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SUSTAINABLE URBAN AGRICULTURE: VECTOR FOR ECOLOGICAL TRANSITION

From environmental data acquisition to assessment of gardeners' exposure: feedback in an urban context highly contaminated with metals

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Abstract

Although growing vegetables in urban gardens has several benefits, some questions in relation with the safety of foods remain when the self-production is carried out on highly contaminated garden soils. To better assess the local population's exposure to Cd and Pb induced by the past activities of a lead smelter, a participatory program was initiated in 115 private kitchen gardens located in northern France to assist gardeners in understanding their soil environment. The challenge included contributing to the database of urban garden soils with the collection of a large number of samples: 1525 crops grouped into 12 types (leaf, fruiting, root, stem and bulbous vegetables, tubers, cabbages, leguminous plants, celeriac, fresh herbs, fruits, and berries), 708 topsoils, and 52 samples of self-produced compost. The main results were as follows: (i) topsoils were strongly contaminated by Cd and Pb compared to regional reference values; (ii) great variability in physicochemical parameters and metal concentrations in topsoils; (iii) the highest concentrations of Cd and Pb for celeriac and fresh herbs and the lowest for fruits and fruiting vegetables; (iv) a high percentage of vegetables that did not comply with the European foodstuff legislation; and (v) most self-produced compost samples were strongly contaminated. This study aimed to raise awareness and generate functional recommendations to reduce human exposure and to provide useful data that could be considered in other environmental contexts.

Keywords Urban gardens · Soil metallic pollution · Homegrown produce · Soil-plant transfer · Self-produced compost · Exposure assessment

Introduction

Urban gardens play recreational and food production roles, promote health, and have economic and social benefits. However, they are potentially highly disturbed by human activities and are real sinks for contaminants (Augustsson et al. 2015; Avila et al. 2017; Bretzel et al. 2016). This is a result of industrial and traffic emissions and other activities including moving construction materials, construction, manufacturing, fossil fuel combustion, and incinerator emissions (Alloway 2004; Biasioli et al. 2007; Bradley et al. 1994; Norm et al. 2001; Peltola and Aström 2003). Recently, much more research attention has been paid to urban community gardens (e.g., Bretzel et al. 2016; Brown et al. 2016; Clarke et al. 2015; McBride et al. 2014; Mitchell et al. 2014). In domestic gardens, practices and production are little known and totally unregulated, and uncertainty remains as to the exposure of populations to pollutants. These residential soils may contain elevated levels of metallic pollutants due to past and current anthropogenic activities but also due to habitual homeowner activities (Nezat et al. 2017). Indeed, the preservation of the agronomic quality of soils is also of great concern and some gardeners attempt to resolve the problem of poor soil quality through the use and/or overuse of soil improvers. Pesticides, inorganic and organic fertilizers, compost, and contaminated irrigation water may result in metal accumulation (Szolnoki

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et al. 2013). Consequently, urban garden soils can be moderately to severely contaminated by a mixture of metals and metalloids and more specifically by Cd and Pb, which may be hazardous for human health (McBride et al. 2014). Cadmium exposure may pose adverse health effects, including kidney dysfunction and skeletal disorders, and may also affect bones and result in fractures (Jarup 2003). Long-term exposure to Pb may cause neurological disorders such as memory deterioration, prolonged reaction times, and reduced cognitive ability, particularly in young children (Jarup 2003; Oliver 1997).

The consumption of crops produced in contaminated soils, as well as ingestion or inhalation of contaminated soil particles, are the main pathways of human exposure to Cd and Pb. Cultivation of crops on contaminated soils can potentially lead to the accumulation of metals in the edible plant parts, resulting in a risk to human health (Attanayake et al. 2014; Augustsson et al. 2015; Cui et al. 2004; Hough et al. 2004; McBride 2007; Nabulo et al. 2010; Wang et al. 2005). The contamination pathways for the plants resulted from both root uptake and dust deposition on the foliar system (Douay et al. 2008; Uzu et al. 2010). Numerous studies have investigated the relationships between metal contamination of garden-raised foods and urban garden soils, particularly for Cd and Pb (e.g., Alloway 2004; Bielinska 2009; Huang et al. 2012; Spliethoff et al. 2014). However, other soil parameters, including pH, organic matter, and phosphorus contents and crop type, have proven to be determinants of the mobility of metals in soil and therefore of potential translocation in edible crops (Alexander et al. 2006; Atkinson et al. 2012; Douay et al. 2013; Hough et al. 2004; Nabulo et al. 2011; Zhang et al. 2018).

Soil quality is a major concern, especially in the former coal mining area of the North of France. For more than a century up to 2003, the main European lead smelter (Metaleurop Nord) generated significant quantities of dust that have led to substantial contamination of the surrounding soils (Sterckeman et al. 2002). The pollutants were mainly Cd, Pb, and Zn but also to a lesser degree As, Hg, Sb, and In (Sterckeman et al. 2000, 2002). For any public land use, the authorities defined strict recommendations (Douay et al. 2013). Moreover, they planned to exclude the most heavily contaminated fields from agricultural production and to promote non-foodstuff plants with a great biomass value as an alternative to manage metal-polluted sites (Nsanganwimana et al. 2015). However, no ban has been imposed on the production and consumption of homegrown vegetables in private gardens. In this specific context characterized by a high population density, an environment highly degraded by mining and smelting activities, and a very difficult socioeconomic context, kitchen gardens are numerous (Pelfrêne et al. 2015). On the studied area, first investigations with pot experiments were conducted on lettuce and showed (1) transfer of metals from the contaminated kitchen garden soils to the edible part of the vegetable and (2) a high availability of Cd compared to Pb (Waterlot et al. 2013). An exploratory in situ study was then conducted on 34 kitchen gardens located in three municipalities (Douay et al. 2013; Pelfrêne et al. 2013). The results showed that urban topsoils were strongly contaminated by Cd and Pb and a considerable proportion of the vegetables produced in kitchen gardens did not comply with the European foodstuff legislation that defines the maximum permissible concentrations in foods for sale. However, in order to compare the results obtained between the kitchen gardens, the study investigated a limited number of vegetables with the same vegetable cultivars.

In most studies, metal concentrations are measured in the edible portion of a limited number of vegetable types, i.e., the most common vegetables in the country considered (e.g., Ferri et al. 2015; Mombo et al. 2016; Nabulo et al. 2012). Moreover, little attention has been paid to the potential integral exposure resulting from ingesting soil and a wide range of food (e.g., vegetables, fruits, herbs; McBride et al. 2014) and using self-produced compost. To better assess the local population's exposure to Cd and Pb induced by the historic pollution of Metaleurop Nord, a participatory program was initiated in 2012 to assist gardeners in understanding their soil environment. The challenge included the following: (1) measuring the metal contamination in topsoils, a range of crops (vegetables, fruits, and herbs), and self-produced compost; (2) comparing the metal concentrations in garden produce with regulations; (3) determining soil-to-plant transfer of metals into a range of vegetables; and (4) providing advice to gardeners for safer gardening. This program aims to contribute to the database of urban kitchen garden soils, to raise awareness and provide functional recommendations to reduce human exposure, and to propose a useful approach that could be considered in other degraded environmental contexts.

Materials and methods

Collection of kitchen gardens

The study area is located in the vicinity of the former Metaleurop Nord smelter (50° 25′ 42 N and 3° 00′ 55 E) and was selected according to the knowledge of the expected spread of Cd and Pb concentrations in topsoils (i.e., above 200 mg of Pb kg^{-1} and/or 4 mg of Cd kg^{-1}; Pelfrêne et al. 2015), including seven municipalities in full or in part. In this area, more than 900 kitchen gardens adjoining houses were identified using aerial photography (2006–2009). Gardeners were contacted in our door-to-door survey among which 153 agreed to participate in the study (Fig. 1). The approach consisted in: (1) data processing from a self-administered questionnaire to establish the gardening profile, (2) collection

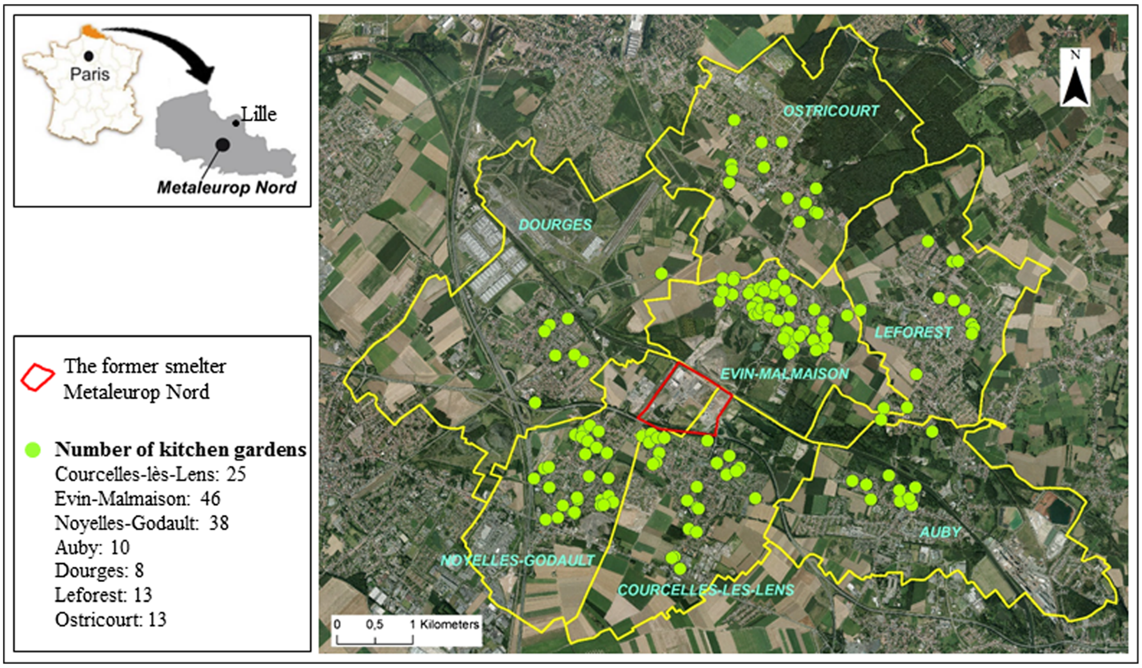

Fig. 1 Location of the 153 kitchen gardens studied around the former Metaleurop Nord smelter and distribution among the seven municipalities, favoring those most impacted by the smelter's past activities

of paired vegetable/soil samples during the 2013 gardening season from 115 gardeners who agreed to continue the study, and (3) information from the gardeners in 2016 about the results of the study and potential risks of exposure from contaminants in their kitchen gardens.

Sample collection, preparation, and analysis

The vegetables, herbs, and fruits were sampled in 2013 (from June to October) at their consumption stages, taking care to obtain a representative sample for analysis. The crop samples were prepared in the same manner as a careful consumer would prepare them to eat, with the elimination of the inedible parts, the peeling of some crops and meticulous cleaning in three successive washings with tap water. All samples were cut into small pieces to obtain a representative sample for analysis and were then dried (40 °C for 2–4 days). They were crushed with a cutting mill in tungsten carbide with a 0.5-mm grid. A representative part (300 mg) was digested with 5 mL of nitric acid (70%) at 90 °C for 1.5 h and then with 5 mL of hydrogen peroxide at 95 °C for 3 h using Hot Block system-assisted digestion (Environmental Express® SC100, Charleston, SC, USA). After mineralization, digestion products were completed to 25 mL with bidistilled water and stored at 4 °C prior to analysis.

At each sampling plot, paired vegetable and soil (0–25 cm deep) samples were collected. From three to seven random soil samples on each plot (depends on the kitchen garden surface) were taken and bulked together as one composite sample. In some cases, depending on the layout of crops, one composite soil sample was considered for several crops. The soil samples were prepared according to the NF ISO 11464 standard. Samples were oven-dried at 40 °C and crushed to pass through a 2-mm stainless steel sieve. For each soil sample, a representative subsample was obtained with an automatic sieve using an ultracentrifugal mill less than 250 μm (ZM 200, Retsch, Haan, Germany). Soil pH (NF ISO 10390) and contents of organic matter (NF ISO 10694), carbonates (NF ISO 10693), and available phosphorus (NF X 31-161) were determined in all soil samples. Concentrations of Cd and Pb in soils were obtained by Hot Block digestion: 300 mg of soil samples were digested in a mixture of 1.5 mL of HNO_3 (70%) and 4.5 mL of HCl (37%). After mineralization, digestion products were completed to 25 mL with bidistilled water and stored at 4 °C prior to analysis.

A total of 1525 samples of crops (several varieties of 32 vegetables, 12 herbs, and 12 fruits; Table 1) and 708 soil samples were collected from the 115 kitchen gardens.

During this cultural season, 52 self-produced compost samples at different composting stages were also collected. The samples were prepared in the same manner as the soil samples and were digested in the same manner as the crop samples.

The concentrations of Cd and Pb in the different samples (crops, soils, and self-produced compost) were determined by flame or furnace atomic absorption spectrometry (AA-6800, Shimadzu, Japan; Waterlot and Douay 2009).

Quality control of the soil and crop digestions was based on the use of blanks, certified reference materials (soil from NIST

Table 1 Vegetables collected from the 115 kitchen gardens and legislation limits of Cd and Pb for each vegetable group (European Directive of 25 June 2015)

Group	Vegetable	Number of samples	Legislation limits (mg kg^{-1} FW)	
			Cd	Pb
Leaf vegetables	Endive, spinach, sorrel, lettuce	197	0.20	0.30
Fruiting vegetables	Eggplant, cucumber, gherkin, marrow, zucchini, bean pod, hot pepper, sweet pepper, winter squash, pumpkin, tomato	371	0.05	0.05
Root vegetables	Red beet, chard, carrot, radish	182	0.10	0.10
Stem vegetables	Celery, leek, rhubarb	116	0.10	0.10
Tubers	Potato, Jerusalem artichoke	64	0.10	0.10
Cabbages	Cabbage, turnip	93	0.05	0.30
Bulbous vegetables	Garlic, shallot, onion	44	0.05	0.10
Leguminous plants	Grain bean, pea	17	0.05	0.20
Celeriac	Celeriac	54	0.20	0.10
Fresh herbs	Dill, chervil, lemongrass, cilantro, tarragon, bay, mint, parsley, rosemary, sage, thyme	260	0.20	0.30
Fruits (except berries)	Fig, peach pear, apple, plum, grape	60	0.05	0.10
Berries	Black currant, cherry, strawberry, raspberry, red currant, blackberry	67	0.05	0.20

2710a and CTA-VTL-2 Virginia tobacco leaves) and internal control vegetable samples. The results provided good recovery for Cd and Pb (91–105% for NIST 2710a, $n = 20$; 93–103% for internal control, $n = 30$ and 89–108% for reference tobacco, $n = 10$).

Data analysis

Soil metal concentrations expressed in dry weight were compared with regional agricultural references, i.e., 0.4 mg kg^{-1} for Cd and 32 mg kg^{-1} for Pb (Sterckeman et al. 2002).

Crop metal concentrations expressed in milligrams per kilogram of dry weight were used to study the crop/soil behavior, i.e., to calculate the transfer factor (TF) defined as the ratio between the metal concentration in the edible part of plant and the concentrations in soil (Cui et al. 2004; Kachenko and Singh 2006). Those expressed in fresh weight were used to evaluate the inhabitants' exposure and were compared with the legislation limits for human consumption (European Directive of 25 June 2015 modifying the European Directive no. 1881/2006), which define the maximum permissible concentrations in foods for sale (Table 1).

For the compost samples, the metal concentrations expressed in dry weight were compared with the NF U 44-051 standard, which defines the maximum permissible concentrations in organic amendments for sale, i.e., 3 mg kg^{-1} for Cd and 180 mg kg^{-1} for Pb.

Statistical analyses (i.e., distributions, box plots, and linear regressions) were performed using XLSTAT 2013.5-09 (Addinsoft).

Results and discussion

Gardening practices and gardeners' profile in the area studied

The gardening practices and gardeners' profile in the area studied were established from the questionnaires completed by the 153 gardeners. The data recorded included in particular the age, gender and socioprofessional categories of the gardeners, the number of family members in the household, the gardens' characteristics (age, surface area, gardening practices, etc.), and the vegetables grown (species and cultivars). The main data are presented in Table 2.

To summarize, the gardeners are mainly male and pensioners. A total of 374 people from the 153 households consume their homegrown vegetables. Overall, the most common reasons reported by gardeners for having a kitchen garden were to have access to fresh and better tasting food and organic food, to enjoy a leisure activity and to save money. A substantial number of gardens (56%) were established 50 or more years ago. The surface area of the kitchen gardens ranges from 15 to 1600 m^2 with a mean surface area of 115 m^2. Most gardeners reported using chemical fertilizers, organic and inorganic amendments, phytosanitary products, and others (e.g., ashes, nettle manure, coffee grounds, and eggshells). Moreover, in past times, some gardeners added exogenous materials (especially slag resulting from the combustion of coal) to improve soil permeability and facilitate cropping practices. The majority of gardeners irrigate their vegetables with rainwater. In 69% of the gardens, gardeners produce compost and use their self-produced compost on vegetable gardens.

Table 2 General characteristics from the answers to the kitchen garden questionnaires ($n = 153$)

Gardeners				
Age years	*Gender*	*Socioprofessionnal categories*	*Number of family members*	*Reasons for having a kitchen garden*
21–40 (7%)	Women (20%)	Workers (24%)	Between 1 and 7 people - a total of 374 people	Leisure activity (92%)
41–50 (10%)	Men (80%)	Pensioners (67%)		Taste of food (61%)
51–60 (24%)		Others (9%)		“Organic Farming” (44%)
61–70 (30%)				Economic constraints (33%)
71–80 (21%)				
81–100 (8%)				
Garden’s characteristics				
Age-years	*Surface area (m^2)*			
< 10 (9%)	< 50 (10%)			
10–20 (4%)	50–100 (36%)			
20–30 (12%)	100–50 (19%)			
30–40 (9%)	150–300 (24%)			
40–50 (10%)	>300 (11%)			
> 50 (56%)				
Gardener’s practices				
Cultural practice-use	*Farm animals*	*Vegetable productions*	*Eating habits*	
Fertilizers (51%)	39% mainly chickens	74 vegetables and herbs	% self-consumption for each product	
Amendments (84%)		27 fruits	Gives away vegetables (87%)	
Phytosanitary products (82%)		More than 500 different cultivars		
Compost (69%)				
Irrigation (84%)				

When possible, results are expressed in percentage of total values

Approximately 40% of gardeners have farm animals (mainly chickens) and consume the different products (meat, eggs). Based on the questionnaire, 74 vegetables and herbs, and 27 fruits were identified with more than 500 different cultivars with, however, a frequent misreading of varieties, particularly for fruits. For each production, gardeners provided the percentage of self-consumption (e.g., 58% and 18% of gardeners declared being self-sufficient with radishes and carrots, respectively). Moreover, 87% of gardeners give away vegetables.

Characteristics of kitchen gardens

Soil samples

The distribution of physicochemical parameters and metal concentrations measured in the kitchen garden soil samples are described in Table 3. The results showed (i) great variability in physicochemical parameters, from 13 to 223 g kg^{-1} for the contents of organic matter, from 5.5 to 8.1 for pH values, from 0.1 to 178 g kg^{-1} for the contents of carbonates, and from 0.04 to 3.20 g kg^{-1} for the available phosphorus contents and (ii) a wide range of metal concentrations, which varied for Cd from 0.8 to 40.2 mg kg^{-1} and for Pb from 40 to 3972 mg kg^{-1}.

The comparison with the agricultural regional references confirmed their high level of contamination where the mean Cd and Pb concentrations were 18- and 15-fold, respectively, greater than the reference values. Moreover, compared to the agricultural soils located in the same environmental context (Douay et al. 2013), the kitchen garden topsoils were more polluted. This degree of contamination appeared to be related to the use of the soils studied, the past or present anthropogenic activities (i.e., removal and deposition of various contaminated materials, gardening practices, atmospheric fallout linked to circulating traffic, urban heating, and industrial activities), the corrosion of building materials, etc.

Self-produced food samples

Vegetables were grouped into 12 types for statistical analysis: leaf, fruiting, root, stem and bulbous vegetables, tubers, cabbages, leguminous plants, celeriac, fresh herbs, fruits, and berries. The concentrations of Cd and Pb measured in homegrown vegetables by crop type are presented in Fig. 2 (dry weight) and Table 4 (fresh weight).

Table 3 Statistical distribution ($n = 708$) of topsoil physicochemical parameters and pseudototal concentrations of metals

		Mean	Min	Percentile				Max
				25th	50th	75th	95th	
Clay	g kg^{-1}	187	110	163	179	210	249	315
Silt	g kg^{-1}	557	289	467	579	653	705	730
Sand	g kg^{-1}	256	97	169	217	339	497	601
Organic matter	g kg^{-1}	90	13	59	80	115	163	223
Water pH	g kg^{-1}	7.1	5.5	6.9	7.1	7.3	7.5	8.1
Total $CaCO_3$	g kg^{-1}	18	0.1	2.0	6.4	20	86	178
Available P	g kg^{-1}	0.89	0.04	0.48	0.80	1.25	1.89	3.20
Cd	mg kg^{-1}	7.3	0.8	4.0	5.7	9.2	18.6	40.2
Pb	mg kg^{-1}	495	40	245	383	603	1347	3972

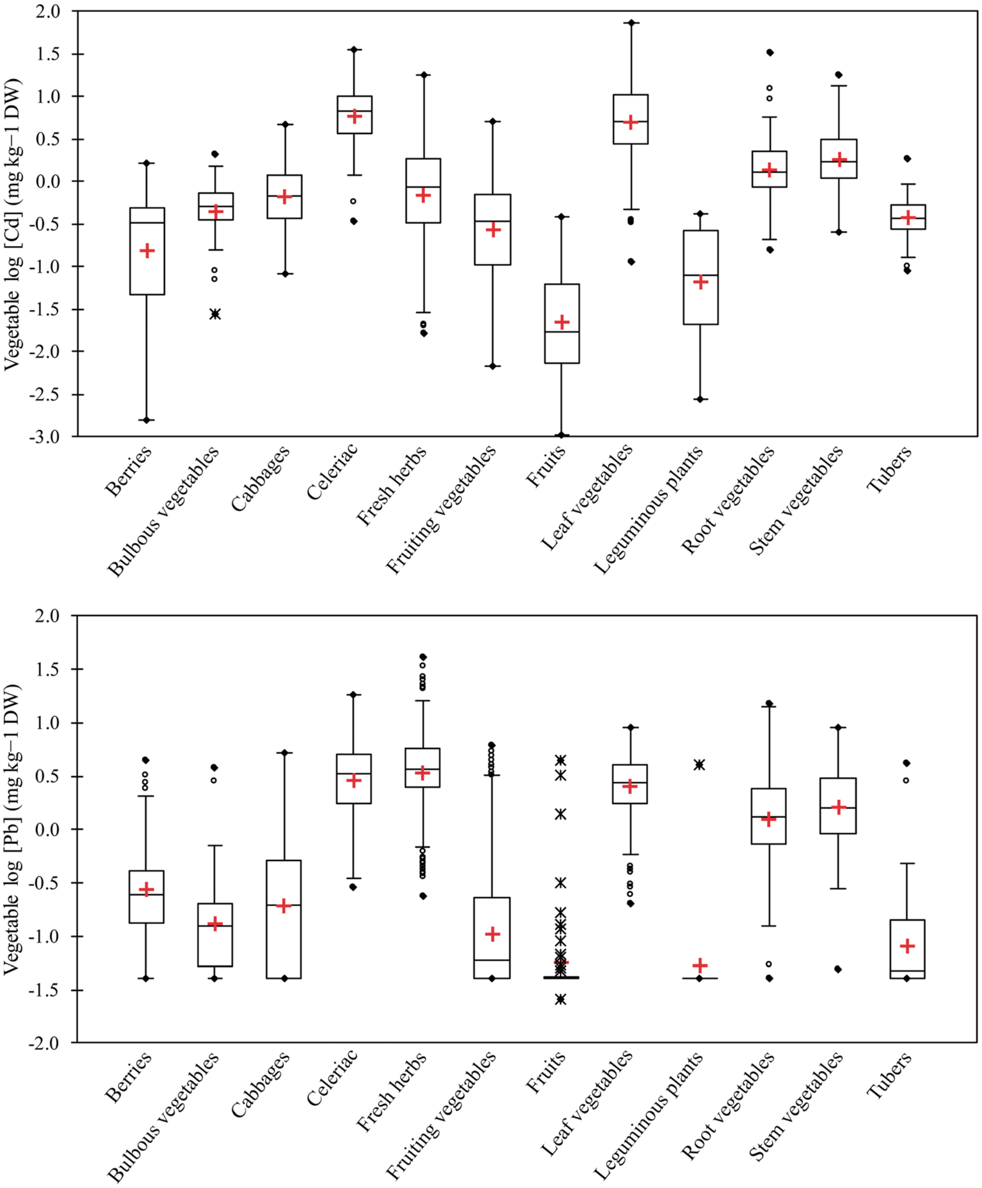

Fig. 2 Concentrations of Cd and Pb in homegrown vegetables by crop type (mg kg^{-1} dry weight). Boxes represent the means (red crosses), the medians (central horizontal bars), the first and third quartiles (lower and upper limits of the box, respectively), the minimum and maximum values, and outliers. Data were transformed $\log_{10}(x)$

Table 4 Concentrations of Cd and Pb in homegrown vegetables by crop type (mean, minimal, median and maximal values expressed in mg kg^{-1} fresh weight) and the noncompliance ratio (i.e., number of samples not in compliance with the legislation compared with the total sample number)

Metal	Vegetable group	Measured values (mg kg^{-1} FW)				Non-compliance ratio	Non-compliance percentage
		Mean	Min	Median	Max	ratio	
Cd	Leaf vegetables	0.4663	0.0076	0.2728	4.2064	117/197	59
	Fruiting vegetables	0.0346	0.0004	0.0190	0.4048	69/371	19
	Root vegetables	0.1838	0.0186	0.1275	2.5615	119/182	65
	Stem vegetables	0.2280	0.0145	0.1397	2.0562	79/116	68
	Tubers	0.0928	0.0166	0.0792	0.4344	25/64	39
	Cabbages	0.0723	0.0057	0.0487	0.4007	43/93	46
	Bulbous vegetables	0.0775	0.0033	0.0708	0.2820	31/44	70
	Leguminous plants	0.0506	0.0002	0.0282	0.1564	6/17	35
	Celeriac	1.2581	0.0620	0.9204	6.0751	51/54	94
	Fresh herbs	0.2666	0.0029	0.1481	1.8945	104/260	40
	Fruits (except berries)	0.0101	0.0002	0.0021	0.0486	0/60	0
	Berries	0.0369	0.0003	0.0290	0.1451	19/67	28
Pb	Leaf vegetables	0.1729	0.0134	0.1427	0.6116	27/197	14
	Fruiting vegetables	0.0213	0.0011	0.0045	0.9493	26/371	7
	Root vegetables	0.1820	0.0043	0.1284	1.1884	108/182	59
	Stem vegetables	0.1824	0.0022	0.1376	0.7479	73/116	63
	Tubers	0.0456	0.0066	0.0098	0.9043	4/64	6
	Cabbages	0.0401	0.0026	0.0148	0.3878	3/93	3
	Bulbous vegetables	0.0426	0.0047	0.0184	0.5055	2/44	5
	Leguminous plants	0.0893	0.0028	0.0135	1.3173	1/17	6
	Celeriac	0.6330	0.0314	0.5062	4.0374	48/54	89
	Fresh herbs	0.9902	0.0209	0.5994	11.8449	208/260	80
	Fruits (except berries)	0.0280	0.2032	0.0058	0.5912	3/60	5
	Berries	0.0515	0.0056	0.0299	0.3174	4/67	6

On a dry weight basis (Fig. 2), leaf vegetables and celeriac contained the highest Cd concentrations, while fruits, berries, leguminous plants, tubers, bulbous, and fruiting vegetables had lower concentrations. For Pb, fresh herbs, celeriac, leaf, and stem and root vegetables showed the highest concentrations, while the lowest concentrations were recorded in the same vegetable groups as for Cd. Our results are in agreement with those of McBride et al. (2014) who showed that the highest concentrations of Cd and Pb were measured in leafy vegetables and herbs instead of roots and fruits. Moreover, both Cd and Pb concentrations varied considerably among vegetable types having the highest concentrations.

On a fresh weight basis and on average, celeriac and fresh herbs had the highest concentrations of Cd and Pb, respectively, while fruits and fruiting vegetables were the crop types with the lowest metal concentrations. More specifically, the orders of accumulation were: (i) celeriac > leaf vegetables > fresh herbs > stem vegetables > root vegetables >> tubers > bulbous vegetables ≥ cabbages > leguminous plants > berries ≥ fruiting vegetables > fruits for Cd and (ii) fresh herbs > celeriac > stem vegetables ≥ root vegetables ≥ leaf vegetables >> leguminous plants > berries > tubers ≥ bulbous vegetables ≥ cabbages > fruits ≥ fruiting vegetables for Pb (Table 4). These results were comparable with those published by other authors (McBride et al. 2014; Spliethoff et al. 2016). For some vegetables (i.e., celeriac, chard, endive, or red beet), the standard deviation values were very high (Table S1 in Supplementary material), which was consistent with the high heterogeneity of metal concentrations in some kitchen gardens (Douay et al. 2013). Moreover, these results showed that the accumulation of metals in the crops could vary according to the metal speciation, the vegetable species, and the physicochemical parameters of the soils, as observed by Banat et al. (2005) and Cobb et al. (2000). These authors also highlighted that the accumulation of metals in crops varied according to the type of vegetable cultivar. In the present study, more than 500 different cultivars were identified. The results showed certain trends but they were not statistically significant (data not shown), which can be explained by (1) in situ data obtained in uncontrolled environmental and cultural conditions; (2) a high degree of metal contamination of topsoils; (3) the high variability of physicochemical parameters in relation to the urban garden features (i.e., alkaline pH, high contents of organic matter, and available phosphorus); and (4) dust deposition on the foliar system.

The concentrations of metals obtained in all homegrown vegetables were compared with the legal European values. Table 4 shows the proportion of noncompliant samples by crop type and for each metal. According to Cd, (1) a significant proportion of some vegetable groups did not comply with the European foodstuff legislation, i.e., celeriac (94%), bulbous vegetables (70%), stem vegetables (68%), root vegetables (65%), and leaf vegetables (59%); (2) nonconformity was not systematic for berries (28%), fruiting vegetables (19%), and fruits (0%); and (3) leguminous plants (35%), tubers (39%), fresh herbs (40%), and cabbages (46%) presented an intermediate position. According to Pb, (1) 89% of celeriac, 80% of fresh herbs, 63% of stem vegetables, and 59% of root vegetables were over the limit values and (2) the proportion of noncompliant samples was very low for leaf vegetables (14%), and for cabbages, fruits, bulbous vegetables, berries, tubers, and fruiting vegetables (between 3 and 7%).

Transfer of metals from soils to homegrown vegetables

Based on dry weight, the TF was calculated for each vegetable group as the ratio of the metal concentrations in the edible parts of homegrown vegetables to the metal concentrations in the topsoils (Fig. 3).

On average, the TF of metals were Cd >> Pb where the values for Cd were from 17- to 151-fold greater than for Pb, indicating that it is much easier for Cd to transfer from soil to the edible parts of vegetables. Low TF values for Pb were also recorded in previous studies (Attanayake et al. 2014, 2015; Defoe et al. 2014). The higher uptake of Cd compared to Pb is also consistent with previous studies (Intawongse and Dean 2006; Wang et al. 2012; Xu et al. 2013).

The results showed that TF values for Cd and Pb varied greatly between the vegetable groups. On average, the highest TF values for Cd were obtained in celeriac (1.327) and leaf vegetables (0.992) and to a lesser extent in stem and root vegetables (0.493 and 0.358, respectively), while the lowest values were recorded in fresh herbs (0.237), cabbages (0.186), bulbous vegetables (0.131), fruiting vegetables (0.133), tubers (0.074), berries (0.065), leguminous plants (0.026), and fruits (0.013). On average, the highest TF values for Pb were found in fresh herbs (0.013); celeriac (0.011); and stem, leaf, and root vegetables (0.009, 0.007, and 0.006, respectively), while the lowest values were obtained in fruits, berries, cabbages, tubers, leguminous plants, fruiting vegetables, and bulbous vegetables (0.0008, 0.0012, 0.0012, 0.0006, 0.0012, 0.0012, and 0.0011, respectively). In previous studies, distinctive differences were also identified between vegetable groups. Leguminous plants tended to be low accumulators, root vegetables tended to be moderate accumulators, and leaf vegetables were high accumulators (Alexander et al. 2006; Augustsson et al. 2015; Lehoczky et al. 1998; Li et al. 2006; Swartjes et al. 2013).

Since the differences in TF observed may be related to the crop's physiological properties, the physicochemical parameters of soils as well as gardening practices and self-produced compost were studied. Indeed, the latter can potentially contribute to the contamination of crops.

Self-produced compost samples

The use of compost is one of the most common practices used by gardeners. Several studies have shown the immediate beneficial effect of amending soils with compost (e.g., Attanayake et al. 2014, 2015; Brown et al. 2016; Defoe et al. 2014). Compost addition increased plant biomass production, improving soil fertility parameters, such as plant nutrient concentrations in soil, soil structure, and water-holding capacity, and helping to further reduce food-chain transfer of pollutants. In the present study, concerns were raised regarding the quality of the self-produced compost from garden waste (vegetable peelings, grass cuttings, animal excrement, etc.). The statistical distribution of metal concentrations in the self-produced compost samples is presented in Table 5. The concentrations ranged from 1.9 to 34.5 mg kg^{-1} for Cd and from 76 to 865 mg kg^{-1} for Pb DW.

Relationships were sought between the concentrations of metals measured in compost samples and those in the corresponding kitchen garden soils. The metal concentrations in compost tended to increase when the concentrations of metals measured in the soil samples increased (linear regressions where $R^2 = 0.65$ for Cd and $R^2 = 0.40$ for Pb; $p < 0.0001$; Fig. 4).

These results showed that soil is a contributor of Cd and Pb in self-produced compost, which can be explained by the materials used in the composting, i.e., mainly garden waste such as vegetable peelings and grass cuttings (contaminated vegetables and/or presence of soil particles attached to plants). Moreover, the relationship between metal concentrations in self-produced compost and those in soils was better for Cd than for Pb (65% versus 40% of the variability), which can be explained by the better phytoavailability of Cd compared to Pb, and more specifically by the TF presented previously. This assessment tends to accentuate the link between vegetable waste and compost.

To prevent the pollution of soil or groundwater by metals from compost, many European countries such as Belgium, France, Germany, and Holland have established standards. In France, the maximum concentrations of Cd and Pb allowed in compost are 3 and 180 mg kg^{-1}, respectively (NF U 44-051). The comparison confirmed their high level of contamination where the mean Cd and Pb concentrations were 2.2-

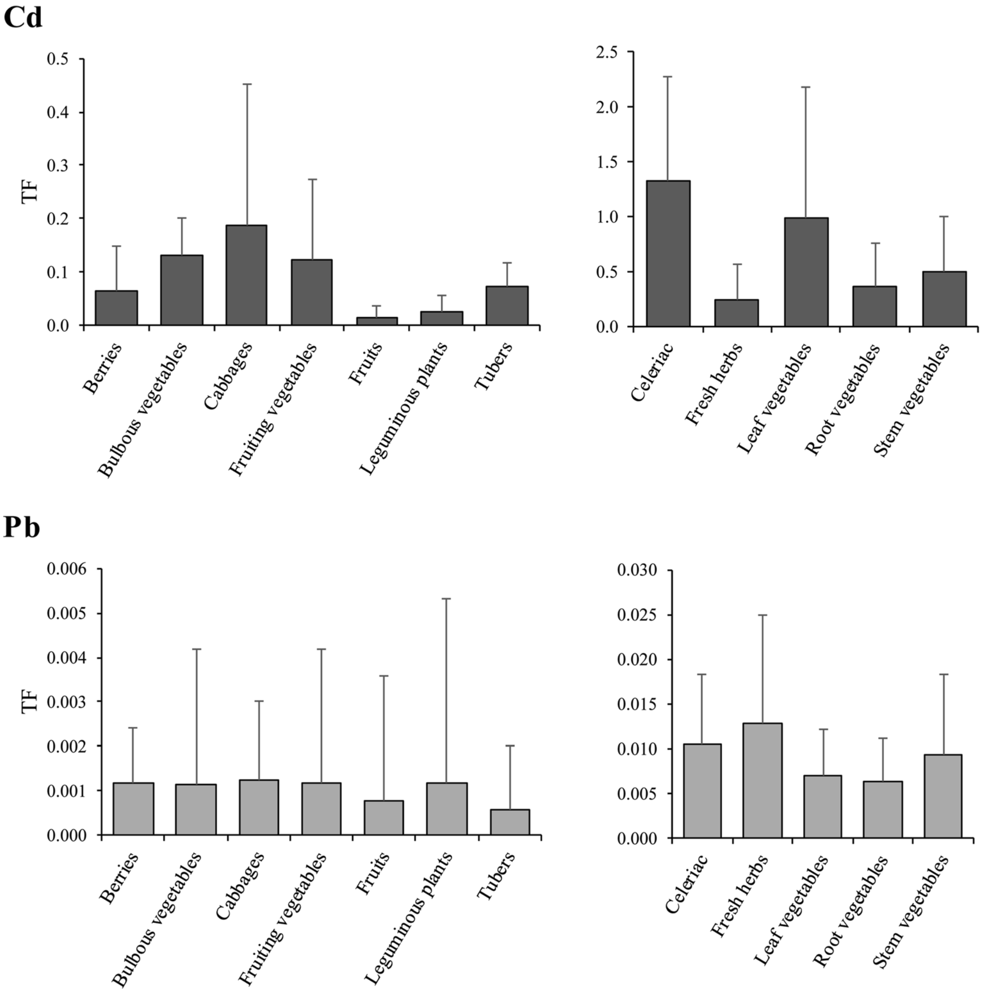

Fig. 3 Transfer factors (TF; mean and SD) of Cd and Pb from kitchen garden soils to the edible parts of vegetables according to crop type

and 1.7-fold, respectively, greater than the legislation limits. For the most contaminated compost samples, the Cd and Pb concentrations were 11.5- and 4.8-fold, respectively, greater than the limits. A high percentage of self-produced compost did not comply with the legislation for sale. Indeed, 85% of the samples were over the limit values; more specifically, 85% because of Cd and 73% because of Pb.

Few studies have been carried out on the behavior of metals after application of contaminated compost to soil (Businelli et al. 2009; Chen et al. 2010; Fang et al. 2017). Businelli et al. (2009) showed that application of municipal waste compost (5.0 ± 0.4 mg kg^{-1} of Cd and 750 ± 105 mg kg^{-1} of Pb) to soil led to a significant enrichment in metal loadings in the amended topsoils. In their study, Fang et al. (2017) applied sewage sludge compost to soil annually and continuously, which caused fresh release of metals and accumulation of some metals in the topsoil.

Table 5 Statistical distribution of metal concentrations in the self-compost samples ($n = 52$; mg kg^{-1} dry weight)

	Cd mg kg^{-1}	Pb
Mean	6.5	307
Min	1.9	76
25th percentile	3.3	174
50th percentile	4.8	260
75th percentile	7.8	389
95th percentile	13.8	749
Max	34.5	865
Legislation limit	3.0	180

Level of conformity of the production according to the degree of soil contamination

Linear regression analysis (Figs. S1 and S2 in Supplementary material) indicated that there were no strong positive relationships between vegetable and soil metal concentrations, and this whatever the crop type considered. However, for some vegetable groups, there was a tendency for crops grown in higher metal-contaminated soils to be more metal-contaminated, i.e., bulbous vegetables, celeriac, leaf vegetables, and tubers for Cd, and bulbous vegetables, cabbages, celeriac, and root vegetables for Pb. The lack of correlation between soil and vegetable type metal concentrations was true even after

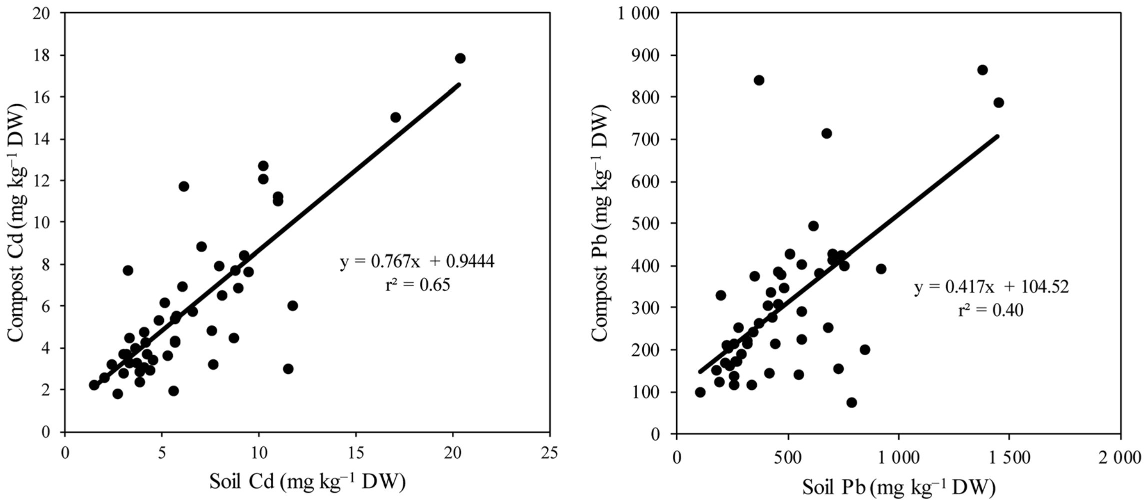

Fig. 4 Relationship between metal concentrations in self-produced composts (mg kg^{-1} dry weight) and metal concentrations in soils (mg kg^{-1} dry weight)

stratifying by vegetable (not shown) and has also been recorded in other studies (McBride et al. 2014; Spliethoff et al. 2016). However, considering each crop separately, some trends can be observed with regard to soil metal contamination. To evaluate the extent to which concentrations of metals may contribute to the exposure of gardeners, Figs. 5 and 6 show, for Cd and Pb, respectively, the proportion of crop samples (only those with more than five samples) for human consumption that respected the legal values with regard to the scale of the soil metal contamination studied.

For Cd (Fig. 5), the results showed at different scales of soil Cd contamination that apple, pod bean, cucumber, gherkin, mint, pear, pumpkin, red currant, rosemary, sage, and sorrel presented 100% conformity, while eggplant had 0% conformity. For example, the total conformity of pod bean ($n = 84$) was observed between 1 and 27 mg of Cd per kg of soil and the total nonconformity of eggplant ($n = 9$) was recorded between 2 and 15 mg of Cd kg^{-1}. Other vegetables presented high percentages of conformity, i.e., cabbage ($n = 41$), where 85% complied with the legislation limit when the Cd concentrations in soil ranged from 1 to 21 mg kg^{-1}, while other vegetables had low percentages, i.e., turnip ($n = 52$), where only 29% complied with the limit when soil Cd levels were between 2 and 25 mg kg^{-1}. For some crops, trends were observed with regard to the soil Cd contamination. For example, lettuce ($n = 134$) and red beet ($n = 49$) presented 52% and 29%, respectively, conformity when soil Cd concentrations ranged from 1 to 10 mg kg^{-1} and had 0% conformity when the Cd contamination was higher (up to 31 mg kg^{-1} and 21 mg kg^{-1} for lettuce and red beet, respectively).

For Pb (Fig. 6), the results showed at different scales of soil Pb contamination that blackcurrant, cabbage, cucumber, eggplant, gherkin, hot pepper, pea, pumpkin, raspberry, red currant, shallot, and sweet pepper presented 100% conformity, while thyme had 0% conformity. For example, the total conformity of cabbage ($n = 41$) was observed between 100 and 1700 mg of Pb per kg of soil and the total nonconformity of thyme ($n = 76$) was recorded between 100 and 1900 mg of Pb kg^{-1}. Other vegetables presented high percentages of conformity, i.e., tomato ($n = 150$) and turnip ($n = 52$), where 93 and 94%, respectively, complied with the legislation limit when the Pb concentrations in soil ranged from 100 to about 2000 mg kg^{-1}, while other vegetables had low percentages, i.e., leek ($n = 72$), where 46% complied with the limit when soil Pb was between 100 and 4000 mg kg^{-1}. For some crops, trends were observed with regard to the soil Pb contamination. For example, carrot ($n = 84$) and parsley ($n = 89$) presented 29% and 28%, respectively, conformity when soil Pb concentrations ranged from 100 to 600 mg kg^{-1} and had 0% conformity when the Pb contamination was higher (up to 1900 mg kg^{-1} and 1700 mg kg^{-1}, respectively, for carrot and parsley).

Advice for safer gardening

According to the results obtained in this polluted area, several recommendations can be given to inhabitants who practice gardening activities:

- In some cases (especially when pH values are < 7.0), use of liming treatment in acidic soils to limit the availability of Cd and Pb.
- To improve the long-term fertility and quality of soil, it is recommended to limit the use (and overuse) of chemical fertilizers and pesticides.
- The type of crops cultivated in kitchen gardens can be selected (Mombo et al. 2016; Spliethoff et al. 2016). With regard to the legislation for sale, the crops have to

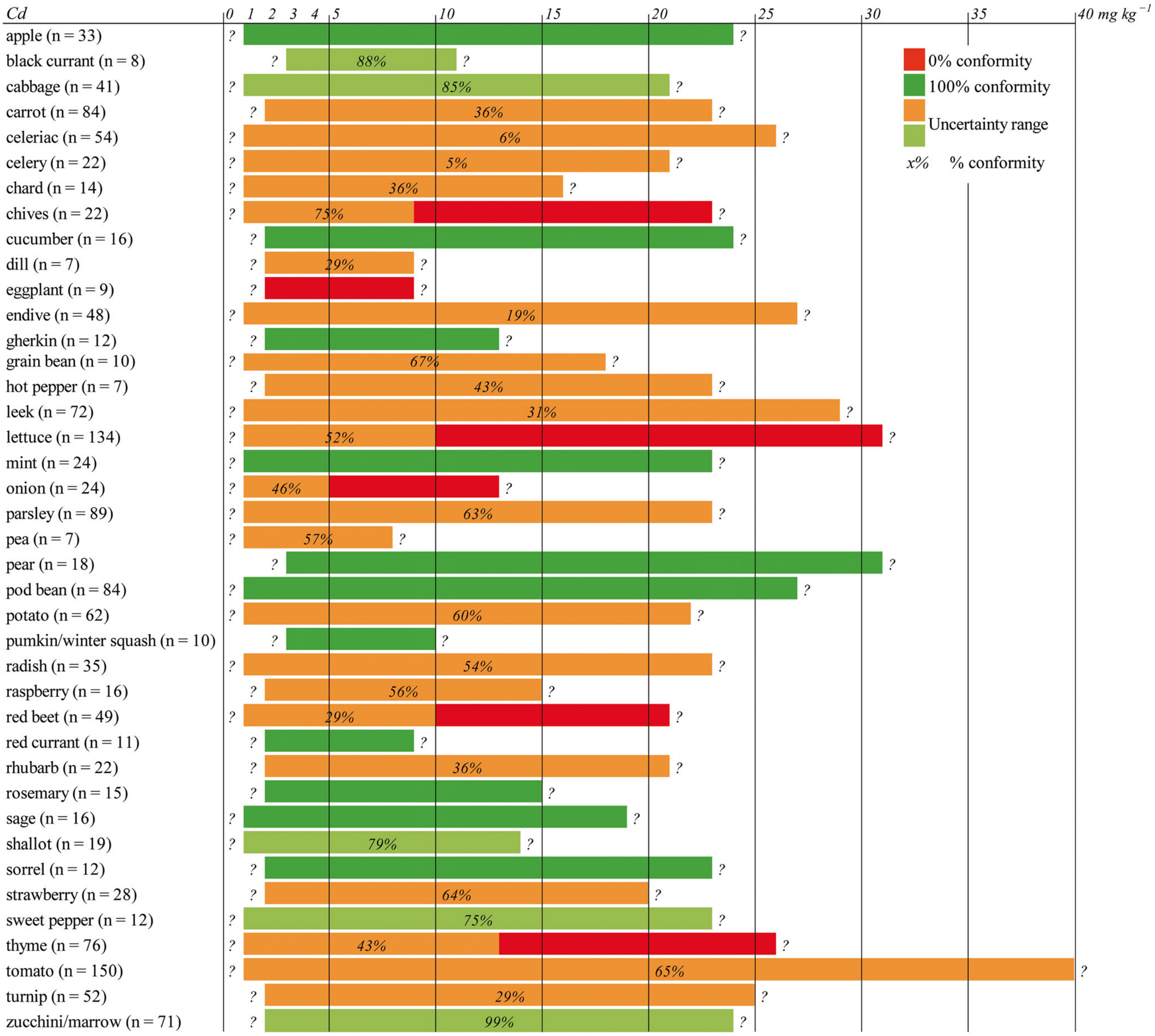

Fig. 5 Percentages of conformity for each crop according to the degree of contamination of soils by Cd. In green: 100% conformity for the crop; in red: 0% conformity; in orange and light green: uncertainty range with % conformity < 75% and > 75%, respectively

contain both Cd and Pb concentration levels below the limits considered as acceptable for human consumption. According to the results for both metals (i) crops weakly loaded in metals can be preferentially cultivated, more specifically fruits and vegetables such as cucumber, gherkin, zucchini, cabbage, sorrel, and pod bean, while (ii) vegetables that accumulate metals should be avoided, more specifically fresh herbs, onion, red beet, endive, carrot, eggplant, turnip, and celery. Because high concentrations of metals were measured in fresh herbs, the gardeners were advised to cultivate them in flower display cases with uncontaminated soil. The best solution will be to cultivate in raised bed with clean soil. Globally, to minimize chemical exposure, it is important to have a diversified diet (food type and origins).

- Preventive measures to ensure safer gardening include actions to limit the direct ingestion of contaminated soil particles, i.e., washing crops thoroughly before consumption and washing hands after gardening.
- The results on the compost samples highlighted their strong contamination. To our knowledge, no study has been reported in the literature on the potential transfer of metals after application of contaminated self-produced compost to kitchen garden soils. That is why gardeners were advised to avoid using self-produced compost on vegetable gardens.

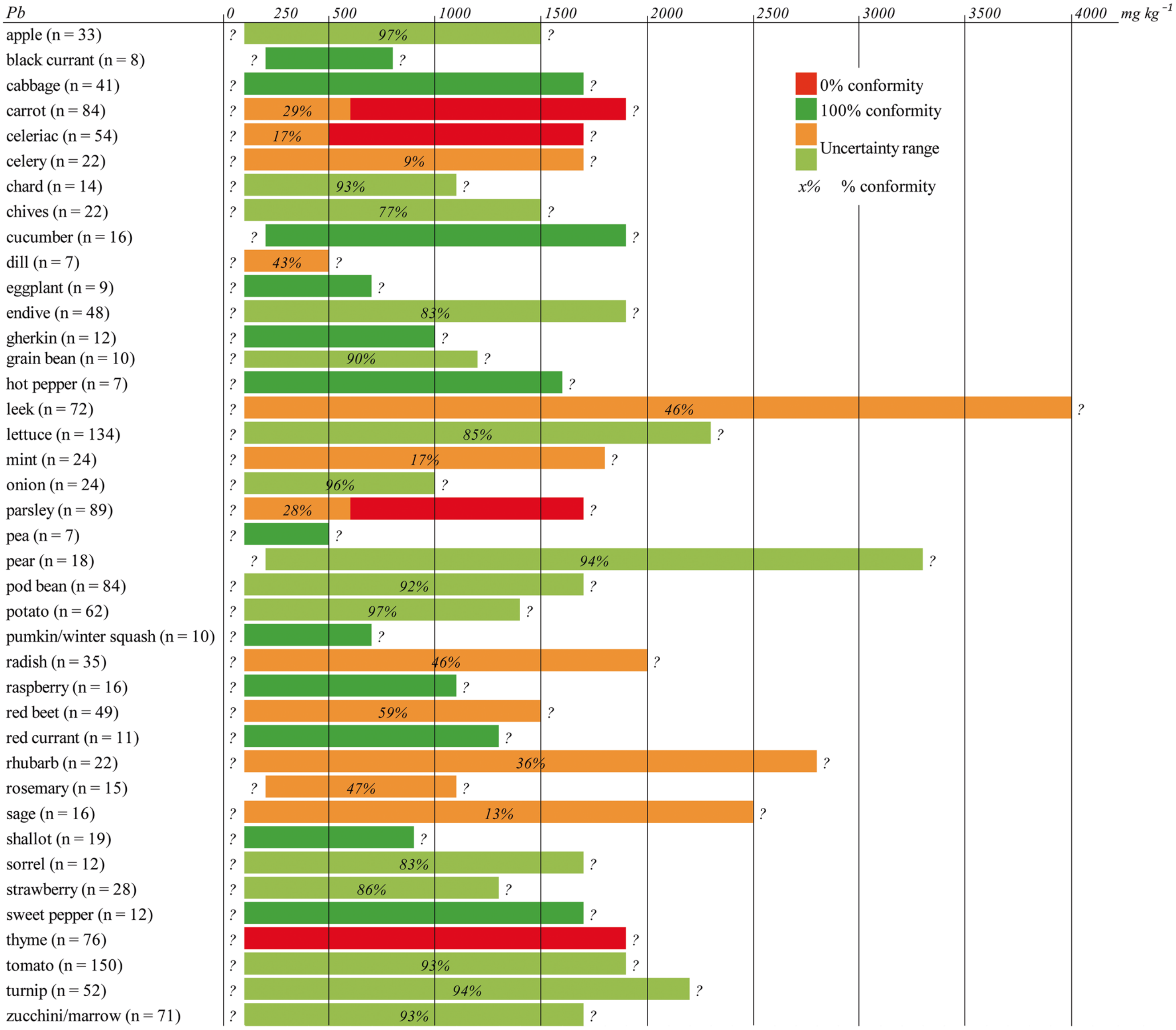

Fig. 6 Percentages of conformity of each crop according to the degree of contamination of soils by Pb. In green: 100% conformity for the crop; in red: 0% conformity; in orange and light green: uncertainty range with % conformity < 75% and > 75%, respectively

- In the present study, a first investigation was conducted on chicken eggs from 16 family plots; the results are presented in Supplementary material (Table S2 and Fig. S3). The results highlighted high concentrations of Cd and Pb in chicken eggs and showed that soil is an important contributor of metals in chicken eggs. Gardeners could be advised to reduce chickens' contact with high-metal soils to reduce metal concentrations in eggs. Thus, chicken eggs, and probably family gardening in general, may significantly contribute to the exposure of gardeners and their families.

Gardeners were informed about the results and the potential risks of exposure from contaminants in their kitchen gardens. During these individualized interviews, a significant proportion of the gardeners showed awareness of the health issue and the motivation to change certain practices. Further perspectives include new interviews with gardeners to extend the information on their gardening practices and assess the implementation of the advice.

Conclusion: feedback in an urban context highly contaminated with metals

A participatory program was carried out in a specific environmental context where soils have been highly contaminated by past lead smelter activities. However, this study was based on numerous kitchen gardens and the collection of many samples of crops, soils, and self-produced compost, as well as social data. This study aimed to feed reflection and functional recommendations to reduce human exposure and to provide useful data that could be considered in other environmental contexts, in particular:

- Great variability and heterogeneity were observed within some urban garden soils in terms of physicochemical parameters and metal concentrations. Few studies have examined this variability within urban garden soils and shown that greater numbers of soil samples may be required, and more specifically soil–crop pairs should be examined.
- Most kitchen garden soils are rich in carbonate, organic matter, and available phosphorus contents, which are capable of modifying the phytoavailability of metals.
- Even if the use of compost has an immediate beneficial effect on soil, it appeared that the self-produced compost in contaminated areas may be contaminated.

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