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Geospatial analysis and assessment of garden soil contamination in New York City

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Abstract. Elevated trace metal concentrations, in particular, lead (Pb), are prevalent in urban soils and it is one of the main hurdles for urban agriculture. The growing popularity of gardening in urban areas could also mean increased public health risk. In this study, the spatial distribution of Pb in New York City gardens was analyzed and visualized by Geographic Information System (GIS) tools. Pollution level and ecological risks of gardens and overall New York City (NYC) were evaluated with different indices. The degree of the contamination factors was ranked as follows: Pb >Cu > Zn > Cr>As>Ni>Cd. The single ecological risk index and potential ecological index indicated that Pb had moderate to significantly high risk to the local garden ecosystems. Based on the pollution load index, soil quality of the majority of NYC gardens were characterized as polluted. Geostatistical, geoprocessing, and spatial tools were used to create color-coded maps to support decision making related to gardening and to estimate potential human health risks from gardening, living, or working in/or near these gardens. These findings have important implications for the development of pollution prevention and mitigation strategies to reduce public health risk from garden soil trace metal contamination.

Key words: trace metals, GIS map, ecological index, lead, digital soil mapping, urban gardening

Notes. Authors declare no competing interests.

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Introduction

Soil contamination in urban environments has only started to receive attention over the past few decades, while water and air pollution have been widely recognized and federal and state legislation were developed in the US since the early part of 20th century [1]. Significant health risks to urban residents and particularly to gardeners can come from interaction with contaminated soil and consumion of garden produce. Urban gardening has increased significantly in recent years; therefore, the inherent risks of gardening in contaminated soil has become an important issue of public health as more urban residents become affected by soil contamination.

Urban soil is a sink for anthropogenic Pb and other contaminants. Trace metals are among the most recalcitrant and lasting contaminants in cities, posing major health concerns [2]. In urban gardening, principal contaminant exposure pathways to human body consist of ingestion and inhalation of soil particles (including those lodged in vegetables through splash and local re-deposition), as well as ingestion of trace metal-contaminated vegetables [3—5]. Lead is a known neurotoxin affecting nearly all bodily systems [1, 6, 7]. Common health consequences for children are behavioral or learning issues, decreased IQ, hyperactivity, delayed growth, hearing problems, anemia, and in rare cases, Pb exposure can lead to seizures, coma, or death [8, 9].

Soil trace metal contamination is mainly the result of historical deposition from past land use and proximity to polluting sources, such as power plants, incinerators, old houses, and vehicular traffic [10, 11], as well as geogenic sources [12,13]. According to an EPA report (14), three main sources responsible for the elevated soil-lead levels have been identified: (1) lead-based paint; (2) point source emitters; and (3) leaded gasoline emissions. Many studies cite more than one source as commonly responsible for elevated soil-lead levels at a given location.

Starting in 1973, the U.S. federal government initiated a gradual phase-out of Pb in gasoline, and by 1996, banned the sale completely [15]. However, gardens near busy streets may have accumulated higher levels of Pb in the topsoil. Today, Pb is still emitted from some manufacturing sites such as metal smelting, battery manufacturing, and other factories that use Pb in industrial processes. Although the Toxic Substances Control Act (TSCA) banned the use of Pb-based paint in 1978, flakes of lead-based paint on the outside of the old buildings can also get into the soil close to the foundation of buildings. Contaminated soil dust can be re-suspended by wind, and mobilized into homes and yards. Lead contaminated soil has been recognized as one of the major sources of Pb exposure in urban settings [16].

Urban soils are known to be very spatially heterogeneous, varying in parent material and biological, chemical, and physical properties [17]. High concentrations of trace metals are often reported around the world with high degree of variability. Trace metals in a soil vary in their availability to plants, soil creatures, and humans depending how these characteristics spatially fluctuate in the urban landscape due to functional zoning, proximity to roads, emissions, etc. [17]. Soil Pb distribution in many large cities has been investigated (e.g., [18—21], including New York City [22—25]. Previous studies have called for further detailed geospatial analysis of the data using large-scale Geographic Information Systems (GIS) for a better health-based assessment [26], as well as the evaluation of soil contamination in the context of risk to human health and threat to ecological systems. Thus, the aims of this study were: 1) to analyze the spatial distribution of Pb in NYC gardens, and 2) to assess pollution and ecological risk indices using available trace metal data.

Materials and methods

Data sources

The data on soil trace metal concentrations have been collected by the Brooklyn College Urban Soils Lab since 2009and the NYC Urban Soils Institute since 2016.This is part of a soil screening and testing service provided by the Labs to the public. Gardeners were instructed to collect soil from the surface down to depths of 14 to 20 cm (i.e., 6 inches) and composite soils collected from 5 to 10 locations around the garden. Each sample was recorded with a unique identification number, location, type of garden, soil trace metal concentration, and other soil characteristics such as pH, salts, organic matter content, and soil texture.

Soils are mostly screened by a portable X-ray fluorescence (pXRF) analyzer Innov-X Delta Classic [27], with some samples analyzed by Inductively coupled plasma mass spectrometry (ICP-MS) Perkin Elmer, Elan DRCe (EPA Method 6020a) following acid digestion with EPA Method 3052 [28, 29]. The pXRF scans were done directly on zip lock bags containing air-dried soil sent in by gardeners. Each sample was scanned three times with 90 sec exposure time. Samples were thoroughly mixed again between scans. Mean concentrations from the three scans were then recorded.

For external quality control for the ICP-MS analyzed samples reference standards SRM-2702, SRM-2586, SRM-2587, and SRM-2702a were used. Each batch digestion of up to 20samples always included at least three of these reference standards. Germanium was used as an internal standard for instrumental drift correction in all analyses. For the samples with both ICP-MS and pXRF analyses performed, there was good agreement between the two sets of Pb concentration data, with correlation coefficient of 0.94. It should be noted that Pb data include both ICP-MS data and pXRF data, but for other trace metals only ICP-MS data were used for this study.

The first map of Pb contamination for garden soils in New York City(NYC) was published in 2015 based on data for 1,652 garden soil samples, collected during the 2009—2014 period [23]. Li et al. (2017) added data from other land uses and from various sources and published a more comprehensive Pb distribution map for NYC. New data have been continuously collected, georeferenced and added to the original database. In total, there are 2322 garden soil samples in this study, collected during the 2009—2017 period (Fig. 3). A few samples could represent one garden with different soil management practices.

Shape files of Green Thumb Gardens, parks, schoolyards, playgrounds, NYC borough, and zip codes boundaries were downloaded from NYC Open data (https://nycopendata.socrata.com/). The list of NYC neighborhoods (Table 2) was found at the NYC Department of Health and Mental Hygiene Environment & Health Data Portal. Boundaries for 42 neighborhoods were retrieved from the Official Website of the City of New York (http://www.health.ny.gov/).

Geospatial analysis and visualization

ESRI ArcGIS 10.5 was used for geospatial analysis and visualization of the trace metal data. Lead concentration was interpolated by ordinary kriging (Fig. 3). Kriging allows predicting the value in unmeasured points based on the known data in neighboring points and spatial relationships between the points. Ordinary kriging uses dimensionless points to estimate other dimensionless points, e.g. Pb contour plots.

The Pb levels are shown in mg/kg and are classified into four categories (0 – 149 mg/kg, 150 – 399 mg/kg, 400 – 1200 mg/kg and > 1,200 mg/kg). The 1200 mg/kg threshold reflects USEPA standard for non-children play areas and the 400 mg/kg threshold reflects USEPA standard for children play areas (USEPA 2001). The 150 mg/kg value is an estimated threshold for soil Pb, reflective of the new Center for Disease Control and Prevention (CDC) guidance. Based on research conducted by the Toxics Cleanup Program Policy and Technical Support Unit, 2010, a level of 150 mg/kg of Pb in soil can lead to an approximate blood Pb level of 5μg/dl [31].

Soil pollution level and ecological risk assessment

To assess pollution levels and ecological risk of the garden ecosystems the following indices were used:

1. The contamination factors CF_i for the same metal was determined as $CF_i=C_m/B_m$, where C_m is the measured concentration of the examined metals in the soil samples, and B_m is the background concentration in unpolluted soils [32]. The following values used in this study Cd=0.5, Pb=19, Zn=65, As=5, Ni=17, Cu=14, Cr=13 were adapted from New York State Department of Environmental Conservation Rural Soil Background Survey [33].

2. The single ecological risk index $E_i=T_i \cdot CF_i$, where T_i is the toxic-response factor for a given metal (e.g. Cd=30, Pb=5, Zn=1, As=10, Ni=5, Cu=5, Cr=2) [32];

3. The potential ecological risk index $(PERI)=\sum(E_i)$ posed by multiple element pollution was originally proposed by Hakanson (1980) to assess heavy metal contamination of sediments. Later, it was adopted to evaluate heavy metal contamination in soils and to relate ecological and environmental effects with their toxicology and the toxic-response factor [34, 35].

4. The pollution load index introduced by Tomlinson et al. (1980): $PLI=(CF_1 \cdot CF_2 \cdot \ldots \cdot CF_n)^{(1/n)}$, where is the number of metals studied), gives simple comparative means for assessing a site quality. The PLI shows the number of times by which the metal concentration in the soil exceeds the average natural background content. It provides a total indication of the overall level of trace metal toxicity in a given sample. The PLI value of > 1 is considered as polluted, PLI <1 — no pollution and PLI=1 means that trace metal load is close to the background level [37].

Results and discussion

Assessment of soil quality using pollution and ecological risk indices

To assess quality of soils and their contamination levels different indices were used. Using the contamination factors (CF) showed in Table 1, it was possible to rank the following degree of contamination factors based on the mean values for 746 samples analyzed with the ICP-MS: Pb > Cu > Zn > Cr > As > Ni > Cd. The contamination factors were classified as follows: low (CF<1); moderate (1<CF<3); considerable (3<CF<6); and very high (CF>6). This shows that Pb had the highest CF, followed by Cu, Cr and Zn, and all of them fall into the “very high” contaminant factor category. In comparison, overall Cd and Ni fall into the “low” category. It should be noted that, however, the CF values for individual samples are highly variable, and sometimes can differ by 2-3 orders of magnitude. This is consistent with the extreme heterogeneities commonly found for urban soils.

Table 1

Summary statistics of the contamination factors (CF) for *n* = 746

	Cr	Ni	Cu	Zn	As	Cd	Pb
Mean	7	3	11	7	4	2	32
Max	254	131	342	265	120	96	379
Min	0.49	0.01	0.01	0.51	0.02	0.04	0.08
Std Dev	11	6	16	11	5	9	41

The calculated E_i — Single ecological risk index of the individual contaminants is represented on logarithmic scale in Fig. 1. It indicates that Pb had moderate to significantly high risk to the local ecosystem, while Zn, Cr, and Ni indicated low risks and other elements (As and Cd) showed low to moderate risk or moderate risk (Cu).

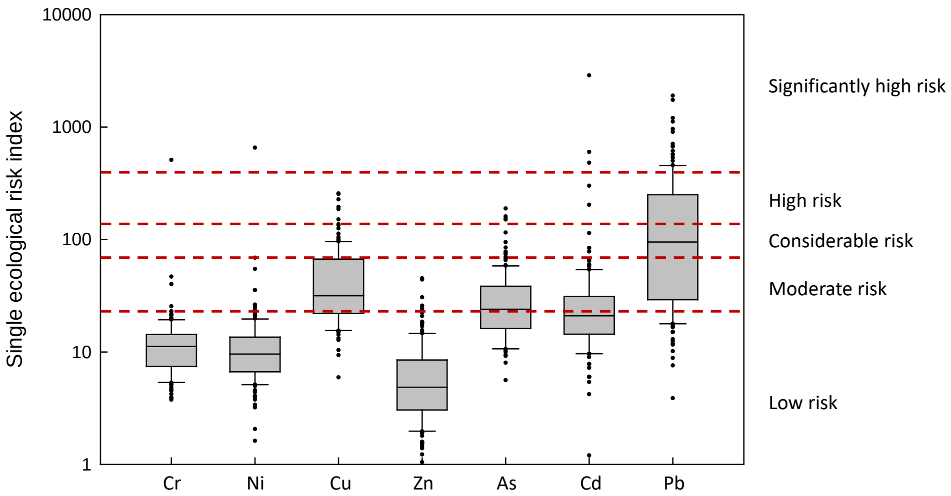

Fig. 1. Single ecological risk indices of the individual contaminants represented on the logarithmic scale

Contributions of individual trace elements to the overall potential ecological risk of the soil are represented on Fig. 2. The ecological risk comes mainly from soil pollution with Pb (46 %), consistent with the single ecological index (Ei) and the contaminant factor (CF). When the overall potential ecological risk (PERI) to the local ecosystems is considered, 12 % of the studied samples had very high PERI (>600), 28 % had considerable PERI (300-600), 30 % had moderate PERI (150-300), and another 30 % of the samples had low PERI (<150).

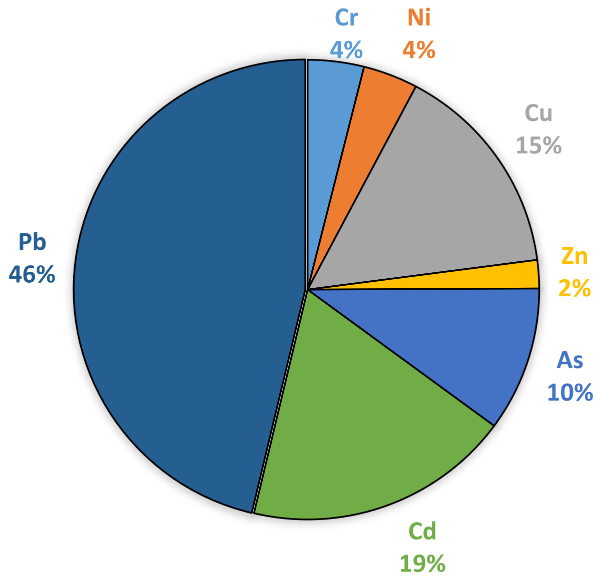

Fig. 2. Makeup of the mean potential ecological risk index calculated as the sum of the mean risk factors of the trace elements (351). The number next to the element represents percent contributions of individual trace elements to the mean potential ecological risk of the soils

The pollution load index gives simple comparative means for assessing a site quality. For the 746 samples, PLI ranged from 0.59 to 50 with mean of 4.6.PLI > 1 (polluted soil quality) indicates progressive deterioration [37]. Only 9 gardens or 1.2 % of samples were below 1.

Distribution of soil Pb in NYC gardens

Spatial patterns in Pb distribution was mapped and analyzed based on 2322 samplepoints from the compiled database (Fig. 3, Table 2). Each point on the map is a garden and may represent multiple samples that are from the same street address. Total Pb concentrations ranged from 3.3 to 45,076 mg/kg (mean 630 mg/kg and median 344 mg/kg). The highest Pb concentrations vary among different neighborhoods of northern and central Brooklyn. Two gardens were identified with Pb concentration over 10,000 mg/kg. The garden from the 11205 zip code (Downtown-Heights-Park Slope) had the highest Pb concentration found in this study 45,076 mg/kg (Fig. 3). There were 282 soil samples from 245 gardens with Pb concentrations exceeding 1,200 mg/kg. The largest number of samples (219) was from the 11238 zip code (Prospect Heights). If neighborhood (a district comprised of several zip code areas) is considered, the most number of samples (486) was collected from the Downtown-Heights-Park Slope area. The highest median Pb level among all zip codes (1,052 mg/kg) was found in the 11211 zip code in Greenpoint. The highest median (1,019 mg/kg) among the neighborhoods was found also in Greenpoint (Brooklyn). Columbia University study of soils from about 50 homes in Greenpoint show that 92 % of the yards tested had at least one sample above the residential soil standard for New York (https://greenpointpost.com/nearly-85-of-greenpoint-backyard-soil-samples-show-unsafe-lead-levels-by-epa-standards-study). It should be noted that there were not enough samples collected in eastern Queens, the Bronx and throughout Staten Island to confident lymap and predict Pb distributions in those areas.

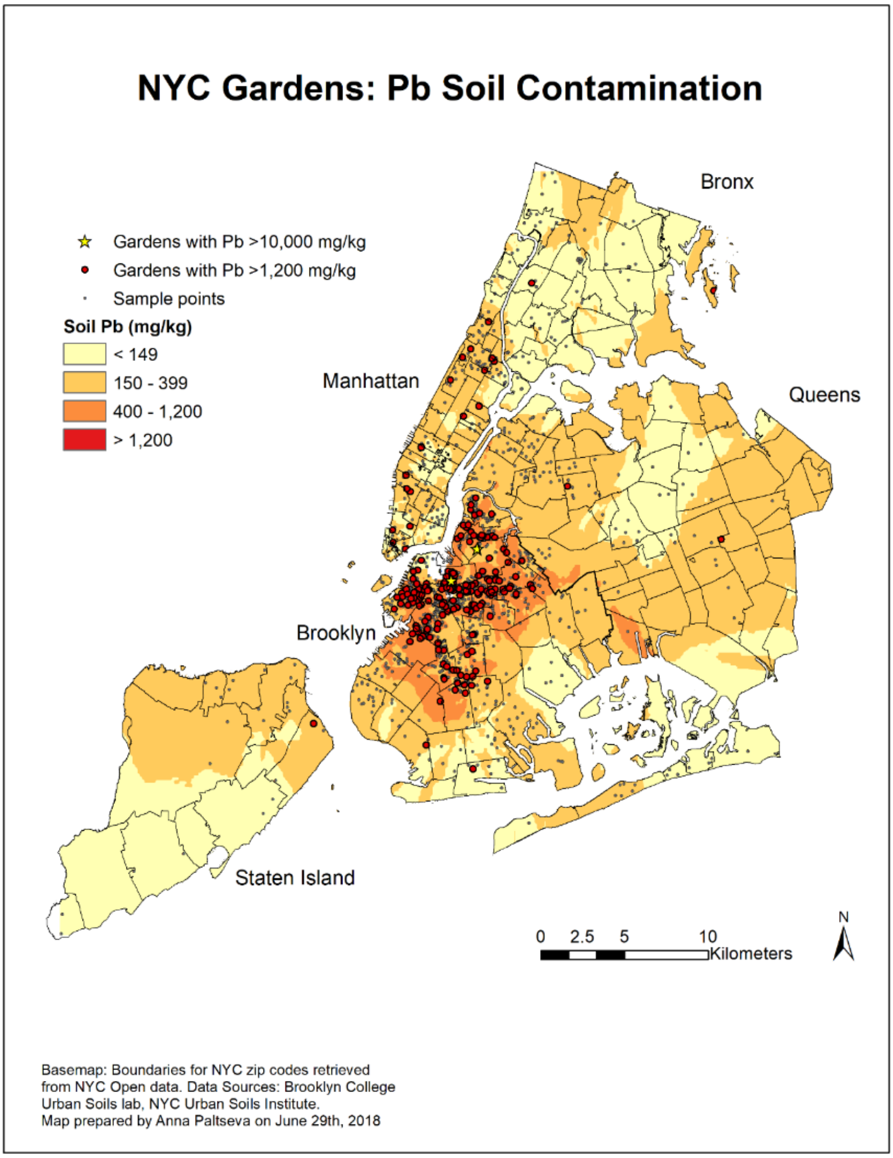

Fig. 3. NYC Gardens: Pb Soil Contamination map shows predicted soil Pb distribution by kriging based on 2322 garden soil samples. (Note: there were not enough samples collected in eastern Queens, the Bronx and throughout Staten Island to confidently map and predict Pb distributions in those areas)

Table 2

Lead concentrations in garden soils of NYC neighborhoods (mg/kg) (total n = 2322)

Neighborhood	Median	Max	Min	# of samples
Greenpoint	1019	15911	26	71
Williamsburg-Bushwick	586	3970	14	97
Downtown-Heights-Park Slope	558	45076	4	486
Bedford Stuyvesant-Crown Heights	488	4026	3	362
East New York	523	1863	57	24
Sunset Park	519	3515	57	48
Borough Park	498	5474	11	148
East Flatbush-Flatbush	302	9112	10	168
Canarsie-Flatlands	169	863	26	36
Bensonhurst-Bay Ridge	276	1609	11	36
Coney Island-Sheepshead Bay	111	1425	12	44
Kingsbridge-Riverdale	122	965	34	45
Northeast Bronx	147	515	21	16
Fordham-Bronx Park	110	761	23	25
Pelham-Throgs Neck	370	2015	29	5
Crotona-Tremont	97	1374	40	21
High Bridge-Morrisania	172	742	25	20
Hunts Point-Mott Haven	233	541	46	15
Washington Heights-Inwood	196	2439	38	37
Central Harlem-Morningside Heights	154	6395	29	77
East Harlem	92	2639	21	31
Upper West Side	215	2273	31	20
Upper East Side	131	1905	13	31
Chelsea-Clinton	155	2077	14	14
Gramercy Park-Murray Hill	107	1105	11	39
Greenwich Village-Soho	71	3478	10	15
Union Square-Lower East Side	222	1439	32	54
Lower Manhattan	240	3051	24	28
Long Island City-Astoria	295	1039	11	50
West Queens	288	2766	27	36
Flushing-Clearview	147	508	39	15
Bayside-Little Neck	417	673	86	2
Ridgewood-Forest Hills	196	550	19	24
Fresh Meadows	158	653	62	8
Southwest Queens	618	685	82	5
Jamaica	163	1726	54	15
Southeast Queens	67	82	52	2
Rockaway	148	780	14	21
Port Richmond	433	840	89	13
Stapleton-St. George	562	1418	27	17
Willowbrook	117	170	64	2
South Beach-Tottenville	44	155	12	8

Sources of Pb and other contaminants

The Pb distribution map (Fig. 3) shows that, in general, soil Pb content decreases from the inner city towards outskirts, which is commonly seen for cities with an industrial history [1]. Li et al. (2018) found a general correlation between Pb levels and historical land use, where highly elevated levels of soil Pb corresponded with industrialized areas. Specific hotspots of Pb were identified in neighborhoods with extensive industrial history such as Red Hook, Brooklyn Heights, Gowanus, Park Slope, Boerum Hill, Fort Greene, Williamsburg, and Bedford-Stuyvesant. These observations are consistent with our findings with the highest soil Pb found in the same neighborhoods.

Historically, leaded gasoline, lead-based paint, and many other lead-based products were widely used until around 1990's [38]. It has been recognized that these contributed to the widespread Pb deposition into the soil, especially in urban areas. An estimated 4-5 million metric tons of Pb from car exhaust released into the environment from 1929 to 1986 throughout the United States [39] is a big contributor to the soil legacy of Pb. Although lead-based paint is no longer being used, some old houses with leaded paint still serve as a source of Pb for soil. Moreover, solid waste incineration (common in the US and New York City during the 20th century) could be another source of trace metals (including Pb) causing excessive deposition of contaminants in soil (Walsh et al. 2001). Deposition of 34 million tons of refuse incineration throughout NYC landfills caused the release of 1 million tons of air pollutants, which eventually settled onto the topsoil. Manufacturing and smelting activities involving lead-bearing products, as point sources, also have contaminated soil with large quantities of Pb deposited into the topsoil within the industrial site and neighboring areas. It is highly likely that at many places both point and non-point sources of Pb contributed to the elevated levels of Pb in soil.

Lead distribution changes over time

Fig. 5 shows the spatial distribution of garden soil samples the two labs received from NYC gardeners between 2009 and 2017, color-coded for every three years. There are no noticeable changes in terms of spatial distributions of the samples received over time. This, on one hand, may suggest the spatial distribution of gardens in the city, and on the other hand may point to how effective the information regarding to soil contamination has been delivered.

It is very important to note, however, that over time the Pb levels we found in soil samples received have not shown any significant decline. One would expect that with increased awareness and educational campaign, remediation and mitigation actions had been taken (including replacing with new, clean soil), thus more soil samples would have lower Pb levels. Our study shows that there is only a slight increase in the % of samples < 400 ppm, comparing 2009—2011 (51 %) with 2015—2017 (55 %). In the 2015—2017 samples, there were still 13 % above 1,200 mg/kg and 44 % above 400 mg/kg, highlight significant health risk. The environmental challenge remains after nearly ten years of research and outreach, while more and more urban residents are getting involved in urban gardening and greening.

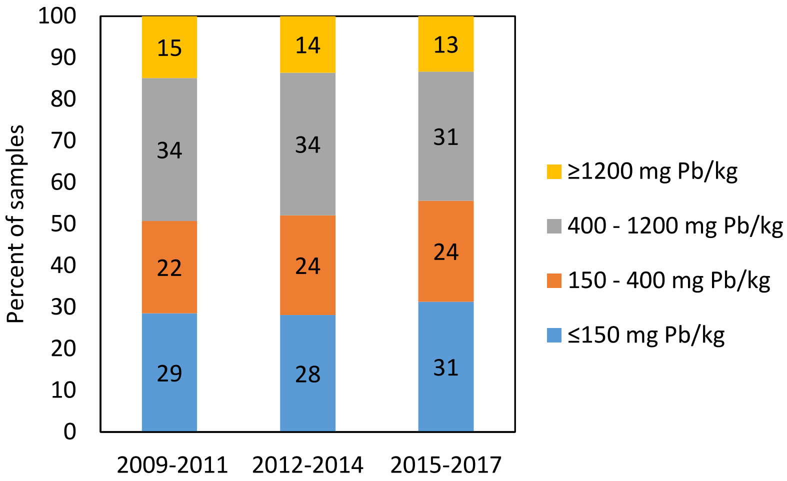

Fig. 4. Distribution of Pb levels in garden soil samples received

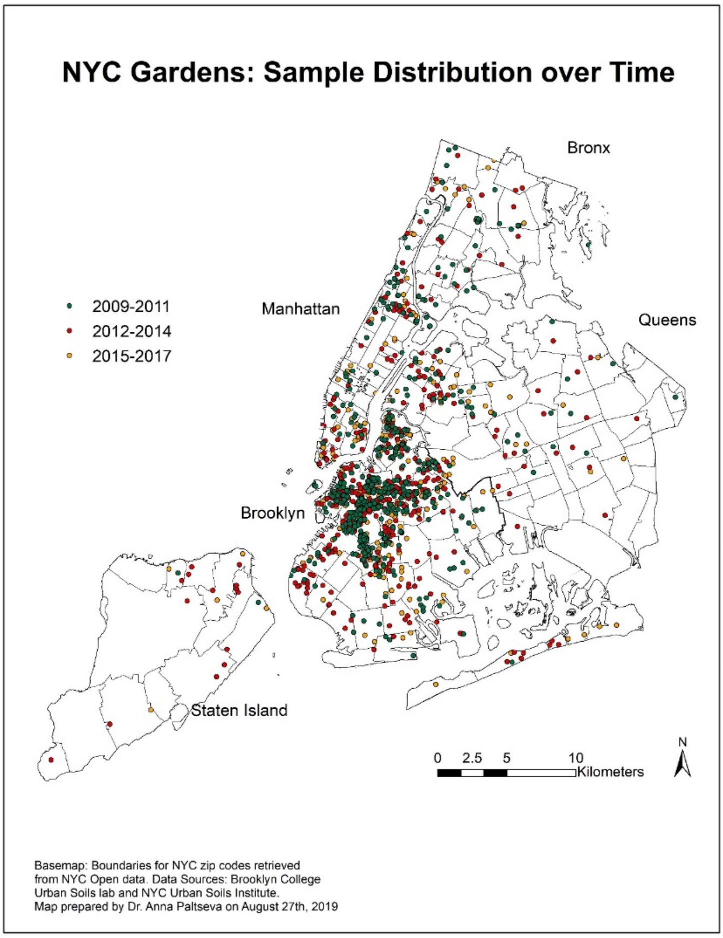

Fig. 5. Sample spatial disctribution over time between 2009 and 2017 (*n*= 2322 garden soil samples)

Conclusions

In this study, soil quality assessment indices were calculated based on individual metals (Pb, Zn, Cd, As, Cu, Cr, Ni) for 746 garden samples. The majority of soils is contaminated and poses significant risks to human health and ecological systems, particularly by Pb. A consolidated garden soil Pb database was compiled (total of 2,322 garden samples), from which color-coded map was created to visualize areas with potential health risk from soil contamination. The highest Pb levels were found in northern and central Brooklyn. Generally, Pb levels became lower toward the suburban areas. The Pb contamination map would be valuable not only to guide remediation efforts but also for urban planning such as developing gardens and green spaces or sitting of new parks.

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Научная статья

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Геопространственный анализ и оценка загрязнения садовых почв в Нью-Йорке

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Аннотация. Повышенные концентрации микроэлементов, в частности, свинца (Pb), распространены в городских почвах, и это является одним из основных препятствий для городского сельского хозяйства. Растущая популярность садоводства в городах также может означать повышение риска для здоровья населения. Пространственное распределение свинца в садах Нью-Йорка было проанализировано и визуализировано с помощью инструментов географической информационной системы (ГИС). Уровень загрязнения и экологические риски садов и Нью-Йорка в целом оценивались по разным показателям. Степень загрязнения была ранжирована следующим образом: Pb> Cu> Zn> Cr> As> Ni> Cd. Единый индекс экологического риска и потенциальный экологический индекс указывают на то, что Pb умеренно или значительно повышал риск для местных садовых экосистем. На основе индекса нагрузки загрязнения качество почвы большинства садов Нью-Йорка было охарактеризовано как загрязненное. Геостатистические, геообрабатывающие и пространственные инструменты использовались для создания карт с цветовой кодировкой для поддержки принятия решений, связанных с садоводством, и для оценки потенциальных рисков для здоровья человека, связанных с садоводством, проживанием или работой в / или вблизи садов. Эти выводы имеют большое значение для разработки стратегий предотвращения загрязнения, смягчения его последствий и снижения риска для здоровья населения от загрязнения почвогрунтами садовых почв.

Ключевые слова: микроэлементы, ГИС-карта, экологический индекс, свинец, цифровое картирование почвы, садоводство городское

Конфликт интересов отсутствует.

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