Lead (Pb) and other metals in New York City community garden soils: factors influencing contaminant distributions

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ABSTRACT

Urban gardens provide affordable fresh produce to communities with limited access to healthy food but may also increase exposure to lead (Pb) and other soil contaminants. Metals analysis of 564 soil samples from 54 New York City (NYC) community gardens found at least one sample exceeding health-based guidance values in 70% of gardens. However, most samples (78%) did not exceed guidance values, and medians were generally below those reported in NYC soil and other urban gardening studies. Barium (Ba) and Pb most frequently exceeded guidance values and along with cadmium (Cd) were strongly correlated with zinc (Zn), a commonly measured nutrient. Principal component analysis suggested that contaminants varied independently from organic matter and geogenic metals. Contaminants were associated with visible debris and a lack of raised beds; management practices (e.g., importing uncontaminated soil) have likely reduced metals concentrations. Continued exposure reduction efforts would benefit communities already burdened by environmental exposures.

Keywords: urban agriculture; community garden; urban soil; lead (Pb) exposure; soil contaminants

Capsule Pb and Ba, which exceeded health-based guidance values in 10-14% of NYC community garden soil samples, are associated with non-raised beds, visible debris, higher pH and Zn.

INTRODUCTION

Urban community gardens are growing in popularity as a source of healthy, affordable, locally grown foods in neighborhoods where such foods may not otherwise be readily available. By our estimate, New York City (NYC) has around 1500 community gardens, including neighborhood, senior, public housing, and school gardens, and some reports suggest even greater numbers ([ACGA] American Community Gardening Association, 1998). These gardens, which are often located in areas with limited access to fresh food (Figure 1), low rates of fresh vegetable consumption and relatively high rates of poverty (Table 1), provide many benefits to communities. Community gardeners have been reported to eat more fresh fruits and vegetables than non-gardeners (Alaimo et al., 2008), and a diet rich in these foods can reduce risk for stroke, diabetes, heart disease, obesity and some types of cancer (Abdulla and Gruber, 2000). Community gardens also provide many other benefits associated with urban green space, opportunities for recreation and community building (Alaimo et al., 2010; Leake et al., 2009).

However, urban soils often have elevated concentrations of lead (Pb) and other contaminants as a result of historical human activities such as waste incineration, coal and oil combustion, and the use of leaded gasoline and paints containing Pb and other metals. Gardening and related activities can increase the potential for adults and children to be exposed to soil contaminants through incidental soil ingestion, soil resuspension and subsequent exposure (Zahran et al., 2013), produce consumption, chicken egg consumption (Spliethoff et al., 2013), and other pathways. People living in some urban neighborhoods with community gardens may already be subject to greater environmental exposures, and exposures to soil contaminants can add to this burden. For example, community gardens were often located on vacant lots in neighborhoods with historically elevated blood Pb (Witzling et al., 2010) primarily resulting from factors such as deteriorating housing and associated lead paint. In NYC, the percentage of housing built before 1950 is significantly ($p = 0.002$) higher in the 83 ZIP Code Tabulation Areas (ZCTAs) with mapped community gardens ($n = 484$) than the 96 ZCTAs without those gardens (Table 1) (OASIS, 2012; US Census Bureau, 2011). It is important to note that blood Pb levels throughout NYC as a whole have declined 85% since 2000 (NYC DOHMH, personal communication). Incidence of elevated (> 10 µg/dL) blood-Pb levels by ZIP code in NYC for the year 2000, the most recent year for which ZIP-code-level data are available, was significantly higher (Student's t-test, $p < 0.0001$) in the 84 ZIP codes with mapped community gardens (median 26.7 cases per 1000 tests) than in the 106 ZIP codes without (median 14.3 cases per 1000 tests) (NYC DOH, 2002; OASIS, 2012; Spliethoff et al., 2011). (Note that incidence data for children's blood lead levels above the present-day CDC reference level of 5 µg/dL are not yet available.) It is important to recognize environmental sources of lead exposure such as urban garden soil in these vulnerable communities and take steps to minimize exposures for gardeners and their families. However, the nature and extent of community garden soil contamination in many urban areas remain poorly defined. Tests for chemical contaminants can be prohibitively expensive for gardeners with limited resources, often preventing them from learning whether their garden soil contains elevated levels of contaminants.

The *Healthy Soils, Healthy Communities* project is a community-research-Extension partnership formed to address concerns expressed by gardeners and others about the potential for exposure to contaminants in urban community gardens. As a first step, project partners conducted a study to assess the distribution of Pb and other metals in soil at a subset of NYC community gardens and to evaluate the extent to which concentrations of metals pose a health risk for gardeners. The study also examined potential associations between contaminant concentrations and garden characteristics that were easily observed (e.g., whether a garden has raised beds or is growing directly in the ground) or measured (e.g., soil pH). Such associations could be useful in helping gardeners make efficient use of resources for soil testing and/or mitigative measures to help reduce exposure to soil contamination. Finally, the study used principal component analysis (PCA) to identify common groupings of chemical elements in garden soil samples.

MATERIALS AND METHODS

Forty-four community gardens on New York City Department of Parks and Recreation (NYC Parks) property in four NYC boroughs (8 in the Bronx, 24 in Brooklyn, 10 in Manhattan, and 2 in Queens) were selected for the initial phase of the study between October 2009 and June 2010. These gardens were selected for sampling for the initial phase of the study from a pool of gardens with a history of actively producing food, size of a minimum of 0.25 acres, and NYC Parks records indicating that they had likely received at least one delivery of "clean" (uncontaminated) soil and/or compost within the previous eight years. An additional 10 gardens (1 in the Bronx, 7 in Brooklyn, 2 in Manhattan), all of which met the same criteria met by the first 44 gardens, except that they had been cited recently by NYC Parks for maintenance-related violations, were selected for a second phase of the study in August and September 2010. Records of soil and compost delivery were obtained from NYC Parks, and publicly available information about garden neighborhoods was compiled (NYC DOH, 2002; NYC DOHMH, 2012; OASIS, 2012).

The layout of each of the 54 gardens was mapped, and food-growing beds (typically approximately 1.2 m by 2.4 m in size) were identified and assigned numbers. A smartphone random-number generator application was used to select 10 beds from each garden for soil sampling (fewer if the garden had fewer than 10 beds). From each bed, one composite soil sample was created from 5 subsamples of soil, each from a depth of 0 - 12 cm. In addition, one discrete 0 – 12 cm soil sample was collected from a non-growing area ("non-bed") at each garden. An additional non-bed sample was collected at two gardens, for a total of 508 bed samples and 56 non-bed samples across all 54 gardens. At each sample location, detailed field observations were recorded on a sampling survey and one or more photographs were taken.

Soil samples were air dried and passed through a 2-mm plastic sieve. A portion of the < 2 mm fraction was then digested using US EPA Method 3051A (US EPA, 2012) and analyzed for total Al, B, Ca, Co, Fe, K, Li, Mg, Mo, Na, P, S, Ti, V, As, Ba, Be, Cd, Cr, Cu, Pb, Mn, Ni, Zn by inductively coupled plasma-optical emission spectrometry (ICP-OES) (US EPA Method 6010C)(US EPA, 2012). Quality control for the ICP-OES analysis of acid soil digests was attained by including blanks, sample duplicates, and a laboratory reference soil standard in each sample set. Soil pH was measured with a glass electrode in distilled water (2:1 soil to water ratio by weight), and carbon (C) and nitrogen (N) content were measured with a Leco CN-2000 C analyzer. For quality control, each sample set included several blanks, primary C standards (pure EDTA) and a soil standard (NIST SRM 2702 Marine Sediment) containing known amounts of total C.

Because of concerns about the quality of the ICP-OES analytical results for Cd (McBride, 2011), and because of previously reported associations between Cd and Zn, a subset of 107 samples was analyzed for strong-acid labile cadmium (Cd) and zinc (Zn). The samples were extracted by adding 50 mL of 1.0 M HNO_3 to 5 g dry soil (initially pulverized by mortar and pestle) in a 125 mL Erlenmeyer flask, agitating on a rotary shaker at 150 rpm for 1.0 hr and filtering through Whatman #42 paper. Direct determination of Cd and Zn on the filtered extracts was done by flame atomic absorption (FAA) spectroscopy at 228.8 nm and 213.9 nm, respectively. Cd and Zn standards in the concentration range of 0.10 to 2.00 mg/L were made in 1 M HNO_3. Zn determination generally required dilution of the extracts by from 25 to 100-fold in 1 M HNO_3 in order to bring the Zn concentrations within the range of the standards.

Several soil samples were analyzed with a scanning electron microscope (JEOL 8900 Electron Probe Microanalyzer operating at 15.0 kV) equipped with an energy-dispersive X-ray detector. Samples were pulverized to pass a 1-mm sieve, after which a small amount of sample was mounted to an aluminum holder with adhesive tape and coated with a thin carbon layer prior to observation. The system was used to create images of soil particles (from secondary and backscattered electrons) and to map selected elements of interest (from secondary X-rays) in soil particles.

Statistical analysis of data was done with the SAS software package (SAS Institute, Inc., 2010). Non-parametric methods were used to evaluate the soil data because most results were not normally distributed, and some were not easily transformed to a normal distribution. Spearman rank correlations were calculated to assess potential associations among the measured parameters. Wilcoxon signed-rank tests were used to compare the means of results for bed samples with corresponding paired non-bed samples, and a modified Wilcoxon rank-sum test (Rosner et al., 2006) was used to compare results for different types of garden areas (e.g., raised vs. non-raised beds) across gardens while accounting for the potential influence of "clustering" of beds within gardens. Statistical test results with p values less than 0.05 were considered significant. A principal component analysis was done to further assess the structure of the data, with principal components having eigenvalues greater than one retained and subjected to a varimax orthogonal rotation.

RESULTS AND DISCUSSION

Garden characteristics

Most of the 54 gardens in this study (89%) included at least some raised beds (Table 2), but non-raised (ground-level) beds were also present in nearly half the gardens in the study. Raised beds were particularly common in the first phase of the study, accounting for 81% of the 414 beds sampled in the first 44 gardens, but less common in the second phase (just 44% of the 94 beds sampled in the 10 gardens with recent NYC Parks violations). NYC Parks records included information on the age of 21 of the 54 gardens; they ranged from 1 to 57 years, with a median age of 20 years. NYC Parks records showed that many of the study gardens (69%) had a record of importing clean soil and compost within the past 10 years; however, a significant percentage of study gardens (26%) had visible evidence of debris (e.g., brick fragments) in some garden bed soils.

ICP analytical results and comparison to guidance values

Most analytes were detected in 100% of the soil samples. The exceptions were boron (B) (detected in 7% of samples; detection limit 16.7 mg/kg), molybdenum (Mo) (2%; 3.8 mg/kg), arsenic (As) (55%; 5.3 mg/kg), beryllium (Be) (89%; 0.1 mg/kg), Cd (15%; 0.4 mg/kg), and nickel (Ni) (97%; 2.8 mg/kg). Summary statistics for all analytes are presented in supplementary Table S1.

Given the absence of health-based soil standards for community gardens, metals concentrations were compared to guidance values based on residential-use soil cleanup objectives from New York State's Environmental Remediation Programs (the definition of "residential use" includes vegetable gardening (NYSDEC, 2006)). Those guidance values exist for ten metals (As, barium (Ba), Be, Cd, chromium (Cr), copper (Cu), Pb, manganese (Mn), Ni, and Zn). Metals concentrations were also compared to ranges of New York State rural soil background concentrations (NYSDEC and NYSDOH, 2006) and "urban background" concentrations measured in a study of ornamental gardens, cemetery lawns, grass-covered vacant lots, and grass-covered courtyards in NYC (ConEdison, 2007).

One or more samples exceeded at least one guidance value in 70% of gardens in the study (Table 3). However, most soil samples (78%) were below guidance values for all ten metals. Garden bed samples were below guidance values more often (81%) than non-bed samples (59%).

Ba was the metal most frequently exceeding a guidance value, exceeding 350 mg/kg in 12% of beds and 14% of all samples. Nearly half (46%) of the gardens in the study had at least one sample above the 350 mg/kg Ba guidance value, with concentrations ranging up to 1420 mg/kg. The median Ba concentration (93 mg/kg) was similar to the median of urban background concentrations (99 mg/kg; n = 25), but higher than the rural background median of 67 mg/kg (n = 118) (Figure 2). Twenty-nine percent of samples exceeded the 95th percentile of NYS rural soil background concentrations, suggesting an anthropogenic source. Possible sources of Ba include $BaSO_4$ in construction debris (e.g., some types of glass and brick products, dyes and pigments used in paints) , wear of tires and brake linings (Harrison et al., 2012) and $BaCO_3$ in rodenticides (ATSDR, 2007a). Although rodenticides are commonly used in community gardens, $BaCO_3$-containing rodenticides are not registered for use in NYS.

Pb concentrations also exceeded guidance values relatively frequently, with 9% of beds and 10% of all samples exceeding the 400 mg/kg guidance value, and a maximum concentration of 2,450 mg/kg. In 44% of gardens, at least one sample exceeded the Pb guidance value. The median Pb concentration in all bed and non-bed samples (102 mg/kg) exceeded the median rural background concentration of 23 mg/kg but was below the median urban background concentration (211 mg/kg), and Pb concentrations were generally at the low end of the range reported in studies of urban garden soils (Table 4). Pb is a common urban soil contaminant, attributed to sources including lead-based paint, leaded gasoline emissions, and point sources such as waste incinerators and metal smelters (ATSDR, 2007b; ConEdison, 2007; US EPA, 1998).

As and Cr exceeded guidance values in 3% and 2% of samples, respectively. The laboratory's reporting limit for As (5.3 mg/kg) was too high to allow comparison with rural background concentrations (median 5 mg/kg), but As was generally below the range of urban background concentrations and did not appear to be a significant contaminant in NYC community garden soils. Cr concentrations exceeded rural background concentrations but were not elevated with respect to the range of urban background concentrations. Cu and Zn concentrations were elevated, with 59% of Cu results and 49% of Zn results exceeding the 95th percentile of rural background concentrations, but were similar to urban background concentrations and exceeded guidance values in just one sample each. Be, Mn and Ni were not elevated with respect to rural background (1% of results exceeded median background concentrations for Be and Mn, and 43% for Ni) and were below guidance values in all samples.

Cd, which was detected in 15% of samples analyzed by ICP-OES, exceeded the 2.5 mg/kg guidance values in 0.5% of samples; however, ICP-OES analysis may be unreliable because of spectral interferences, tending to overestimate Cd content at low (near-background) levels in soil (McBride, 2011).

1M HNO_3 extraction/FAA analysis results

Extraction using 1M HNO_3 and measurement of Cd and Zn by FAA provides a simple, inexpensive and rapid means of reliably estimating total Cd and Zn in urban garden soils. This screening method has advantages over the standard digestion and ICP-OES analysis method (EPA Method 3051A/6010C) for Cd in particular both because of the different characteristics of the detection methods (atomic absorption vs. emission spectrometry) and because 1M HNO_3 extracts contain lower concentrations of interfering elements than concentrated acid digests of soils.

FAA analysis for acid-extractable Cd was more sensitive than ICP-OES analysis for total Cd, showing detectable Cd in all 107 samples analyzed by this method. Extractable Cd measurements correlated only weakly ($r^2 = 0.336$) with ICP-OES Cd results, a phenomenon reported previously by McBride (2011). Fortunately, previous research with Cd-contaminated soils from urban gardens and other sites has established that 1 M HNO_3-extractable Cd measured using FAA provides a very good estimate of total Cd as determined by ICP-mass spectrometry analysis of acid digests of soil (McBride, 2011). The relationship between acid-extractable and total Cd is given by :

$$\text{Cd}(HNO_3) = 0.036 + 0.82\ \text{Cd (Total)} \quad (r = 0.95)$$

This relationship allows total Cd concentrations to be estimated in the subset of 107 samples. Estimated total Cd ranged from <0.02 mg/kg to 4.2 mg/kg, with a median concentration of 0.41 mg/kg. Estimated total Cd exceeded the 2.5 mg/kg guidance value in 3 samples (2.8%).

HNO_3-extractable Zn concentrations correlated very well with ICP-OES Zn results:

$$\text{Zn}(HNO_3) = -26 + 0.85\ \text{Zn (Total)} \quad (r = 0.96)$$

The HNO_3-extractable Cd concentration measured by FAA was strongly correlated with both HNO_3-extractable Zn measured by FAA and total Zn measured by ICP-OES.

$$\log (Cd) (HNO_3) = -1.97 + 0.76 \log (Zn) (HNO_3) \quad (r = 0.87)$$

$$\log (Cd) (HNO_3) = -2.25 + 0.83 \log (Zn) (Total) \quad (r = 0.90)$$

The latter relationship is shown in Figure 3. These correlations show that urban garden soils higher in Zn tend to have proportionately higher Cd as well.

On a linear scale, the best-fit relationship between 1 M HNO_3-extractable Cd and 1 M HNO_3-extractable Zn is:

$$(Cd) (HNO_3) = 0.23 + 0.0016 (Zn) (HNO_3) \quad (r = 0.78)$$

The slope of this line represents the average Cd/Zn ratio in the 1 M HNO_3 extracts, corresponding to a Zn/Cd ratio of 620, which is within the expected range based on the relative geochemical abundance of the two metals (McDonough and Sun, 1995).

The strong correlation between Cd and Zn concentrations suggests a common source. Galvanized steel, found in fences, gutters and metal roofs, is a possible source of both metals in urban garden soils. Other possibilities include rubber tires, which are often used in urban gardens, and particles from tire abrasion along streets and highways.

The correlation suggests that concentrations of Zn – a micronutrient measured in standard, inexpensive agricultural soil tests – may be considered as an indicator of concentrations of Cd in soils, which may be a health concern if elevated. Testing for soil nutrients (including Zn) can be relatively simple and inexpensive (on the order of US$10 - $15 per sample), whereas testing for environmental contaminants such as Cd can be much more costly for a gardener. Gardeners in NYC can consider that soils with unusually high Zn concentrations may be likely to have higher concentrations of Cd, and they can use that information to inform decisions about further soil testing or exposure reduction efforts.

Electron microprobe results

In a number of urban garden soils selected based on their high Pb concentrations, we identified both Pb-rich and Ba-rich particles with dimensions on the order of 5-20 µm. Elemental mapping showed the Pb-rich particles to contain relatively high phosphorus (P) and chlorine (Cl) (results not shown), consistent with the presence of the lead phosphate mineral pyromorphite. In contrast, the Ba-rich particles were invariably associated with high S (Figure 4), suggesting the Ba is likely present in the form of barite ($BaSO_4$), which is highly insoluble and much less toxic than more soluble forms of the element (Lamb et al., 2013).

Factors influencing soil contaminant concentrations

Summary statistics for all analytes are available in supplemental Tables S1 and S2. Elements that were detected in fewer than 20% of samples (B, Mo, Cd) or that were most often present at concentrations close to laboratory reporting limits (As, Be) were excluded from further statistical analysis.

Concentrations of Ba, Pb and Zn were higher in non-bed samples than in bed samples (Wilcoxon signed-rank test comparing paired non-bed samples with garden means for bed samples; $p = 0.002$ (Ba and Zn), $p = 0.0002$ (Pb)), higher in non-raised beds than in raised beds (Figure 5; modified Wilcoxon rank-sum test; $p = 0.003$ (Ba), $p = 0.002$ (Pb), $p = 0.005$ (Zn)), and higher in beds with visible brick fragments – considered an indicator of the presence of "native" urban soil rather than imported soil – than in those without (Figure 6; modified Wilcoxon rank-sum test; $p = 0.0004$ (Ba); $p = 0.007$ (Pb); $p = 0.002$ (Zn)). These results are consistent with the advice often given to urban gardeners to use raised beds and imported soil and compost to help reduce exposure to soil contaminants (Clark et al., 2008; Finster et al., 2004). Maintaining raised beds by adding clean compost often is also important, as airborne soil particles from outside the beds can be a source of contamination to garden beds over time (Clark et al., 2008).

There were some other significant differences ($p < 0.05$) between categories. Iron (Fe), Ni and pH levels were significantly higher in non-bed samples than in garden beds, while C and N concentrations were higher in beds (likely a result of plant cultivation and/or soil amendment in the growing beds); P was significantly higher in raised beds than in non-raised beds (also possibly related to soil amendment); and Ca, Na, and pH levels were significantly higher in beds with visible brick fragments than in beds without.

The association between pH and metals concentrations (Figure 7) may indicate that the same practices that result in lower metals concentrations (e.g., adding clean soil or compost) may also tend to reduce pH in the existing urban soil, which has a tendency to be neutral to slightly alkaline before amendment. Many metals tend to be more soluble at lower pH (Sauvé et al., 2000), which causes them to leach out of soil more readily. Furthermore, the addition of high levels of organic matter to soils can mobilize some metals into the soluble phase by the formation of complexes with dissolved organic matter (Kalbitz and Wennrich, 1998).

No significant differences in metals concentrations were observed between the 44 gardens in the initial study and the 10 gardens in the second phase (those that had recently been cited for violations) (modified Wilcoxon signed-rank test; $p > 0.05$).

A number of elements were significantly correlated with one another (summarized in Table S3). A particularly strong intercorrelation was observed among Ba, Pb, and Zn (Figure 8; Spearman $\rho = 0.85$ – 0.92, $p < 0.0001$). These metals may share some common sources in an urban environment – all have been used in paints, for instance (Toch, 1916), and all are associated with historical or ongoing automobile usage (Ba in brake linings and tires; Zn in tires; and Pb in leaded gasoline). As discussed for Cd above, the strong relationship among metals may allow Zn, which is commonly measured in soil nutrient analyses, to function as an indicator of other anthropogenic heavy metals in urban garden soils. Soils in which relatively inexpensive soil nutrient tests show unusually high Zn concentrations may be more likely to be contaminated with other metals, and gardeners can use this information to help guide efforts to reduce exposure to Pb and other metal contaminants.

Principal component analysis

Principal component analysis (PCA) of the soil results yielded four components with eigenvalues greater than 1, explaining 75% of the total variance in the results (Table 5). The first of the rotated components, explaining 25% of the total variance, had relatively high loadings of Al, cobalt (Co), Fe, titanium (Ti), vanadium (V), Mn, Ni, potassium (K), and lithium (Li), elements that occur naturally in soils over a wide range of concentrations and can be related to natural properties such as soil mineralogy and texture. Component 2 accounts for 19% of the variance and has higher loadings of C, N, P and sulfur (S), elements associated with organic matter and nutrient content. Components 3 and 4 (explaining 17% and 14% of the variance) have higher loadings of elements that likely indicate anthropogenic contamination: Ba, Cu, Pb, and Zn in component 3 and Ba, Ca, Na, Zn in component 4, which also has a strong loading for pH. The groupings suggest there may be two different types of sources of heavy metal contamination, one of which is associated with higher pH soils (component 4). The predominant elements of component 3 are consistent with contamination sources such as paint and auto emissions, while the elements in component 4 may be associated with masonry building materials such as brick, concrete and mortar, which can contain calcium compounds (carbonates and oxides) that are likely to raise soil pH.

The PCA results suggest that concentrations of anthropogenic contaminants, represented in components 3 and 4, to some degree vary independently of soil type (component 1) and organic matter/nutrient content (component 2). Fe is an exception; its high loading on components 1 and 3 are consistent with its being a native element in soil whose concentrations may be enriched anthropogenically. The results also suggest that, while Pb, Ba and Zn are strongly intercorrelated, there is an additional source of Ba and Zn that is not associated with Pb, but that is associated with Ca, Na, and higher pH.

Conclusions

This is the first systematic study of the nature and extent of metals contamination in NYC community garden soils. While Pb and other metals were frequently found in excess of rural background concentrations, the majority of samples were consistent with urban background concentrations measured by others. Pb and Ba, which tended to be co-located with one another and with Zn, were generally below health-based guidance values but exceeded these values much more frequently than other metals such as As and Cr.

Pb poses the most significant exposure concern of the metals measured in this study. Although Ba exceeded guidance values more often than Pb, it is likely present primarily as insoluble $BaSO_4$, which is much less toxic than the soluble Ba for which soil guidance values were derived (NYSDEC, 2006). Nearly half (44%) of the 54 gardens had at least one sample above the guidance value for Pb, although only 10% of all soil samples in this study exceeded the guidance value, and Pb concentrations in NYC community garden bed soils (median 96 mg/kg) and non-bed soils (median 181 mg/kg) are relatively low compared to concentrations reported in other studies of urban garden soils in the US and UK (Table 4). Still, background levels of exposure to Pb have been elevated in many neighborhoods with community gardens, and exposure to Pb is considered potentially harmful even at concentrations below the guidance value, as no threshold for adverse effects has been identified (Miranda et al., 2007). Community gardeners would benefit from efforts to reduce exposure to Pb. Practices already in use by some gardeners, such as gardening in raised beds, importing clean soil and compost (without elevated concentrations of Pb or other contaminants) for bed establishment, and maintaining beds by frequently adding clean compost are helping to reduce the potential for gardening-related exposures to soil contaminants. These practices should continue to be encouraged among urban gardeners.

The spatial variability of contaminant concentrations presents a challenge to urban community gardeners with a limited budget for soil testing. Within any single garden in this study, Pb concentrations varied by a factor of 1.3 to 61, and Ba concentrations varied by a factor of 1.3 to 37. On average, there was an 11-fold difference between the lowest and highest Pb concentrations and an 8-fold difference in Ba concentrations within a garden. While soil testing is the only way to determine whether garden soil in a particular location has elevated concentrations of contaminants such as Pb, the results of this study suggest that other indicators of contamination – such as higher soil pH, higher concentrations of Zn measured in soil nutrient tests, presence of native soil as indicated by brick fragments or other debris, and lack of raised beds – may be useful in guiding soil sampling to efficiently identify areas of concern with fewer soil samples and lower analytical costs where resources are limited. Additionally, the widespread adoption of healthy gardening practices (e.g., using raised beds, importing clean soil and compost, maintaining soil pH near neutral, covering areas of bare soil, limiting disturbance of dry soil to minimize soil resuspension, and using proper hygiene and food-preparation practices to limit contact with soil) is a fundamentally important strategy to reduce human exposures, particularly where resources for full site assessment are limited.

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Table 1 NYC Community Health Survey and housing age data for areas in NYC with study gardens and other community gardens

Areas in NYC	# of Community Gardens	# of ZIP Code Tabulation Areas (ZCTAs)[a]	# of Neighbor-hoods (UHF 34)[b]	Percentage of Housing Built Before 1950, Median of ZCTA Values, 2007 - 2011[a]	NYC Community Health Survey[c] Median Percentage in UHF 34 Neighborhoods, 2009	
					Below Poverty Level	Ate No Fruits or Vegetables Yesterday[d]
With Study Gardens	54	30	16	57%[e]	24%[f]	17%
Without Study Gardens	429	149	18	49%[e]	13%[f]	11%
With Community Gardens	483	83	29	56%[g]	19%[d]	12%
Without Community Gardens	0	96	5	45%[g]	12%[d]	8%

[a] U.S. Census Bureau, 2011. "Zip Code Tabulation Areas" are geographic areas defined by the U.S. Census Bureau to align census data with U.S. Postal Service ZIP Code service areas.

[b] NYC is divided into 34 United Hospital Fund Neighborhoods ("UHF34").

[c] NYC DOHMH, 2012

[d] Differences are not statistically significant; $p > 0.05$ (Student's t test)

[e] Difference is not statistically significant; $p > 0.05$ (Mann-Whitney U test)

[f] Statistically significant difference; $p = 0.03$ (Student's t test)

[g] Statistically significant difference; $p = 0.002$ (Mann-Whitney U test)

Table 2 Study garden characteristics

Number of study gardens	54 gardens
Number of beds per garden, median (range)	22 (2 - 115) beds
Garden size (acres), median (range)	0.160 (0.032 - 1.17) ac.
Garden age[a] (years), median (range)	20 (1 - 57) years
Gardens with raised beds (%)	89%
Gardens growing in non-raised beds (%)	48%
Gardens with observable brick chips in beds (%)	26%
Gardens with bare soil in non-bed areas (%)	56%
Gardens receiving soil delivery in last 5 years (%)	39%
Gardens receiving soil delivery in last 10 years (%)	69%
Gardens receiving compost delivery in last 10 years (%)	66%

[a] Garden age information available for 21 of 54 gardens

Table 3 Soil guidance value[a] exceedances in 508 beds and 56 non-bed areas from 54 NYC community gardens

Element	Guidance Value (mg/kg)	Gardens with Bed Exceedances	Gardens with Bed or Non-bed Exceedances	Beds with Exceedances	Non-Beds with Exceedances
Arsenic	16	15%	17%	3.1%	3.6%
Barium	350	31%	46%	12%	29%
Beryllium	14	0.0%	0.0%	0.0%	0.0%
Cadmium	2.5	3.7%	5.6%	0.4%	1.8%
Chromium	36	9.3%	11%	2.2%	1.8%
Copper	270	0.0%	1.9%	0.0%	1.8%
Lead	400	31%	44%	9.1%	23%
Manganese	2000	0.0%	0.0%	0.0%	0.0%
Nickel	140	0.0%	0.0%	0.0%	0.0%
Zinc	2200	1.9%	1.9%	0.2%	0.0%
All Metals		54%	70%	19%	41%

[a]Guidance values are NYSDEC Residential Soil Cleanup Objectives (NYSDEC, 2006)

Table 4 Lead concentrations in studies of urban garden soils in order of median concentration

Study	Number of Samples	Lead Concentration (mg/kg)			
		Min.	Median	Mean	Max.
Witzling 2010, garden averages, Chicago, IL	10	35	93	143	449
This study, individual bed samples, NYC	508	11	96	204	1251
Bugdalski 2014, individual garden samples, Detroit, MI	80	17	116	151	882
Stilwell 2008, gridded composite samples, CT	174	10	176	330	3490
This study, individual non-bed samples, NYC	56	27	181	326	2455
Preer 1984, individual garden samples, downtown Washington, DC	95	44	480	680	5300
Chaney 1984, garden averages, inner-city Baltimore, MD	50	46	573	1171	10900
Culbard 1988, individual garden samples, London boroughs, UK	578	60	654	NA[a]	13700
Clark 2008, individual garden samples, Roxbury and Dorchester, MA	692	80	800	950	3680

[a] Culbard et al. presented a geometric mean lead concentration.

Table 5 Rotated component loading matrix and variance explained. Bold numbers indicate the most important elements in each component (> 0.5).

Element/ Parameter	Component			
	1	2	3	4
pH	0.07	-0.09	-0.01	**0.71**
C	-0.07	**0.95**	0.06	0.06
N	-0.12	**0.95**	0.01	-0.01
Al	**0.81**	-0.19	0.21	-0.21
Ca	0.18	0.48	0.12	**0.75**
Co	**0.80**	0.08	0.39	0.22
Fe	**0.73**	-0.10	**0.54**	0.10
K	**0.73**	0.42	-0.07	0.35
Li	**0.89**	0.02	0.23	0.14
Mg	0.42	**0.54**	-0.07	0.44
Na	0.29	0.40	0.23	**0.67**
P	0.20	**0.64**	0.48	-0.21
S	0.07	**0.87**	0.14	0.30
Ti	**0.82**	-0.03	-0.04	0.19
V	**0.69**	0.05	0.48	0.17
Ba	0.09	0.01	**0.56**	**0.68**
Cr	0.22	0.09	0.36	-0.03
Cu	0.19	0.18	**0.79**	0.01
Mn	**0.61**	0.35	0.44	0.12
Ni	**0.52**	0.30	0.45	0.33
Pb	0.16	-0.05	**0.81**	0.26
Zn	0.12	0.04	**0.69**	**0.60**
Total variance	5.4	4.2	3.7	3.2
% of variance	25%	19%	17%	14%
Cumulative %	25%	43%	60%	75%

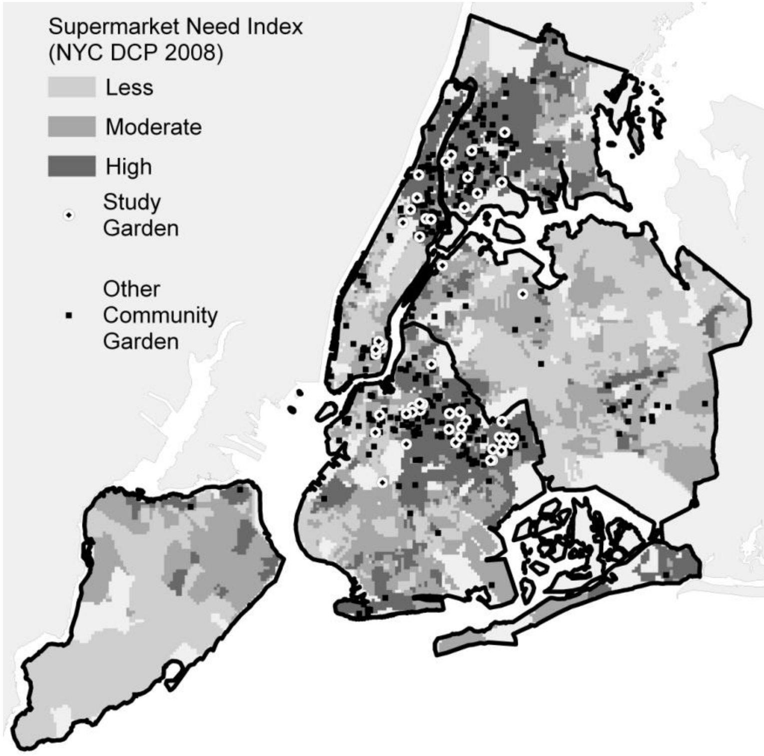

Figure 1 NYC community garden locations and Supermarket Need Index developed by NYC Department of City Planning to determine the areas with the "highest levels of diet-related diseases and largest populations with limited opportunities to purchase fresh foods" (NYC DCP 2008). For various reasons, many community gardens are located in areas with greater need for access to fresh foods. SNI material used with permission of the New York City Department of City Planning.

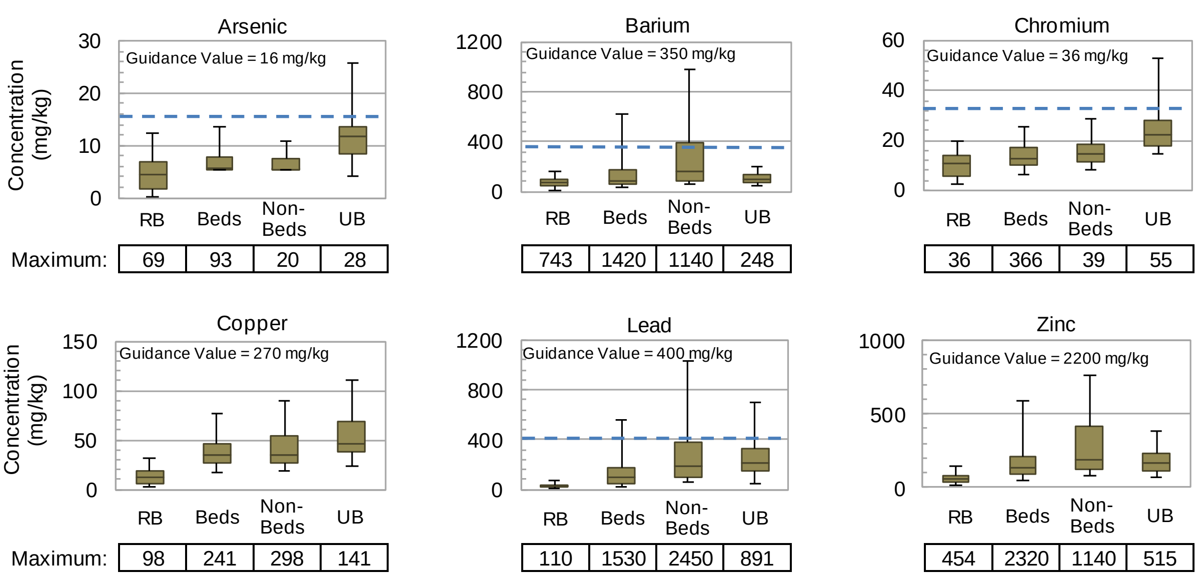

Figure 2 Concentrations of selected metals in study garden beds (n = 508) and non-bed areas (n = 56) compared with NYS rural soil background concentrations (n = 118) ("RB"; NYSDEC 2006), urban soil background concentrations (n = 25-27) ("UB"; ConEd 2007), and guidance values (NYSDEC 2006). Boxes represent 25th, 50th and 75th percentiles; whiskers represent 5th to 95th percentiles. Dashed lines are guidance values.

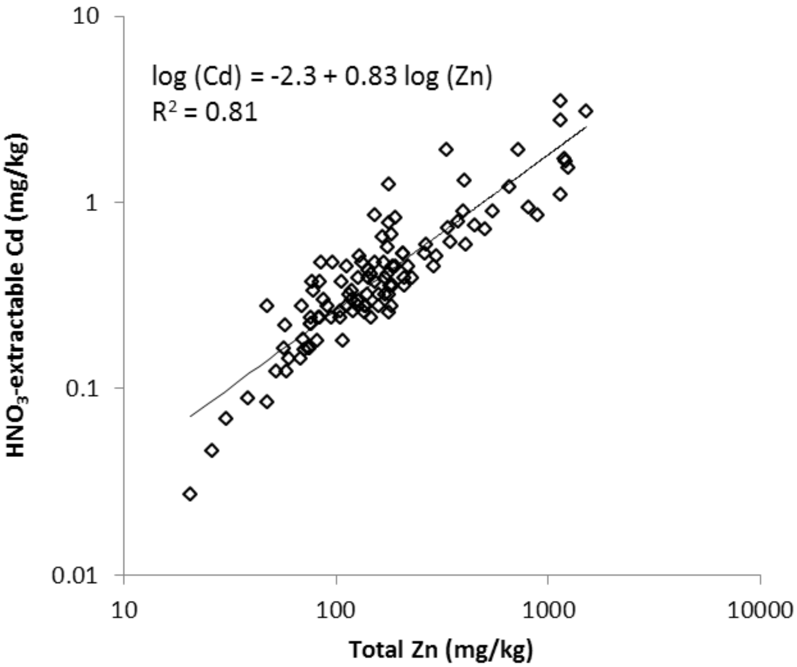

Figure 3 Acid-extractable Cd vs total Zn in 107 NYC community garden soil samples.

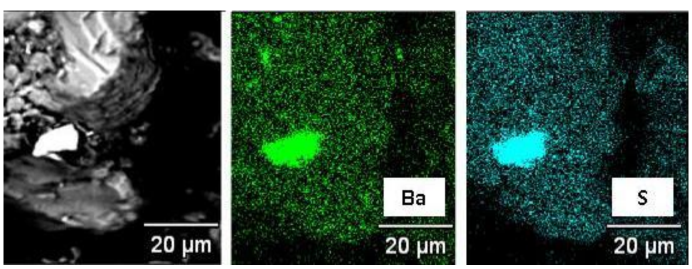

Figure 4 Electron microprobe mapping showing colocation of Ba and S in a soil sample from a NYC community garden.

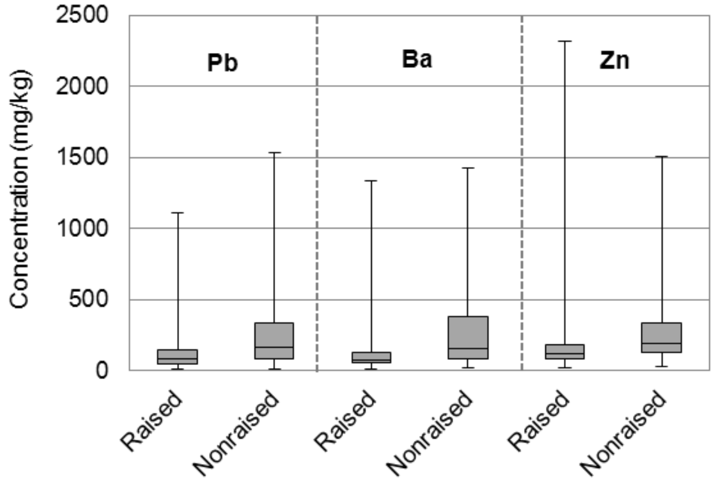

Figure 5 Ranges and 25th, 50th and 75th percentiles of Pb, Ba and Zn in raised (n=376) vs. nonraised (n=120) beds. Concentrations were significantly greater (p = 0.002 - 0.005) in nonraised beds.

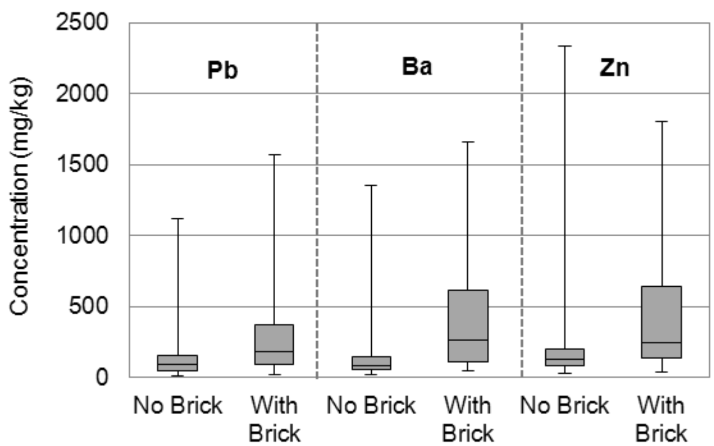

Figure 6 Ranges and 25th, 50th and 75th percentiles of Pb, Ba and Zn n beds with visible brick fragments (n=449) vs. beds without (n=59). Concentrations were significantly greater (p = 0.0004 - 0.007) in beds with visible brick fragments.

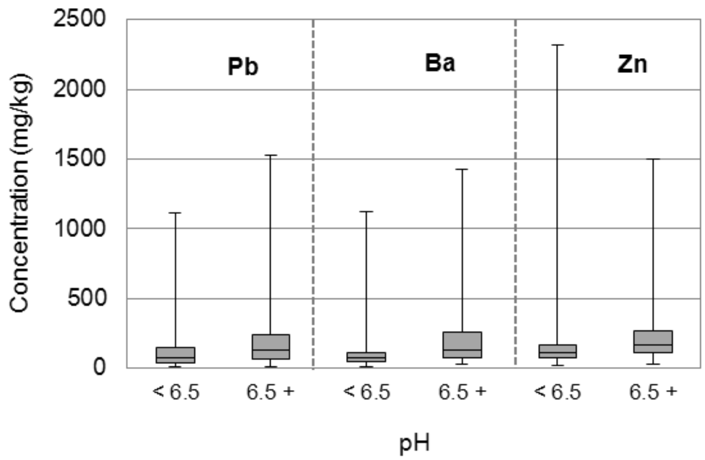

Figure 7 Ranges and 25th, 50th and 75th percentiles of Pb, Ba and Zn in garden beds with pH < 6.5 (n = 261) vs. beds with pH 6.5 or higher (n = 247). Concentrations were significantly greater (p = 0.00003 - 0.001) in beds with pH 6.5 or higher.

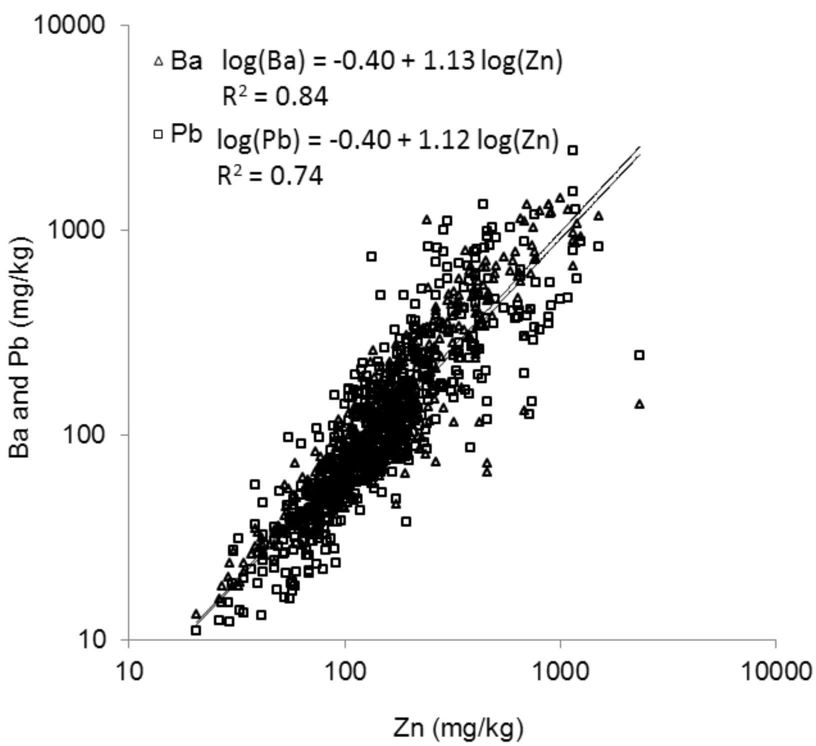

Figure 8 Total Pb and Ba vs total Zn in 564 NYC community garden soil samples

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Supplementary Tables

Table S1 Summary of analytical results for 564 soil samples collected from 54 NYC community gardens

Analyte	Concentration (mg/kg, except pH, C (%), N(%))							% samples detected
		Percentile						
	Min	5	25	50	75	95	Max	
pH	4.78	5.61	6.19	6.52	6.83	7.29	7.85	100%
C	1.0	2.5	3.6	4.8	6.9	13.7	27.2	100%
N	0.01	0.07	0.15	0.22	0.34	0.72	1.48	100%
C:N	14	16	19	22	25	38	172	100%
Al	1624	3663	4658	5679	6835	8856	12535	100%
B	< 16.7	< 16.7	< 16.7	< 16.7	< 16.7	17.8	40.4	7%
Ca	1018	2440	4686	7057	11801	28652	70817	100%
Co	< 0.8	1.9	2.7	3.5	4.6	6.6	10.8	100%
Fe	3178	5904	7690	9376	11856	16612	26724	100%
K	155	302	470	675	957	1671	3572	100%
Li	2.1	3.5	4.6	5.7	7.2	9.7	17.1	100%
Mg	522	1091	1713	2341	3305	5879	27695	100%
Mo	< 3.8	< 3.8	< 3.8	< 3.8	< 3.8	2.9	7.9	2%
Na	9	22	39	54	84	174	311	100%
P	147	424	712	929	1231	1852	2718	100%
S	61	227	341	474	723	1291	2598	100%
Ti	38	71	96	119	149	267	620	100%
V	5.9	10.0	14	17.2	23	33	72.0	100%
As	< 5.3	< 5.3	< 5.3	5.7	7.8	13.1	93.2	55%
Ba	13	34	60	93	189	663	1422	100%
Be	< 0.1	< 0.1	0.1	0.2	0.2	0.4	1.3	89%
Cd	< 0.4	< 0.4	< 0.4	< 0.4	< 0.4	0.8	3.1	15%
Cr	3	7	10	13	17	26	366	100%
Cu	6	17	27	35	47	80	598	100%
Pb	11	24	55	102	189	659	2455	100%
Mn	56	115	166	213	281	382	673	100%
Ni	< 2.8	4	7	10	14	21	38	97%
Zn	21	50	91	138	214	644	2317	100%

Table S2 Median and range of analytical results for 564 bed and non-bed soil samples from 54 NYC community gardens (mg/kg, except pH, C (%) and N (%))

Analyte	All Samples (n = 564)			Beds (n = 508)			Garden Bed Means (n = 54)			Non-beds (n = 54)			Guidance
	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max	Value
pH	4.78	6.52	7.85	4.96	6.48	7.85	5.67	6.53	7.17	4.78	6.81	7.62	-
C	1.0	4.8	27.2	1.0	4.9	27.2	1.4	5.2	14.5	1.7	3.7	14.0	-
N	0.01	0.22	1.48	0.02	0.23	1.48	0.07	0.24	0.85	0.01	0.15	0.44	-
C:N	14	22	172	14	21	110	17	22	44	15	25	172	-
Al	1624	5679	12535	1624	5642	12535	3688	5676	8206	2322	6087	11896	-
B	< 16.7	< 16.7	40.4	< 16.7	< 16.7	40.4	< 16.7	< 16.7	26.5	< 16.7	< 16.7	20.3	-
Ca	1018	7057	70817	1401	7202	56144	1715	7598	41582	1018	6440	70817	-
Co	< 0.8	3.5	10.8	< 0.8	3.4	10.8	1.9	3.6	7.6	1.8	4.1	9.3	-
Fe	3178	9376	26724	3178	9204	26724	5461	9399	16768	5984	12006	25586	-
K	155	675	3572	155	679	3119	337	753	1747	174	596	3572	-
Li	2.1	5.7	17.1	2.1	5.7	14.4	3.3	5.8	9.7	2.1	5.9	17.1	-
Mg	522	2341	27695	522	2379	15747	937	2545	5693	779	2111	27695	-
Mo	< 3.8	< 3.8	7.9	< 3.8	< 3.8	7.9	< 3.8	< 3.8	4.4	< 3.8	< 3.8	< 3.8	-
Na	9	54	311	9	54	311	21	60	215	10	52	298	-
P	147	929	2718	147	947	2718	258	990	1817	261	697	2632	-
S	61	474	2598	87	487	2598	138	514	1399	61	396	1709	-
Ti	38	119	620	41	119	620	69	125	483	38	112	567	-
V	5.9	17.2	72.0	5.9	17.2	61.8	10.6	17.0	32.1	7.2	18.4	72.0	-
As	< 5.3	5.7	93.2	< 5.3	5.8	93.2	< 5.3	< 5.3	22.8	< 5.3	5.6	20.0	16
Ba	13	93	1422	13	89	1422	36	101	1172	44	167	1143	350
Be	< 0.1	0.2	1.3	< 0.1	0.2	1.3	< 0.1	0.2	0.5	< 0.1	< 0.1	0.6	14
Cd	< 0.4	< 0.4	3.1	< 0.4	< 0.4	3.1	< 0.4	< 0.4	0.9	< 0.4	< 0.4	2.9	2.5
Cr	3.2	12.8	366.1	3.2	12.6	366.1	5.9	12.9	64.0	4.7	14.4	39.2	22
Cu	6	35	598	8	35	241	15	37	94	6	35	598	270
Pb	11	102	2455	11	96	1531	25	118	817	27	181	2455	2000
Mn	56	213	673	56	211	673	108	214	362	113	257	442	140
Ni	< 2.8	10	38	< 2.8	10	38	< 2.8	10	18	4.2	13	35	400
Zn	21	138	2317	21	135	2317	41	139	822	53	190	1142	2200

Table S3 Spearman correlation coefficients for pH and elemental concentrations in NYC garden soils. Darker shading indicates stronger correlations.

	pH	C	N	C:N	Al	Ca	Co	Fe	K	Li	Mg	Na	P	S	Sr	Ti	V	Ba	Cu	Cr	Mn	Ni	Pb	Zn
pH	1.00	-0.05	-0.12	0.17	-0.01	0.44	0.19	0.18	0.29	0.15	0.29	0.41	-0.08	0.16	0.41	0.14	0.10	0.41	0.07	0.13	0.16	0.26	0.31	0.36
C	-0.05	1.00	0.93	-0.38	-0.11	0.57	0.16	-0.02	0.40	0.07	0.48	0.43	0.53	0.73	0.62	0.08	0.18	0.15	0.37	0.19	0.35	0.28	0.10	0.25
N	-0.12	0.93	1.00	-0.66	-0.17	0.46	0.03	-0.12	0.29	-0.05	0.38	0.31	0.54	0.66	0.52	0.00	0.03	0.03	0.31	0.09	0.24	0.15	-0.01	0.13
C:N	0.17	-0.38	-0.66	1.00	0.24	-0.09	0.24	0.28	0.04	0.27	-0.06	0.05	-0.33	-0.23	-0.12	0.18	0.27	0.20	-0.04	0.15	0.07	0.17	0.23	0.14
Al	-0.01	-0.11	-0.17	0.24	1.00	-0.03	0.64	0.76	0.43	0.79	0.21	0.22	0.24	0.00	0.07	0.67	0.69	0.21	0.38	0.53	0.49	0.40	0.20	0.19
Ca	0.44	0.57	0.46	-0.09	-0.03	1.00	0.42	0.24	0.62	0.32	0.82	0.77	0.45	0.77	0.94	0.27	0.38	0.57	0.47	0.39	0.52	0.55	0.43	0.62
Co	0.19	0.16	0.03	0.24	0.64	0.42	1.00	0.84	0.74	0.87	0.61	0.63	0.35	0.38	0.56	0.64	0.85	0.57	0.69	0.73	0.82	0.81	0.57	0.63
Fe	0.18	-0.02	-0.12	0.28	0.76	0.24	0.84	1.00	0.57	0.83	0.43	0.47	0.29	0.19	0.38	0.60	0.84	0.52	0.60	0.71	0.73	0.67	0.57	0.55
K	0.29	0.40	0.29	0.04	0.43	0.62	0.74	0.57	1.00	0.70	0.77	0.76	0.45	0.59	0.65	0.66	0.67	0.45	0.57	0.57	0.67	0.71	0.38	0.49
Li	0.15	0.07	-0.05	0.27	0.79	0.32	0.87	0.83	0.70	1.00	0.55	0.56	0.32	0.29	0.43	0.70	0.85	0.48	0.58	0.69	0.72	0.70	0.48	0.50
Mg	0.29	0.48	0.38	-0.06	0.21	0.82	0.61	0.43	0.77	0.55	1.00	0.77	0.45	0.65	0.76	0.47	0.56	0.46	0.52	0.49	0.65	0.65	0.39	0.53
Na	0.41	0.43	0.31	0.05	0.22	0.77	0.63	0.47	0.76	0.56	0.77	1.00	0.40	0.66	0.80	0.47	0.54	0.61	0.58	0.55	0.61	0.68	0.51	0.66
P	-0.08	0.53	0.54	-0.33	0.24	0.45	0.35	0.29	0.45	0.32	0.45	0.40	1.00	0.63	0.60	0.25	0.39	0.30	0.65	0.40	0.48	0.38	0.21	0.36
S	0.16	0.73	0.66	-0.23	0.00	0.77	0.38	0.19	0.59	0.29	0.65	0.66	0.63	1.00	0.81	0.25	0.36	0.40	0.58	0.35	0.51	0.48	0.31	0.47
Sr	0.41	0.62	0.52	-0.12	0.07	0.94	0.56	0.38	0.65	0.43	0.76	0.80	0.60	0.81	1.00	0.31	0.49	0.65	0.65	0.55	0.67	0.68	0.55	0.73
Ti	0.14	0.08	0.00	0.18	0.67	0.27	0.64	0.60	0.66	0.70	0.47	0.47	0.25	0.25	0.31	1.00	0.62	0.29	0.41	0.49	0.43	0.44	0.18	0.27
V	0.10	0.18	0.03	0.27	0.69	0.38	0.85	0.84	0.67	0.85	0.56	0.54	0.39	0.36	0.49	0.62	1.00	0.51	0.65	0.75	0.76	0.74	0.54	0.57
Ba	0.41	0.15	0.03	0.20	0.21	0.57	0.57	0.52	0.45	0.48	0.46	0.61	0.30	0.40	0.65	0.29	0.51	1.00	0.55	0.63	0.55	0.66	0.85	0.92
Cu	0.07	0.37	0.31	-0.04	0.38	0.47	0.69	0.60	0.57	0.58	0.52	0.58	0.65	0.58	0.65	0.41	0.65	0.55	1.00	0.67	0.72	0.70	0.56	0.68
Cr	0.13	0.19	0.09	0.15	0.53	0.39	0.73	0.71	0.57	0.69	0.49	0.55	0.40	0.35	0.55	0.49	0.75	0.63	0.67	1.00	0.69	0.79	0.65	0.70
Mn	0.16	0.35	0.24	0.07	0.49	0.52	0.82	0.73	0.67	0.72	0.65	0.61	0.48	0.51	0.67	0.43	0.76	0.55	0.72	0.69	1.00	0.77	0.58	0.64
Ni	0.26	0.28	0.15	0.17	0.40	0.55	0.81	0.67	0.71	0.70	0.65	0.68	0.38	0.48	0.68	0.44	0.74	0.66	0.70	0.79	0.77	1.00	0.68	0.75
Pb	0.31	0.10	-0.01	0.23	0.20	0.43	0.57	0.57	0.38	0.48	0.39	0.51	0.21	0.31	0.55	0.18	0.54	0.85	0.56	0.65	0.58	0.68	1.00	0.88
Zn	0.36	0.25	0.13	0.14	0.19	0.62	0.63	0.55	0.49	0.50	0.53	0.66	0.36	0.47	0.73	0.27	0.57	0.92	0.68	0.70	0.64	0.75	0.88	1.00