb available for other reactions.

Lead concentrations in vegetables

All the vegetables had detectable amounts of Pb in their edible portions. From this point onward, the Pb concentration in plants refers to the Pb concentration in the edible portion: for tomatoes, it is the fruit; for Swiss chard, it is leaves; and for sweet potatoes and carrots, it is the root. No clear trend was observed for the relationship of Pb concentrations of vegetables to soil total Pb concentration (Figure 5). Compost addition increased the extractable P concentration in soils, as indicated by Mehlich III-P (Table 4 and 5). Although increased soluble P concentration can reduce the solubility of Pb in soils, there was no clear relationship between Mehlich III-P concentrations with the bioconcentration factors of the vegetables.

Effects of compost addition

The effects of compost addition on Pb concentrations in vegetable crops were determined after cleaning with the laboratory procedure, which aims to remove all adhering soil particles from the surface of the produce. In the 2009 study, compost addition did not significantly reduce Pb concentrations in any of the three vegetables (Table 4). The reason could be low soil total Pb concentrations (77–157 mg kg^{-1}) that resulted in only mild elevation of Pb concentrations in vegetables. In 2010, test plots were established in comparatively high total-Pb soils (186 to 388 mg kg^{-1}) and, addition of compost significantly reduced ($P<0.05$) Pb concentrations in Swiss chard and carrots (Table 5). In compost-added plots, Pb concentrations were 59% lower in Swiss chard and 20% lower in carrots compared with Swiss chard and carrots grown in soils that did not receive compost. Lead concentrations of tomatoes were not significantly different in compost-added and no compost-added soils. Concentrations of Pb in tomatoes (average of ~0.07 mg kg^{-1}-dry weight) may be too low to show the effect of compost addition.. In general, Pb bioconcentration factors express the proportion of soil total Pb concentrations absorbed by plants. Carrots and sweet potatoes had the highest bioconcentration factor, followed by Swiss chard, followed by tomatoes, supporting the fact that accumulation of Pb was highest in roots, followed by leaves, then fruits. This could be a result of translocation of Pb within the plant. Finster et al. (2004) found Pb concentration of tomato roots to be 33 times higher than that of the shoot and >72 times higher than that of the fruits in tomatoes grown in Pb-contaminated (3,740 mg Pb/kg) residential soils. Soil P concentration may affect translocation of Pb within a plant (Foy et al., 1978). When plants are grown in soils that have high P concentration, Pb phosphates precipitate in the root organelles. This limits the translocation of Pb from root to shoot. The moderate pH of the root cells and the xylem sap may assist Pb phosphate formation in roots.

The concentration of Pb in vegetables does not necessarily reflect total Pb uptake by that vegetable. Although compost addition reduced Pb concentrations in Swiss chard, it did not reduce its Pb uptake (total Pb) (Table 6), demonstrating that increased plant biomass as a result of compost addition diluted Pb concentrations in Swiss chard. Similar results were observed by Ekvall and Greger (2003). They showed that increasing plant total biomass of seedlings of *Pinus sylvestris* as a response to physiological conditions in the environment diluted Cd concentrations in the plant, especially in the root. In our experiment, one no-compost plot for carrot produced 87% less root biomass than other no-compost plots because the soil was unusually compacted due to high clay content. This plot had the highest concentration of total soil Pb (387.9 mg kg^{-1}). The bioconcentration factor of carrots in this plot was 0.0206, which was 1.8 times higher than the average bioconcentration factor of carrots harvested from the other three no- compost soils (i.e., 0.0112, Table 5). This result indicates that an increase of total biomass of vegetables could be an effective means of reducing potential Pb transfer to humans.

Effects of vegetable cleaning methods

Lead concentrations of vegetables determined after cleaning with different techniques were significantly different for Swiss chard and tomatoes, but not for carrots (Figure 4). Swiss chard cleaned with the kitchen cleaning method contained 2.6 to 4.6 times greater Pb concentrations than that cleaned with the lab cleaning method. Similarly, kitchen-cleaned tomatoes had 3.0 times greater Pb concentrations than lab-cleaned tomatoes.

Transfer of Pb from plants to humans could occur not only because of uptake of Pb by plants, but also because of contaminated soil particles that adhere to the plant surface or are embedded in the waxy outer layer of plants. Fruits, leaves, and non-woody stems such as aerial parts of higher plants have an extra cellular membrane called the cuticle that consists of soluble and polymerized lipid covers (Heredia and Dominguez, 2009). Sodium lauryl sulfate, used in the lab cleaning method, is an anionic surfactant. Anionic (and nonionic) surfactants have the ability to solubilize water-insoluble materials such as cutin and dissolve a larger portion of the cuticle barrier (Furmidge, 1959). By using the lab cleaning method, we may have effectively removed particles embedded in the plant surface by solubilizing the cutin lipid cover; therefore, lab-cleaned tomatoes and Swiss chard showed lower Pb concentrations. In contrast, cleaning methods did not significantly affect Pb concentrations in carrots. This can be explained by the absence of cuticle lipid layer on the roots. Peeling also did not statistically change Pb concentrations in carrots. When peeling, we removed a very thin outer layer of the carrots. Synchrotron-based x-ray fluorescence mapping has shown that the concentrations of Pb in the peel and the phloem of the carrot are low compared with the concentration of Pb in the inner xylem tissues of the carrots (Codling et al., 2007), which could explain the lack of difference in Pb concentrations of peeled carrots in this study.

Comparison of plant Pb with maximum allowable levels

When human health is concerned, it is important to interpret contaminant concentrations with respect to standard values of maximum allowable levels (MLs). The Codex Alimentarius Commission (CODEX), established by the Food and Agriculture Organization (FAO) and World Health Organization (WHO), develops international food standards, guidelines and codes of practice to protect the health of the consumers and ensure fair practices in the food trade. The CODEX committee on contaminants in food established or endorsed permitted maximum levels (MLs) or guidelines levels for contaminants and naturally occurring toxicants in food and feed and includes maximum levels for Pb concentrations in vegetables. We used these MLs as a guideline to compare concentrations of Pb in vegetables. It is important to note here that these limits are not developed based on bioavailability of Pb in food. Research has shown that Pb ingestion along with food reduces bioavailability of Pb in the digestive system (James et al., 1985: USEPA, 2003). Calcium and phosphates in the food may contribute to this reduction, but the exact mechanism is not understood (USEPA, 2003). CODEX MLs might have been developed considering the upper limit or the maximum potential health risk of consuming Pb contaminated vegetables.

According to the CODEX guidelines, the ML of Pb is 0.3 mg kg^{-1} of fresh matter for leafy vegetables and 0.1 mg kg^{-1} of fresh matter for fruiting vegetables and root/tuber vegetables (FAO/WHO-CODEX, 1995; 2010 amendment). Because we analyzed dried plant materials to determine Pb concentrations in the vegetables, for the convenience of interpreting results, we converted the above MLs to a dry weight basis. For Swiss chard, which is a leafy vegetable, the ML of Pb is 5.0 mg kg^{-1} of dry matter (assuming moisture content of Swiss chard was 94%). The ML of Pb for tomatoesis 1.6 mg kg^{-1} dry matter (assuming moisture content of 94%; Pennington et al., 1998), and for carrots and sweet potatoes, the ML is 1.5 mg kg^{-1} of dry matter (assuming the moisture contents of 93%; Pennington et al., 1998).

Average concentrations of Pb in Swiss chard and tomatoes in both compost-added and no-compost soils were lower than the ML for Pb in leafy vegetables and fruiting vegetables both in 2009 and 2010 test plots (Figure 4). Concentrations of Pb in sweet potatoes and carrots were close to the ML for Pb in tuber and root crops. Consumption of leafy and fruiting vegetables grown at this site does not carry any health risk, but consumption of root and tuber crops grown at this site potentially carries the risk of ingesting harmful levels of Pb.

Bioaccessibility of soil Pb

Simplified PBET estimates the bioaccessibility of Pb in the event of direct ingestion of soil. Brown et al. (2003) showed that bioaccessible Pb determined by simplified PBET, which is also known as rapid PBET, correlates well with Pb concentrations in rat bones (at pH 1.5, R^2=0.84; at pH 2.3, R^2=0.90). Furthermore, this correlation is stronger than the correlation between bioaccessible Pb recovered by the original PBET procedure developed by Ruby et al. (1996) and Pb concentrations in rat bones (at pH 2.0, R^2=0.66).

Ingestion of food dilutes and buffers the pH of the gastric solution, making it less acidic at fed states (Davenport, 1984). Bioaccessible Pb as determined at pH 2.5 was 81% (compost-added soils) and 79% (no-compost soils) lower than the bioaccessible Pb determined at pH 1.5 (Tables 2 and 4). This was expected, because dissolution of Pb is highly pH-dependent. Similarly, a 65% reduction in dissolution of soil Pb was observed when pH of the soil-gastric solution increased from 1.3 to 2.5 (Ruby et al., 1996). Soil Pb bioaccessibility determined at pH 2.3 correlate well with bioavailability determined using *in vivo* methods (Medlin, 1997; Brown et al., 2003). Researchers have shown that the reduction of Pb bioaccessibility in the amended soils was prominent at pH 2.5 or 2.2 (Brown et al., 2004; Ryan et al., 2004) and that pH 1.5 overestimates the bioavailability of soil Pb (Brown et al., 2003; Smith et al., 2011). Drexler and Brattin (2007) recommended using pH 1.5, because this pH provides greatest improvement in predicting relative bioavailability and limits the risk of underestimating.

In this study, regardless of the extraction pH, the majority of soil Pb did not dissolve in the gastric solution. Only 33–44% of total Pb in the soils that did not receive compost and 21–32% of total Pb in the soils that received compost were dissolved in the gastric solution at pH 1.5, whereas 3.5 to 6.0% of total Pb was dissolved in the gastric solution at pH 2.5. This result indicated that the majority of soil Pb at this site is not bioaccessible. Past research also observed that a considerable portion of Pb in urban soils was not bioaccessible (Yang et al., 2001; Brown et al., 2003; Farfel et al., 2005). The fraction of bioaccessible Pb can be different from one site to another, depending on Pb speciation and other soil chemical properties. Unpublished x-ray absorption data from our laboratory shows most Pb in this soil was in either ferrihydrite adsorbed- or humic acid adsorbed forms. Smith et al. (2011)

showed that soil Pb was strongly associated with Fe oxyhydroxide minerals or the soil organic fraction in a study conducted with urban soils. Researchers have found that outer-sphere and inner-sphere adsorption are two major processes of Pb immobilization in soils (Zimdahl and Skogerbo, 1977; Strawn and Sparks, 2000). In urban soils, the concentration of Pb generally may not reach high enough levels to expect significant formation of Pb precipitates; however, we cannot rule out the possibility of localized Pb precipitation when concentration of Pb and other constituents of the common Pb minerals in soils (e.g., carbonates and phosphates) are high (Zimdahl and Skogerbo, 1977; Cotter-Howells, 1996).

Effects of compost addition on bioaccessible Pb after 16 days of compost addition as determined at pH 1.5

Compost addition reduced bioaccessible Pb in the < 2 mm fraction (Table 2). In the < 250 µm fraction, bioaccessible Pb was not statistically different in soils with compost and without compost. Dilution of soil total Pb and increase in soil-available P upon compost addition may have caused the reduction of soil bioaccessible Pb (< 2 mm fraction) in the compost-added soils. Figure 2 shows a comparatively high relationship ($R^2 = 0.71$) between soil total Pb and bioaccessible Pb at 1.5 pH. This dilution of soil total Pb in compost-added soils was not intense in the < 250 µm fraction, because most of the compost materials were removed with larger particles during sieving. The percentage of bioaccessible Pb is a measure of bioaccessibility independent from soil total Pb; therefore, percentage bioaccessibility values are not influenced by the dilution effect of soil total Pb upon compost addition. The percentage of bioaccessible Pb in both < 2 mm and < 250 µm fractions was significantly lower in the compost-added soils than in the soils that did not receive compost (Table 2). This result suggests that in addition to the dilution effect, compost reduced the bioaccessibility of soil Pb. Increased soil-available P upon compost addition (average available P concentrations were 68 mg kg^{-1} in the soils that did not receive compost and 438 mg kg^{-1} in the soils that receive compost) might partially contribute to the decreased percentage of bioaccessible soil Pb in compost-added soils. Figure 3 shows the relationship of bioaccessible Pb to available P concentrations. Reductions in Pb bioaccessibility with increases in available P concentrations have been observed by past researchers (Hettiarachchi et al., 2000; Yang et al., 2001; Hettiarachchi et al., 2003). Available P reacts with Pb in soil and forms relatively stable Pb species such as hydroxypyromorphite (or hydroxypyromorphite-like minerals) and chloropyromorphites (or chloropyromorphite-like minerals) (Hettiarachchi et al., 2000).

In addition to total soil Pb and soil-available P concentrations, soil total organic C (Ruby et al., 1996) also affect bioaccessibility of soil Pb. Ruby et al. (1996) argued that total organic C in soil increases the bioaccessibility of Pb as estimated by the stomach phase of the original PBET procedure (Ruby et al. [1996] consisted of two phases, stomach and intestinal). The authors explain that organic C provides additional sorptive surfaces that may readily desorb Pb in the gastric environment. Although total organic C concentrations were higher in the compost-added soils (3.2%) than in soils without added compost (2.1%) in our study, the effects of soil organic C on Pb bioaccessibility might have been counteracted by the effects of increased P concentrations in the compost-added soils. Further, Fe and Mn oxides in compost reduce bioaccessibility of soil Pb (Hettiarachchi et al., 2000; Brown et al., 2003). In a recent study, Brown et al. (2012) demonstrated that not only the Fe concentration but also the reactivity of Fe in the biosolids affected the bioaccessibility of Pb in soils. The compost we used in our experiment was a leaf-based compost, which had only 3.8 g kg^{-1} total Fe and 0.2 g kg^{-1} of total Mn, which were fairly low concentrations compared with the composted biosolids used by Brown et al. (2003) and Brown et al. (2012). Therefore, the higher concentration of soil-available P was the predominant factor that reduced the percentage of Pb bioaccessibility in compost-added soils compared with the soils without added compost.

Effects of compost addition on bioaccessible Pb after 16 days of compost addition as determined at pH 2.5

Compost addition did not reduce bioaccessible Pb at pH 2.5 in both < 2 mm and < 250 µm fractions (Table 3). To improve the statistics, we did PBET extraction at pH 2.5 in soils collected from all 12 blocks (4 blocks per each vegetable) after 16 days of compost addition, but we still did not see a significant reduction in bioaccessible Pb upon compost addition (Table 3 shows only the results of 4 blocks). Unlike at pH 1.5, the dilution of soil total Pb as a result of compost addition seemed to have a minimal effect on reducing bioaccessible Pb at pH 2.5. This result was supported by the poor relationship between bioaccessible Pb and soil total Pb at pH 2.5 (Figure 2).

Percentage of bioaccessible Pb was significantly lower in compost-added soils than in soils that did not receive compost in the < 250 µm fraction ($P<0.15$; $p = 0.12$). This was not significant in < 2 mm fraction (Table 3). As previously explained, lowering the percentage of bioaccessible Pb in compost-added soils can be attributed to enhanced available P in soil through compost addition. Figure 3 also shows a poor relationship of available P and percentage of bioaccessible Pb in the < 2 mm fraction. In this size fraction, the effects of enhanced P on percentage of bioaccessible Pb could have been masked by increased Pb solubility in the compost-added soils as a result of elevated concentrations of DOC. The effects of DOC on percentage of bioaccessible Pb could be minimal in the < 250 µm fraction and not high enough to mask the effects of enhanced available P because the proportion of compost material in this fraction was relatively low. Concentration of DOC at pH 1.5 was expected to be lower than that at pH 2.5. Past research found that at lower pH, the dissolution of soil organic carbon was less than that at high pH (You et al., 1999). Therefore, the increase in Pb solubility by DOC might not have been high enough to override the effects of elevated available P concentration on the percentage of bioaccessible Pb at pH 1.5.

Change of bioaccessibility of soil Pb over the growing period

We used the percentage of bioaccessible Pb instead of bioaccessible Pb to evaluate this time effect because bioaccessible Pb depends on the total Pb concentration, and the total Pb concentrations in two soil samples (16 days and 105 days after adding compost) collected from the same plot can be different depending on the variability of the total Pb concentration at the site: Average difference and standard error of difference in total Pb concentrations of the samples collected 16 days after compost addition (at planting) and 105 days after compost addition (at harvesting tomatoes) were 24 mg kg^{-1} and 5.4 mg kg^{-1}, respectively. These are low and acceptable for a field experiment. The change in bioaccessible Pb concentration throughout the growing period was analyzed only in the compost-added soils 16 days and 105 days after compost addition to evaluate the effects of compost addition on the percentage of bioaccessible Pb through time. Percentage of bioaccessible Pb in compost-added soils did not decrease significantly over time when measured at pH 1.5 in both < 2 mm and < 250 μm fractions (Table 2). As discussed above, high available P concentration reduced the percentage of bioaccessible Pb in the compost added soils. A small reduction in the percentage of bioaccessible Pb in phosphate-applied soils over time was observed in previous research (Hettiarachchi et al., 2000; 2001), which could be because either the majority of the bioaccessible Pb reduction happened within the first 16 days of compost addition or the Pb-P reaction happened under the gastric phase of PBET and was not affected by the contact time of Pb and P in the field, as in Hettiarachchi et al. (2001).

When bioaccessibility was measured at pH 2.5, the percentage of bioaccessible Pb seemed to decrease over time in compost-added soils in the < 2 mm fraction, but at a low significance level ($p < 0.15$; $p = 0.11$; Table 3). This was not significant in the < 250 μm fraction. At pH 2.5, solubility of Pb due to DOC was a prominent factor that affected the percentage of bioaccessible soil Pb, as discussed earlier. Dissolved organic carbon introduced by compost addition decreased over time; therefore, we expect lower Pb solubility in the soils collected 105 days after compost addition compared with 16 days after compost addition. This could explain the significant reduction in the percentage of bioaccessible of Pb in the < 2 mm fraction over time at pH 2.5. The representation of compost material in the < 250 μm fraction would be low, as mentioned before. Therefore, the DOC effect on Pb bioaccessibility could be minimal in this fraction and could explain the lack of significant difference in percentage of bioaccessible of Pb in this fraction of compost-added soils over time.

A significant decrease in percentage of bioaccessible Pb in soils with compost added was observed compared with soils without added compost after 105 days of compost addition in the < 250 μm fraction. This result indicated that the effects of enhanced available P in compost-added soils lasted > 105 days. This difference was not significant in the < 2 mm fraction, which can be attributed to the higher variability of the bioaccessibility values observed in this size fraction compared with the < 250 μm fraction.

Conclusions

The extent of Pb contamination was highly variable within a small area. Compost addition diluted initial total soil Pb concentrations, indicating that the continuous addition of compost would lower total Pb concentration in soils significantly. Compost addition reduced the potential risk of soil Pb transfer to humans indirectly through consumption of vegetables grown at this site and directly through soil ingestion by decreasing plant Pb and bioaccessible Pb concentrations. Dilution of soil total Pb concentration and increase in soil-available P followed by compost addition helps reduce soil Pb transfer to humans through direct ingestion of soils. In addition, compost addition helps maintain good soil nutrient status in soils. Maintaining good soil fertility and thereby increasing biomass production diluted Pb concentrations in the vegetables. The highest concentrations of Pb in edible portions were found in root/tuber crops, followed by leafy and fruiting vegetables. Thorough cleaning and removal of soil/dust particles deposited on edible portions of vegetables, especially leafy and fruiting vegetables, further reduces food chain transfer of soil Pb to humans.

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Figure Captions

Figure 1. Distribution of soil total Pb concentrations in the site and locations of test plots in 2009 and 2010 and community sample points.

Figure 2. Relationship of soil bioaccessible Pb in the < 2 mm size soil fraction to soil total Pb concentration in the same fraction.

Figure 3: Relationship between percentage of bioaccessible Pb and soil Mehlich III-P in the < 2 mm size soil fraction 16 days after compost addition.

Figure 4. Comparison of vegetable Pb concentrations with maximum allowable levels† of Pb in vegetables. †Maximum allowable levels: leafy vegetables, 0.3 mg kg^{-1}-fresh weight; fruiting vegetables, root and tuber crops, 0.1 mg kg^{-1}-fresh weight (FAO/WHO-CODEX, 1995; 2010 amendment). (A) Swiss chard in 2010; ML=5.0 mg kg^{-1}-dry weight, moisture

content 94%. (B) Tomato in 2010; ML=1.6 mg kg^{-1}-dry weight, moisture content 94%. (C) Carrot in 2010; ML=1.5 mg kg^{-1}-dry weight, moisture content 93%. (D) Vegetables in 2009; ML 5.0, 1.6 and 1.5 mg kg^{-1} as in (A), (B), and (C) respectively.

*, ** Two categories are significantly different at 0.05 probability level. Different letters indicates the significance difference within the category at 0.05 probability level and similar letters indicates no significant difference within the category.

Figure 5. Relationship of Pb concentrations of vegetables to soil total Pb concentrations in 2009 and 2010 test plots and 2010 community samples.

Table 1. Selected nutrients and fertility parameters in preliminary soil samples (soil), compost, and plot soils at planting and at harvest of vegetables (in 2010).

	Soil	Compost	No-compost plot soils				Compost-added plot soils†			
				At harvest				At harvest		
			At planting	Swiss chard	Tomato	Carrot	At planting	Swiss chard	Tomato	Carrot
			Days after compost addition							
			16	69	105	121	16	69	105	121
Total Pb, mg kg^{-1}	68-305	24	208±14‡	-	-	-	146±13‡	-	-	-
pH (1:10 soil: water)	6.80	8.5	6.9	7.1	7.1	6.7	7.60\	7.5	7.6	7.0
CEC ¶, cmol$_+$ kg^{-1}	-	-	20.4	-	-	-	33.8	-	-	-
Sand, silt and clay, %	4, 75, 21	-		-	-	-	-	-	-	-
Organic C, %	-	21	2.1	0.9±0.1§	0.9±0.1§	1.0±0.1§	3.2	3.1±0.2§	2.7±0.1§	2.9±0.1§
DOC$^{\#}$, mg L^{-1}	-	-	51	-	18	18	158	45	47	44
Electrical conductivity, dS m^{-1}	0.19	5.6	-	-	-	-	-	-	-	-
Total N, mg kg^{-1}	1907	13470								
Available N, mg kg^{-1}	13-127	555	18±0	28±1	12±1	16±2	279±18	46±4	29±3	30±2
Mehlich III-P, mg kg^{-1}	57-154	-	68±06	57±8	63±11	58±10	438±25	355±23	264±28	279±14
Available K, mg kg^{-1}	225-624	-	328±20	285±19	310±20	336±18	1978±97	1091±137	893±15	862±26
C:N ratio		16	-	-	-	-	-	-	-	-
Total P, mg kg^{-1}	-	3150	-	-	-	-	-	-	-	-
Total Fe, mg kg^{-1}	-	6280	-	-	-	-	-	-	-	-
Total Mn, mg kg^{-1}	-	397	-	-	-	-	-	-	-	-

†Rate of compost-28 kg m^{-2}.

‡Average and standard error of 12 blocks: 4 blocks for each of 3 vegetable crops.

§Average and standard error of 4 blocks.

¶Cation Exchange Capacity.

Dissolved organic C in 1:2 soil:water (v/v) extract

Table 2. Soil bioaccessible Pb in tomato-growing plots as determined at pH 1.5.

	16 days after adding compost (at planting)		105 days after adding compost (at harvesting)		Standard soil
	Bioaccessible Pb	% bioaccessible Pb†	Bioaccessible Pb	% bioaccessible Pb	% bioaccessible Pb
	mg kg^{-1}		mg kg^{-1}		
< 2 mm fraction (Whole soil)					
No compost	57.4±5.0*‡	37.5±2.5**	55.6±7.0	33.6±3.5	-
Compost	44.1±6.0*	28.7±1.7**	46.2±11.0	26.1±3.3	-
< 250µm fraction					
No compost	78.7±19.5	32.9±2.3*	84.4±27.5	35.4±1.5**	-
Compost	53.9±6.8	29.0±1.0*	56.7±5.7	26.7±0.8**	-
NIST 2711 a	-	-	-	-	78.9§

* Two values in the same column within a size fraction were significantly different at 0.1 probability level.

** Two values in the same column within a size fraction were significantly different at 0.05 probability level.

† Bioaccessible Pb as a percentage of soil total Pb. Soil total Pb in the < 2mm or < 250 µm fraction was used to calculate percentage of bioaccessible Pb in the corresponding fraction.

‡Standard error of 4 blocks.

§Acceptable range is 75.2-96.2 % when 0.4M glycine is used as the extractant (USEPA, 2012).

Table 3. Soil bioaccessible Pb in tomato-growing plots as determined at pH 2.5.

	16 days after adding compost (at planting)		105 days after adding compost (at harvesting)		Standard soil
	Bioaccessible Pb	% bioaccessible Pb†	Bioaccessible Pb	% bioaccessible Pb	% bioaccessible Pb
	mg kg^{-1}		mg kg^{-1}		
< 2 mm fraction (Whole soil)					
No compost	13.4±6.4‡	6.3±2.0	12.1±3.4	5.2±1.3	-
Compost	9.2±1.3	6.0±0.4*	6.4±1.8	3.6±0.6*	-
< 250µm fraction					
No compost	14.1±4.8	5.6±0.9**	12.8±5.1	5.1±0.5***	-
Compost	7.4±1.4	3.9±0.4**	8.5±1.8	3.9±0.5***	-
NIST 2711 a	-	-	-	-	35.2

* Two values in the same row within a size fraction were significantly different at 0.15 probability level.

** Two values in the same column within a size fraction were significantly different at 0.15 probability level.

***Two values in the same column within a size fraction were significantly different at 0.1 probability level.

†Bioaccessible Pb as a percentage of soil total Pb. Soil total Pb in the < 2mm or < 250 µm fraction was used to calculate percentage of bioaccessible Pb in the corresponding fraction.

‡ Standard error of 4 blocks.

Table 4. Selected chemical properties of soils[†] and Pb concentrations in vegetables (in 2009).

	Soil total Pb	Soil pH	Mehlich III-P	Vegetable Pb‡	BCF§
	mg kg^{-1}		mg kg^{-1}	mg kg^{-1}, dry weight	
Experiment plots					
No compost					
Swiss chard	95±13	6.92	99±6	0.39±0.12	0.0052
Tomato	123±21	7.03	103±2	0.07±0.00	0.0006
Sweet potato	105±8	7.05	99±7	0.83±0.12	0.0081
Compost					
Swiss chard	81±4	7.88	215±10	0.26±0.03	0.0032
Tomato	97±11	8.06	260±22	0.07±0.01	0.0008
Sweet potato	102±16	7.99	240±29	1.32±0.11	0.0132
Community samples ¶					
Swiss chard A				0.89	
Swiss chard B				0.98	
Mustard A				0.17	
Mustard B				0.27	
Carrot				1.03	

† Soils collected immediately after adding compost to the experiment plots.

‡ Pb concentrations of edible portion of vegetables in dry weight basis determined after washing with the lab cleaning technique.

§ Bioconcentration factor: ratio of Pb concentration in the edible portion of plant and total Pb concentration in soil.

¶ Randomly collected plant samples from the rest of the garden. Varieties of plants were not known; different varieties are indicated by A and B. Gardeners added compost prior to planting.

Table 5. Selected chemical properties of soils[†] and Pb concentrations in vegetables (in 2010).

	Soil total Pb	$Sr(NO_3)_2$-extractable soil Pb	Soil pH	Mehlich P	Vegetable Pb ‡	BCF §
	mg kg^{-1}	mg kg^{-1}		mg kg^{-1}	mg kg^{-1}, dry weight	
Experiment plots						
No compost						
Swiss chard	221± 47	<0.005	6.93	62±10	0.71 ±0.084 **	0.0037
Tomato	189±28	<0.005	6.88	75±09	0.09 ±0.029	0.0005
Carrot	224±55	<0.005	6.97	68±12	1.37±0.179**	0.0112
Compost						
Swiss chard	154±35	0.021±0.007	7.70	456±44	0.29 ±0.04 **	0.0020
Tomato	153±15	0.020±0.006	7.57	450±16	0.06 ±0.02	0.0004
Carrot	129±11	0.020±0.005	7.65	409±64	1.41±0.23**	0.0110
Community samples ¶						
Tomato (Red cherry)	66		7.66		0.20	0.0030
Tomato (Yellow cherry)	102		7.77		0.06	0.0006
Sweet pepper	73		7.85		0.08	0.0011
Lettuce	92		7.87		0.32	0.0034
Okra	95		7.47		0.08	0.0009

† Soils collected 16 days after adding compost (at planting) to the experiment plots.

‡ Pb concentrations of edible portion of vegetables in dry weight basis after washing them with the lab cleaning technique.

** Two values of the same vegetable across the compost treatments were statistically significant at 0.05 probability level.

§ Bioconcentration factor: ratio of Pb concentration in the edible portion of plant and total Pb concentration in soil.

¶ Randomly collected soil and respective plant samples from the rest of garden. Samples were collected at harvest. Gardeners added compost prior to planting.

Table 6. Effects of compost addition on Pb concentration and total Pb in Swiss chard leaves (in 2010).

	Pb concentration	Aboveground biomass	Total Pb
	μg kg^{-1}, fresh matter	Kg, fresh mater	μg, fresh matter
No compost	42.3±5.1**	0.92±0.19	44.8±9.3
Compost	17.2±2.6**	2.54±0.30	40.7±12.9

Average±standard error of 4 blocks.

** Two values were statistically significant at 0.05 probability level.

Figure 1. Distribution of soil total Pb concentrations in the site and locations of test plots in 2009 and 2010 and community sample points.

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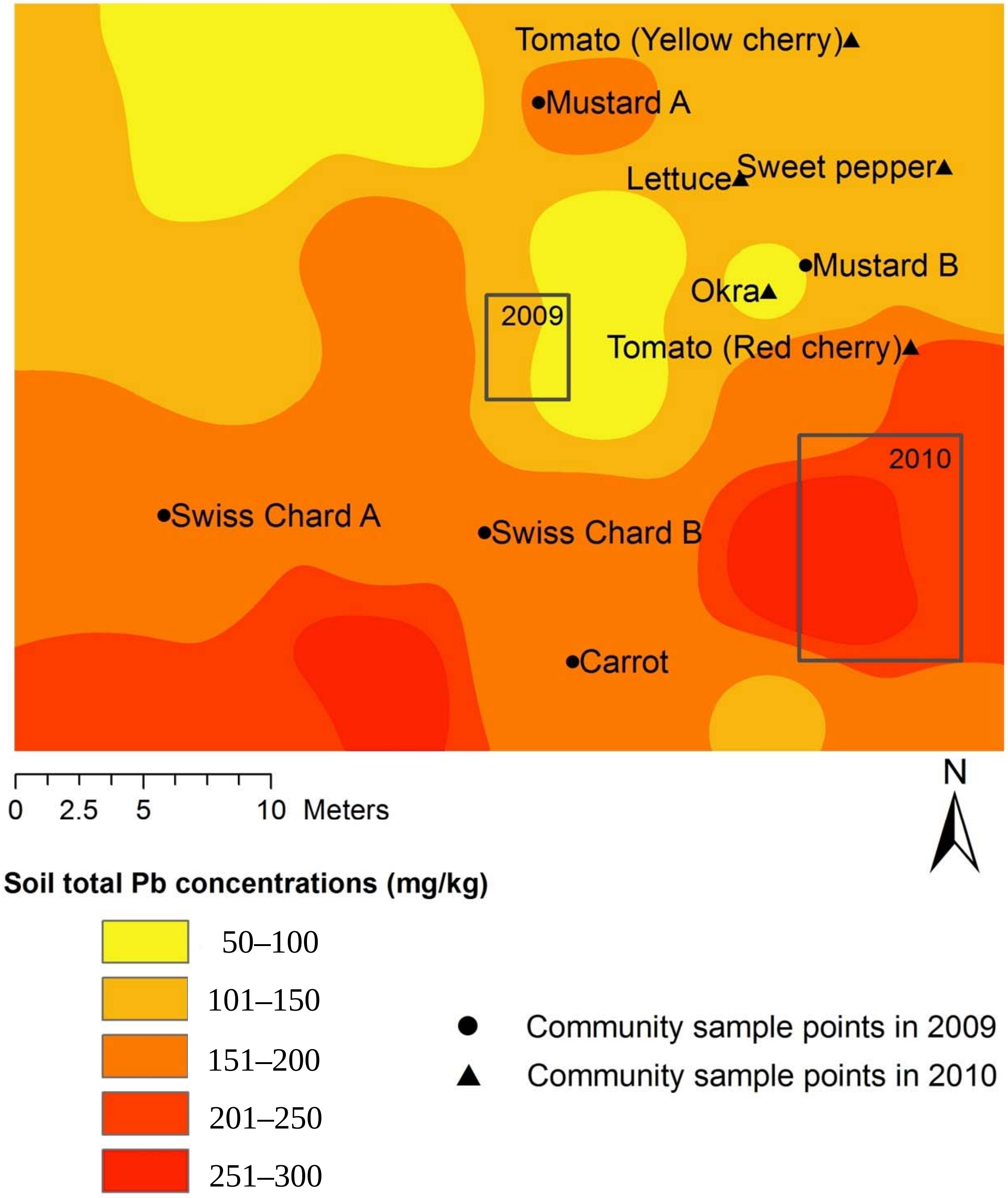


Figure 2. Relationship of soil bioaccessible Pb in the < 2 mm size soil fraction to soil total Pb concentration in the same fraction.

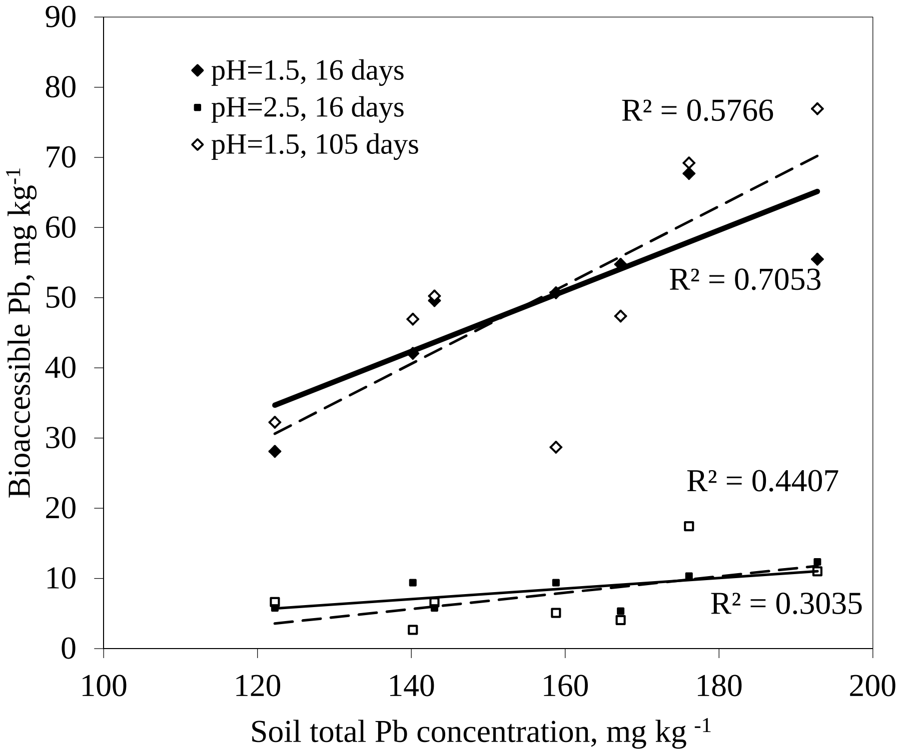
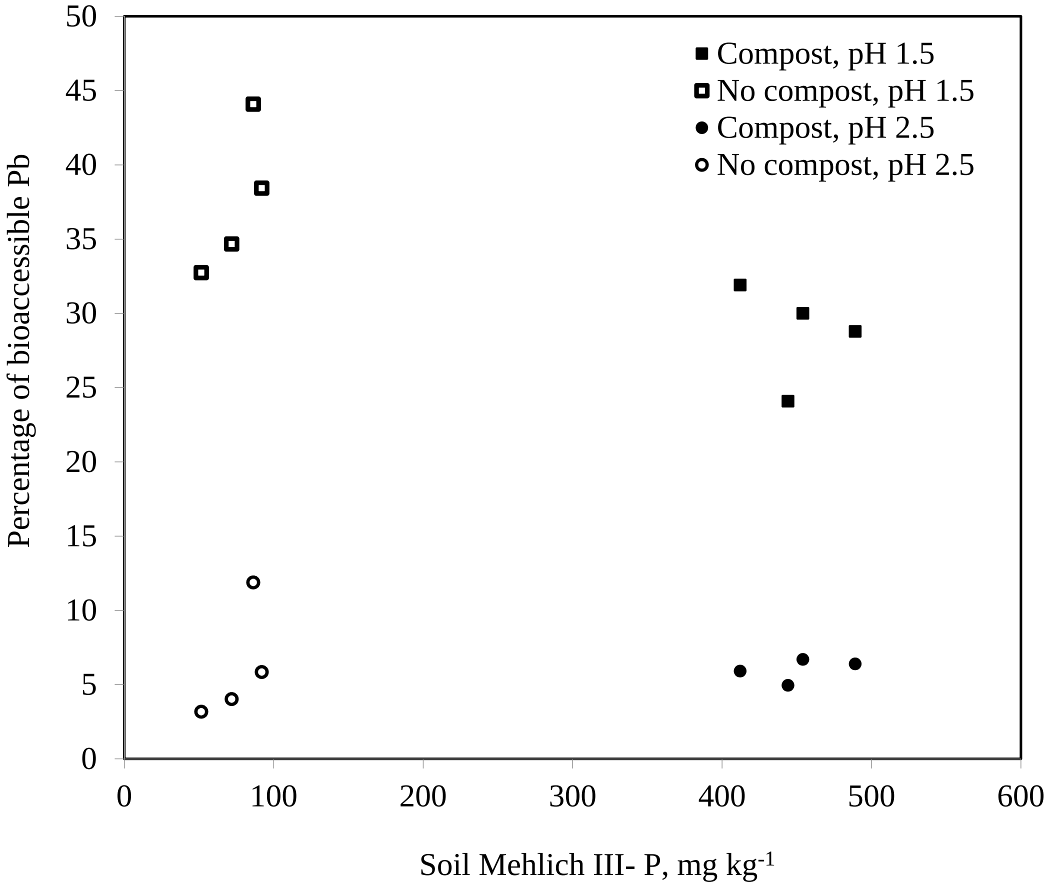


Figure 3: Relationship between percentage of bioaccessible Pb and soil Mehlich III-P in the < 2 mm size soil fraction 16 days after compost addition.



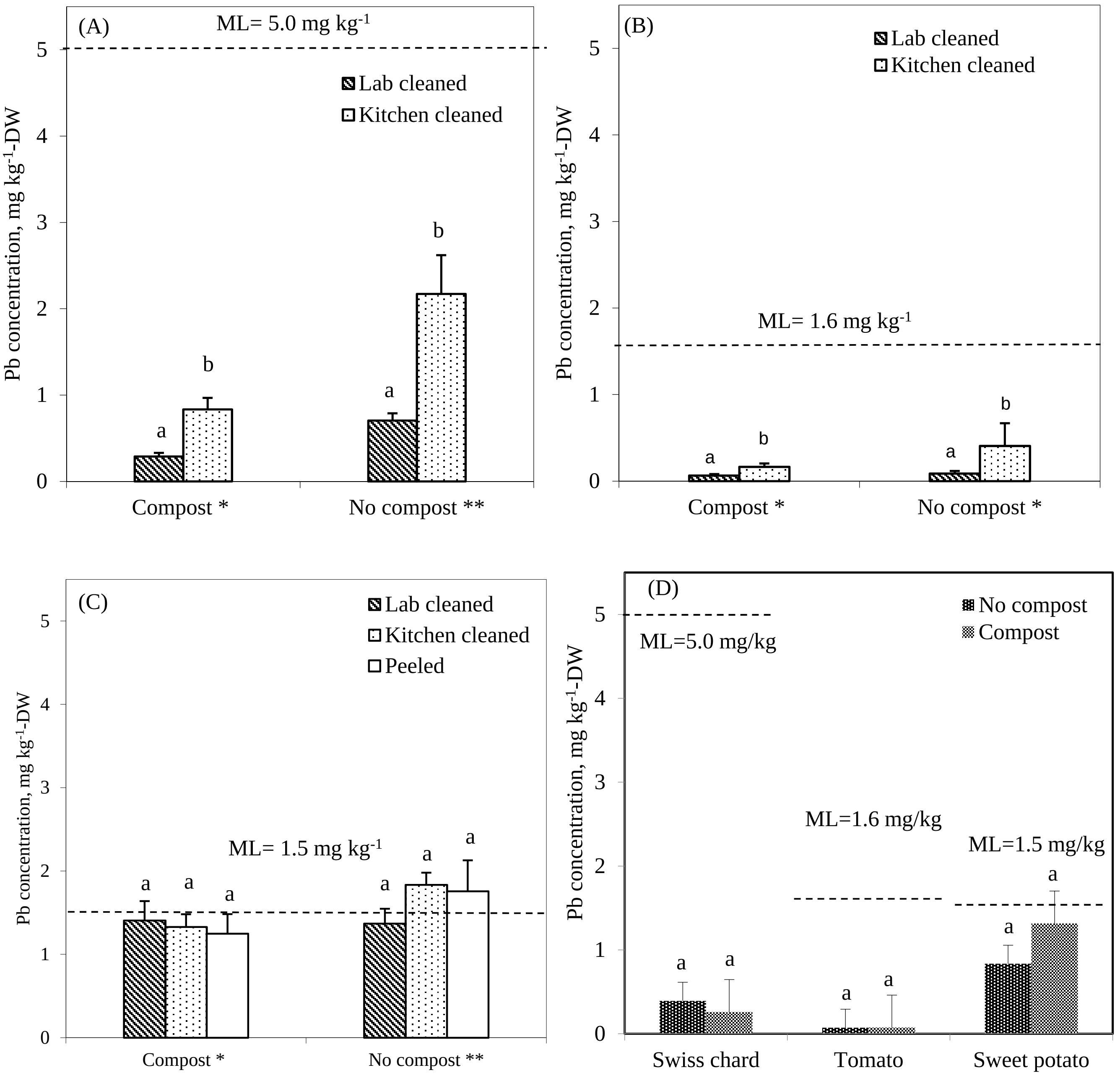


Figure 4. Comparison of vegetable Pb concentrations with maximum allowable levels† of Pb in vegetables. †Maximum allowable levels: leafy vegetables, 0.3 mg kg^{-1}-fresh weight; fruiting vegetables, root and tuber crops, 0.1 mg kg^{-1}-fresh weight (FAO/WHO-CODEX, 1995; 2010 amendment). (A) Swiss chard in 2010; ML=5.0 mg kg^{-1}-dry weight, moisture content 94%. (B) Tomato in 2010; ML=1.6 mg kg^{-1}-dry weight, moisture content 94%. (C) Carrot in 2010; ML=1.5 mg kg^{-1}-dry weight, moisture content 93%. (D) Vegetables in 2009; ML 5.0, 1.6 and 1.5 mg kg^{-1} as in (A), (B), and (C) respectively.

*, ** Two categories are significantly different at 0.05 probability level. Different letters indicates the significance difference within the category at 0.05 probability level and similar letters indicates no significant difference within the category.

Figure 5. Relationship of Pb concentrations of vegetables to soil total Pb concentrations in 2009 and 2010 test plots and 2010 community samples.