

Vertical distribution of heavy metals in wastewater-irrigated vegetable garden soils of three West African cities

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Abstract Application of untreated wastewater to irrigate urban vegetable gardens is raising serious concern about possible health risks associated with the consumption of these vegetables particularly with regard to the concentrations of heavy metals (HM) in their edible portions. The soil concentrations of cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb) and zinc (Zn), were investigated in seven vegetable gardens from the three West African cities of Kano (Nigeria), Bobo Dioulasso (Burkina Faso) and Sikasso (Mali). Also determined were input–output balances of Cd and Zn from five vegetable gardens under 30 years of wastewater irrigation in Kano. In these gardens Cd (2.3–4.8 mg kg⁻¹) and Zn (13–285 mg kg⁻¹) concentrations throughout the profile attained unsafe levels. The concentrations of Cu (0.8–18 mg kg⁻¹), Cr (1.8–72 mg kg⁻¹), Ni (0–17 mg kg⁻¹) and Pb (0.6–46 mg kg⁻¹) were below the safety thresholds for arable soils. Overall, concentrations of Zn, Cd, Pb and Ni were higher in Kano than in Bobo-Dioulasso and Sikasso. Input–output analyses in Kano indicated

that irrigation wastewater contributed annually 400–3,700 g Cd ha⁻¹ and 7,200–22,300 g Zn ha⁻¹, fertilizer 30–2,100 g Cd ha⁻¹ 50–17,600 g Zn ha⁻¹, harmattan dust 0.02–0.4 g Cd ha⁻¹ and 40–200 g Zn ha⁻¹ while 300–500 g Cd ha⁻¹ and 2,700–4,700 g Zn ha⁻¹ came from rainwater inputs. Input–output calculations subtracting the amounts of HM taken out in vegetable biomass and that lost to leaching from total inputs yielded an annual net positive balance of 700–4,160 g Cd ha⁻¹ and 9,350–39,700 g Zn ha⁻¹. If such balances remain unchanged for another 10–20 years vegetables raised in these garden fields are likely to be unsuitable for human consumption.

Keywords Soil contamination · Urban agriculture · Heavy metal balance

Introduction

During the last decade the unique agroecological conditions of urban vegetable soils resulting from their input intensity, year-round vegetative cover, soil and hydrological characteristics and their spatial variability (Landsberg 1981; Witting 1991; Hollis 1992; Renger 1993; Businelli et al. 2009) have raised considerable research interests. This is especially so in developing countries where treatment of wastewaters is limited, thus raising concern about HM

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contamination of these soils when irrigated with untreated wastewater and subsequent accumulation in the food chain through plant uptake. Natural soils of the Nigerian savannah are characterized by low HM concentrations due to their high weathering intensity and long period of pedogenesis (Jones and Wild 1975; Agbenin and Latifatu 2004). However, with intensification of urbanization, agricultural activities and industrialization, the extent of HM accumulation has grown. Among such metals cadmium (Cd) and Zinc (Zn) are notoriously mobile and likely to move down through the soil profile to contaminate ground water (Citeau et al. 2003), even though they are easily intercepted by clay particles in subsurface horizons (Fernandez et al. 2007). Citeau et al. (2003) reported lead (Pb) to be largely stable given its solubility rate. Semlali et al. (2004) observed downward migration of Pb to be negligible. Agbenin (2002) reported lead to accumulate in insoluble forms in a Nigerian savannah soil after 50 years of continuous application of organic manure.

The West African cities of Kano (Nigeria), Bobo-Dioulasso (Burkina Faso) and Sikasso (Mali) are characterized by intensive urban production of vegetables. Even though the cities of Bobo Dioulasso and Sikasso are less populated and industrialized compared to Kano, HM may as well be accumulated in the profiles of these urban garden soils owing to the quality of irrigation water, high inputs of mineral fertilizers (Diogo et al. 2010; Predotova et al. 2010a) and pesticide application. While recent reports stressed the importance of HM loads in irrigation water and soils used for urban vegetable production in Kano (Binns et al. 2003; Abdu et al. 2010), to our knowledge comparative studies of heavy metal pollution of urban vegetable gardens across West African cities are missing.

Balance approaches have been used to assess HM flows in agricultural systems whereby nutrient balances of the surface soil and farm-gate balances are used most often (Bassanino et al. 2007). While the former addresses nutrient flows at the crop scale, the latter quantifies farm-inputs and outputs at the farm level (Velthof et al. 1996; Moolenaar and Lexmond 1998) or at the regional and national scales (Keller et al. 2001; Keller and Schulin 2003; Dach and Starmans 2005).

In view of the above this study aimed at determining the vertical distribution of Cd, Cr, Cu,

Ni, Pb, and Zn in urban vegetable gardens of three West African cities. Given the elevated concentration of Cd and Zn in the Kano urban gardens input–output balances of these two metals (Cd and Zn) were monitored at the garden level.

Materials and methods

Description of the study areas and management practices

Seven urban vegetable gardens were selected for this study. They comprised five farmers' gardens in Kano (Nigeria) and one each in Bobo Dioulasso (Burkina Faso) and Sikasso. Kano is located at 12° 00' N latitude and 8° 31' E longitude at 480 m above sea level in the Sudan savannah zone of Nigeria. Rainfall is seasonal and highly variable with an annual mean of 705 mm recorded during 2008 when this study was conducted. In Kano irrigation of vegetable gardens is intensively practiced along the major rivers which serve as effluent discharge routes for the municipal and industrial wastes produced by local industries.

In Kano the gardens of Koki, Zungeru, Kwakwaci, Gada and Katsina road were evenly distributed across the city and used different wastewater sources. A natural uncultivated reference/control site was selected for comparison of HM contamination in soil profiles. Another well water irrigated garden ('Legal') was also selected as a control in Kano for comparison of vegetable contamination. Management practices and garden sizes were similar across locations. Field plots were mostly between < 0.1 ha to 0.4 ha and planted to fast growing vegetables such as (*Amaranthus caudatus* L.), lettuce (*Lactuca sativa* L.), parsley (*Petroselinum crispum*) and carrot (*Daucus carota* ssp. *sativus*) which is often intercropped with the former ones. Fertilizer use among farmers was only occasional, whereby urea and compound soluble fertilizer in the form of NPK (15-15-15) were the predominant fertilizer types used during the rainy season. However, one farmer (Zungeru) did not use fertilizer throughout the period of the study (November 2007 to April 2009) as he considered wastewater to contain sufficient nutrients for his crops.

In Kano two of the three major industrial estates, Challawa and Sharada, comprise 115 industries

ranging from tanneries, rubber and plastic factories, textile industries and units dedicated to food processing, metal and wood processing of which most discharge their untreated effluents into the city streams. Egboka et al. (1989) reported a severe contamination of boreholes in Kano with residues from food processing industries and Binns et al. (2003) reported Cd concentration as high as 30 mg l^{-1} in urban irrigation water.

Bobo-Dioulasso ($11^{\circ}10' \text{ N}$, $4^{\circ}19' \text{ W}$, 432 m asl) has a typical southern Sudanian climate with the rainy season starting in April/May and lasting until October. Annual rainfall for the study year 2008 was 728 mm.

Sikasso ($11^{\circ} 19' \text{ N}$, $5^{\circ} 40' \text{ W}$, 375 m asl) has a typical Guinean climate comprising two main periods: a 5–6 months rainy season from May/June to October and a subsequent 6–7 months long dry season. Annual rainfall during the study year 2008 was 1,271 mm.

Selection of gardens was based on an in-depth survey comprising a GIS-based mapping and farmer interviews about the various sources of irrigation water and management practices across the cities. According to the farmers in Kano and Bobo-Dioulasso, the gardens selected have been under wastewater irrigation for 30 years while gardeners in Sikasso use mostly well water for irrigation. In Bobo-Dioulasso and Sikasso, all gardens suspected to be affected by high HM loads were located in the same area and irrigated with the same water source; therefore only one garden was selected from each city.

Sampling strategy and analytical procedures

Soil and crop sampling

In Kano at each location duplicate soil samples were taken in 2007 from 0–15, 15–25, 25–35, 35–45, 45–75, 75–100 and 100–150 cm depth. In Bobo-Dioulasso and Sikasso, however, sampling occurred only to a depth of 0.8 and 0.7 m given occurrence of a hard pan and a high water table, respectively. All samples were air-dried, crushed, and passed through a 2-mm mesh sieve prior to analysis.

In Kano, where monitoring of farmers comprised activities such as planting date, frequency, date and duration of irrigation, type and date of fertilizer applied

and date of harvest, the year was divided into three seasons: the cold dry season (CDS), the hot dry season (HDS) and the wet season (WS). The CDS lasted from November to January, the HDS from February to May and the WS from June to October. Vegetable cropping was monitored throughout each season and crop and soil samples consisting of 15–20 auger points at 0–20 cm depth from each farmer's garden were collected at each harvest independently of whether a single or more crops were planted throughout the season. For the vegetable sampling, 20–25 subsamples were taken in each of the five gardens just prior to farmers' harvest. The plant samples were washed with clean tap water to remove adhering soil particles. Vegetable samples were oven-dried to constant weight at 65°C . At Bobo-Dioulasso and Sikasso soil and vegetable samples were only collected once, in November 2007.

Input sources of HM

Irrigation water sampling

At Kano, about 100 ml of wastewater samples used for irrigation were collected fortnightly from January 2008 to March 2009 (the CDS and HDS) into pre-washed 250 ml plastic containers. At each site monthly irrigation water samples were pooled per season yielding a total of three irrigation wastewater samples per year. Two drops of concentrated HCl were added to each sample to suppress microbial activity followed by refrigerator storage until analysis.

Atmospheric deposition and rain water collection

In Kano rain and dust samples were collected during the wet and dry seasons. To this end bulk deposition collectors were made of a 0.1 m^3 plastic container and mounted in each of the five gardens at 2 m above ground level as described by Drees et al. (1993) to minimize potential effects of human activities. The plastic containers were covered with a white cotton mesh to reduce contamination from bird droppings, trees and other unwanted materials. The dust in the trap was collected into a clean plastic bag using a clean brush after removing the cotton mesh. Dust samples were collected every week from December 2007 to April 2008 and monthly samples were pooled

by season yielding three samples per year and location. Rain samples were collected immediately after each rainfall event during three rainy days in August 2008 yielding a total of three rainfall samples per year and mixed with two drops of concentrated HCl to suppress microbial activity prior to refrigeration until analysis.

Fertilizer sampling

Representative samples of NPK and urea fertilizers were collected at each application event in the specific gardens in triplicate, ground and stored until analysis.

Output of HM

Estimation of crop yield

Harvested amaranthus, lettuce and parsley were typically packed in bundles and carrots in sacks prior to being taken to local markets. Total harvested biomass per unit area was estimated by measuring the dry weight of five bundles of amaranthus, lettuce and parsley and of five sacks of carrot harvested from approximately 7.5 m². The average weight obtained was then multiplied by the total number of bundles or sacks harvested.

Leaching losses of metals

Following the description of Bischoff (2007), Lang and Kaupenjohann (2004) and Predotova et al. (2010b), in all five gardens of Kano HM leaching was estimated using PVC cartridges of 0.1 m height and 0.103 m diameter with a nylon net at the bottom. The PVC cartridges were filled with an anion cation exchange resin–sand mixture and installed according to the guidelines of TerraQuat Consultancy (Stuttgart, Germany; www.terraquat.com), the patent holder of this method. The tubes were left buried for 10 months (December 2007–October 2008).

Chemical analyses

Particle size distribution was determined by the hydrometer method following dispersion of the soil with calgon solution (Gee and Bauder 1986) and cation exchange capacity (CEC) was determined by

extracting the soil with silver-thiourea solution as described by van Reeuwijk (1993). Soil pH was measured in 1:2.5 soil:water suspension using a glass electrode pH meter and organic carbon (OC) content of the soil was determined by dichromate oxidation method (Nelson and Sommers, 1986). For total soil N and P, 1 g soil sample was digested with a mixture of H₂SO₄–salicylic acid–H₂O₂ using selenium as a catalyst. Total N was measured colorimetrically in the digest using the Bertholet reaction (Chaney and Marbach 1962) with an N-autoanalyzer (TECHNICON AAII, TechniCon Systems, Emeryville, CA, USA) and total P was determined by the molybdate–blue method of Lowry and Lopez using ascorbic acid as a reductant (van Reeuwijk 1993).

For heavy metal analysis, 1 g each of soil, plant, and dust samples was digested with concentrated HNO₃ (puriss, p.a. 65%; Sigma–Aldrich Corp., St. Louis, MO, USA) and HCl (37%, Sigma–Aldrich Corp.) at 80°C following the procedure described by Lim and Jackson (1986). Fertilizer samples were digested in a beaker with concentrated HNO₃ according to the procedure of the Association of Official Analytical Chemists (Williams 2000). The beakers were swirled gently until white fumes indicated full digestion. The digest was cooled to ambient temperature, filtered and adjusted to 50 ml with distilled water prior to analysis. The water samples were swirled with concentrated HNO₃ at 80°C until the solution turned white. Finally the digest was filtered through Whatman No. 42 and diluted to 50 ml with distilled water prior to analysis. Concentrations of Cd, Cr, Cu, Ni, Pb and Zn were determined by atomic absorption spectrophotometry (AAS; Model AA 6680, Shimadzu, Kyoto, Japan).

Resin extraction

After removal from the soil the resin–sand mixture in the cartridge was separated into four layers to obtain an element concentration profile for each cartridge (Bischoff et al. 1999). A sub sample of exactly 30 g was weighed from each layer into an extraction bottle and extracted four times by mechanical shaking with 100 ml of 2 M HCl for 16 h. The solution was decanted into a beaker and the supernatant solution filtered into a plastic vial. Cadmium and Zn were determined by AAS.

Quantification of HM balance

Heavy metal balances were established for each garden based on inputs and outputs. Major sources of these inputs and outputs were irrigation water, fertilizer, rainwater, atmospheric dust, crop removal and leaching losses.

The quantity of irrigation water used throughout the life cycle of each crop was estimated based on the discharge rate of the irrigation pumps, length of irrigation per day and frequency of irrigation for the individual crops. The amount of water was multiplied by the concentration of Cd and Zn. Cadmium and Zn concentrations in rain water (mg l^{-1}) were converted to kg ha^{-1} by multiplication with the amount of annual rainfall. The Cd and Zn input through dust deposition were calculated by multiplying the concentration of dust in g by a yearly estimated dust input of 936 kg ha^{-1} dust from an average weekly dust deposition of 0.18 g collected per 0.1 m^2 . The total metal content in the harvested biomass was estimated from the metal concentrations of the crops and the harvested dry matter.

Soil metal balance calculation

In this study, measured input variables were irrigation water and atmospheric deposition in the form of rainfall and dust (Eq. 1):

$$\Delta \text{SS}_{\text{HM}} = [\text{IW}_{\text{HM}} + \text{RW}_{\text{HM}} + \text{D}_{\text{HM}}] - [\text{CR}_{\text{HM}} + \text{L}_{\text{HM}}] \quad (1)$$

where $\Delta \text{SS}_{\text{HM}}$ is the balance of heavy metal (HM), IW_{HM} , RW_{HM} and D_{HM} are measured inputs of HM through irrigation water, rainwater and dust deposition, respectively; CR_{HM} is the measured crop removal of HM and L_{HM} denotes losses of HM through leaching. All data are in $\text{g ha}^{-1} \text{ year}^{-1}$.

Statistical analysis

Computed metal balances for each crop were expressed on a hectare basis. Analysis of variance (ANOVA) was conducted using the General Linear Procedure (PROC GLM) and seasonal differences in HM concentration of soil and crop was determined using Least Significant Difference ($\text{LSD}_{0.05}$) tests. Independent variables were season and location,

while dependent variables comprised HM concentration in soil and crop samples. Simple correlation analysis was used to relate the change in HM content at each soil depth to the calculated HM balance. All analyses were conducted using SAS 9.2 (SAS 2007) and Microsoft Excel (2003).

Results and discussion

Distribution of HM in the soil profiles

Heavy metal concentrations ranged from 2.3 to 4.0 mg kg^{-1} for Cd, from 2.6 to 50.1 mg kg^{-1} for Cr, from 4.9 to 13.6 mg kg^{-1} for Cu, from 3.3 to 12.4 mg kg^{-1} for Ni, from 1.7 to 16.5 mg kg^{-1} for Pb and from 17.4 to 233 mg kg^{-1} for Zn (Figs. 1 and 2) whereby concentrations of Cr, Cu, Ni, and Pb were below the threshold levels for agricultural soils as given by the EU and CCME (2001; Table 1). Across sites most HM concentrations decreased with profile depth, reflecting enrichment at the surface. Higher concentrations of some HM at lower profile depth likely reflected the effects of leaching-related translocation. Cadmium concentrations were with sometimes $> 3 \text{ mg kg}^{-1}$ at the bottom of the profile well above safety limits but lower than the 5.3 mg kg^{-1} reported by Awode et al. (2008) and far below the mean value of 10.3 reported by Mashi and Alhassan (2007) from Kano.

At the Gada site Cd concentration ranged from 3.7 to 4.8 mg kg^{-1} and Zn levels were with 233 mg kg^{-1} in the surface horizon surprisingly high (Fig. 2). Affinity of metals to organic matter (Agbenin 2002) could be responsible for this surface enrichment because of the relatively high OC concentration in the topsoil.

In Bobo-Dioulasso and Sikasso the concentrations of HMs were often several times lower than in Kano. In the former city, Cd concentrations ranged from 0.35 to 0.46 and 0.46 to 0.59 mg kg^{-1} , respectively, as compared to the lowest concentration value of $2.3 \text{ mg Cd kg}^{-1}$ in Kano (Fig. 1). Zinc concentrations were up to 20 times higher in Kano than in Bobo-Dioulasso and Sikasso (Fig. 2). However, Cr concentration in the surface layer of the vegetable garden in Sikasso was with 67 mg kg^{-1} almost 25% higher than in Kano. As the few industries of Sikasso are dedicated to the processing and packaging of agricultural crops, oil and soap, and unlike tanning

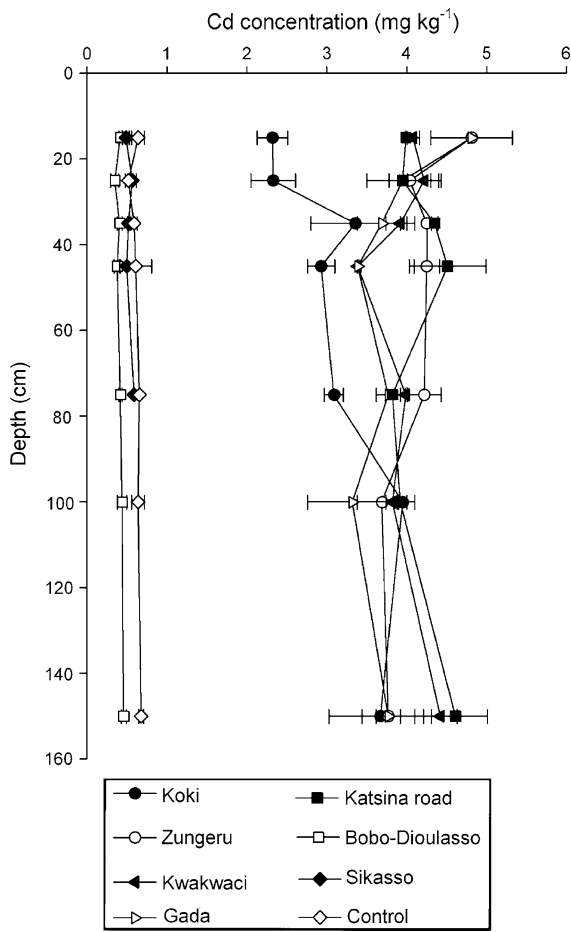


Fig. 1 Distribution of cadmium (Cd) in soil profiles of wastewater irrigated vegetables gardens in three cities of West Africa (Kano, Bobo Dioulasso and Sikasso)

and ginning enterprises do not produce Cr-rich waste, the high values in this Malian city are surprising. In Bobo-Dioulasso, the concentration of Cd and Zn decreased with profile depth (Figs. 1 and 2). As this was similar for the other HMs it may again reflect an anthropogenic origin of the studied HMs in the surface soil. The high concentration of Cr observed in the control soil as well as in the soils from Bobo-Dioulasso and Sikasso likely reflects its association with the soil parent granite and ultramafic rocks. Changes in redox conditions and other chemical properties of the soil as a result of flooding during irrigation and modification of soil pH might have helped to change the oxidation state of Cr in the cultivated soil from the stable Cr(III) to highly mobile Cr(VI) leading to a low residual concentration of this metal. Binding to dissolved organic matter

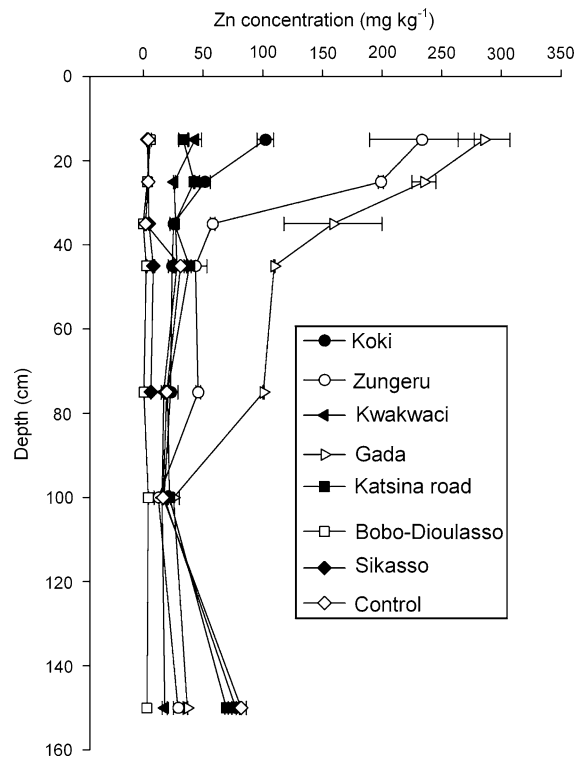


Fig. 2 Distribution of zinc (Zn) in soil profiles of wastewater irrigated vegetables gardens in three cities of West Africa (Kano, Bobo Dioulasso and Sikasso)

Table 1 International threshold values for heavy metals concentrations in soils (mg kg⁻¹)

Heavy metal	Regulatory system			
	EU	UK	USA	Canada
Cd	3.0	3.0	19.5	1.4
Cr	180.0	400.0	1500.0	6.4
Cu	140.0	80.0–200.0	170.0	63.0
Ni	75.0	50.0–110.0	210.0	50.0
Pb	300.0	300.0	150.0	70.0
Zn	300.0	200.0–300.0	1400.0	200.0

Source: CCME (2001)

could also be responsible for low Cr concentration in the cultivated soil.

Seasonal variation of heavy metals in Kano

Mean Cd concentration was with 1.4 mg kg⁻¹ highest at the Zungeru site. Mean Zn concentration in the wastewater irrigated gardens ranged from 90 to

Table 2 Concentration (mg kg^{-1}) of cadmium (Cd) and zinc (Zn) in five wastewater- and one well water-irrigated vegetable garden soils in Kano, Nigeria

Location	Cd	Zn
Koki ($n = 5$)	0.7 ± 0.2	136 ± 21
Zungeru ($n = 5$)	1.4 ± 0.4	118 ± 15
Kwakwaci ($n = 5$)	0.5 ± 0.2	90 ± 32
Gada ($n = 5$)	1.0 ± 0.3	167 ± 31
Katsina road ($n = 4$)	1.2 ± 0.5	110 ± 21
Legal ($n = 4$)	0.1 ± 0.01	23 ± 5

Data show means \pm one standard error

Table 3 Seasonal change of cadmium (Cd) and zinc (Zn) concentration (mg kg^{-1}) in wastewater irrigated garden soils in Kano, Nigeria

Season	Cd	Zn
Cold dry season	$1.1 \pm 0.2\text{a}^\dagger$	$118 \pm 17\text{a}$
Hot dry season	$0.9 \pm 0.2\text{a}$	$127 \pm 21\text{a}$
Wet season	$0.3 \pm 0.09\text{b}$	$68 \pm 21\text{b}$

Data show means \pm one standard error

† Values followed by a different letters are statistically different at $P \leq 0.05$

167 mg kg^{-1} with the highest and lowest concentrations observed in Gada and Kwakwaci, respectively (Table 2). Concentration of Cd and Zn in the well water irrigated garden soil (Legal) were 0.1 and 22.7 mg kg^{-1} Cd and Zn, respectively (Table 2). This indicates the effects of wastewater irrigation on Cd and Zn accumulation in the soil. The highest concentration of metals was observed in the CDS followed by HDS (Table 3). Irrigation was most intensive during these seasons given high evaporation rates and crop water demands. During the period from January/February to March vegetable production largely depends on wastewater, therefore it is not surprising that the concentration of both metals in the irrigation water was highest during this season and that the intensity of wastewater use for irrigation largely determines soil accumulation of HMs.

Input sources of Cd and Zn to soils

Heavy metal concentration in irrigation water, fertilizer, rainfall and atmospheric dust

Gardening in Kano is characterized by very low inputs of mineral fertilizers. Irrigation water and

Table 4 Concentration of cadmium (Cd) and zinc (Zn) in irrigation wastewater (mg l^{-1}), rain water (mg l^{-1}) and atmospheric dust (mg kg^{-1}) in Kano, Nigeria

Location/Source	Cd	Zn
Koki		
Irrigation wastewater	0.05 ± 0.01	0.7 ± 0.02
Rain water	0.07 ± 0.00	0.5 ± 0.02
Atmospheric dust	0.28 ± 0.02	266.8 ± 18.4
Zungeru		
Irrigation wastewater	0.06 ± 0.01	0.7 ± 0.05
Rain water	0.04 ± 0.01	0.6 ± 0.01
Atmospheric dust	0.38 ± 0.01	63.8 ± 3.4
Kwakwaci		
Irrigation wastewater	0.07 ± 0.02	0.4 ± 0.02
Rain water	0.05 ± 0.00	0.4 ± 0.02
Atmospheric dust	0.47 ± 0.01	87.6 ± 6.80
Gada		
Irrigation wastewater	0.05 ± 0.00	1.0 ± 0.34
Rain water	0.05 ± 0.00	0.6 ± 0.04
Atmospheric dust	0.21 ± 0.10	125.2 ± 47.2
Katsina road		
Irrigation wastewater	0.07 ± 0.01	0.7 ± 0.14
Rain water	0.04 ± 0.01	0.4 ± 0.01
Atmospheric dust	0.31 ± 0.16	132.7 ± 42.5

Data show means \pm one standard error

atmospheric depositions were therefore, the major sources of Cd and Zn at all sites. Large seasonal concentration changes of HM in irrigation water, rain and dust and site specific differences were observed (Table 4). In the irrigation water average Cd concentration at the five sites in Kano was higher than the 0.01 mg l^{-1} threshold level set by the FAO. Zn concentrations were highest in Gada and lowest in Kwakwaci. Even though the mean concentration of $0.87 \text{ mg Zn l}^{-1}$ in the irrigation water was less than half of the 2.0 mg l^{-1} threshold, high annual irrigation rates may have caused Zn enrichment as indicated by the significant correlation between irrigation water and soil Zn concentrations ($r = 0.45$, $P < 0.05$). In rain water Zn ranged from 0.4 to 0.6 mg l^{-1} which is 2-3 fold lower than what was measured in the dry season dust. At the Gada location Zn concentration was highest (Table 4) and may reflect the effects of the high concentration of Zn $44\text{--}235 \text{ mg kg}^{-1}$ and Cd ($0.02\text{--}0.45 \text{ mg kg}^{-1}$) in the dust. Their concentration in NPK fertilizers was $16.5\text{--}17.7 \text{ mg Zn kg}^{-1}$ and

0.16–0.22 mg Cd kg⁻¹ while urea contained 0.03–0.1 mg Cd kg⁻¹ and 0.13–0.85 mg Zn kg⁻¹. The rather high concentrations of HMs in NPK fertilizers may be reflect use of Cd-rich phosphate fertilizers.

Wastewater irrigation led to annual additions of 400–3,700 g Cd ha⁻¹ and 7,200–22,300 g Zn ha⁻¹ equivalent to 68 and 78% of the total respective inputs (Table 5). Fertilizer application contributed annually 30–2,100 g Cd ha⁻¹ and 50–17,600 g Zn ha⁻¹. Atmospheric wet deposition from rainfall accounted annually for 250–500 g Cd ha⁻¹ and 2,700–4,700 g Zn ha⁻¹. Cadmium and Zn inputs from the estimated 934 kg dust ha⁻¹, instead, were negligible (Table 5). In Kano total atmospheric deposition of Cd and Zn were thus 750- and 23-fold higher than the 0.5 g Cd ha⁻¹ and the 160 g Zn ha⁻¹ reported by Azimi et al. (2004) for Versailles, France.

While Cd concentrations in irrigation and rainwater were above the 0.01 mg l⁻¹ FAO threshold level, those of Zn were below the 2 mg l⁻¹ threshold but still higher than values reported by Akoto et al. (2008) for five polluted streams in Ghana. At the Gada site, construction activities at about 100 m from the sampling garden might have contributed to the high Zn concentration of 1.59 mg l⁻¹ in the irrigation water (Table 4). Dust at this site also had a Zn concentration of 207 mg kg⁻¹. The highest concentration of Cd (0.07 mg l⁻¹) and Zn (0.96 mg l⁻¹) was measured in irrigation water at Katsina road (Table 4) and might be caused by discharge from a seed and pesticide industry in the vicinity of the sampling site. Although the concentration of HM in the irrigation water may be low, continued use of this wastewater as practiced in Kano can lead to the build-up of HM in soils (Rattan et al. 2002).

Export of metals

Mean Cd concentration in vegetables ranged from 0.1 to 0.3 mg kg⁻¹ while Zn export was between 11.5 and 163 mg kg⁻¹. Highest concentration of Cd and Zn was recorded in amaranthus and lettuce, respectively (Table 6). Amaranthus with its total dry matter (TDM) of 3.5–28 t ha⁻¹ led to annual exports of 0.7–2.0 g Cd ha⁻¹ and 100–1,700 g Zn ha⁻¹ while such values were negligible for carrots with TDM

Table 5 Annual balance of horizontal Cd and Zn fluxes for five vegetable gardens in Kano, Nigeria

Location/Source	Input–output (g ha ⁻¹ year ⁻¹)	
	Cd	Zn
Koki		
Irrigation water	1,400	15,700
Fertilizer (NPK)	160	17,600
Dust	0.3	220
Rainfall	300	4,700
Leaching losses	–300	–1,500
Amaranthus	–1.0	–600
Carrot	–0.5	–300
Total balance	1,560	35,800
Zungeru		
Irrigation water	400	7,200
Dust	0.3	54
Rainfall	500	3,900
Leaching losses	–200	–1,800
Amaranthus	–0.7	–100
Parsley	–0.3	–100
Total balance	700	9,354
Kwakwaci		
Irrigation water	3,700	22,300
Fertilizer (NPK)	210	15,470
Fertilizer (Urea)	50	770
Dust	0.4	70
Rainfall	500	3,900
Leaching losses	–300	–1,100
Amaranthus	–2.0	–1,700
Carrot	–0.2	–50
Total balance	4,158	39,660
Gada		
Irrigation water	700	20,000
Fertilizer (Urea)	80	210
Dust	0.03	41
Rainfall	400	4,000
Leaching losses	–200	–2,100
Amaranthus	–3.0	–1,700
Lettuce	–1.0	–500
Total balance	976	19,950
Katsina road		
Irrigation water	840	13,500
Fertilizer (Urea)	30	50
Dust	0.02	190
Rainfall	500	2,700
Leaching losses	–200	–2,800
Parsley	–1.0	–900
Lettuce	–1.0	–600
Total balance	1,168	12,140

Table 6 Crop dry matter yield, cadmium (Cd) and zinc (Zn) concentration and annual removal of Cd and Zn in crops from five vegetable gardens in Kano, Nigeria

Location	Crop	Yield (t ha ⁻¹)	Concentration (mg kg ⁻¹)		Crop removal (g ha ⁻¹)	
			Cd	Zn	Cd	Zn
Koki	Amaranthus (<i>n</i> = 8)	7.1	0.1 ± 0.02	76 ± 19	1.0	600.0
	Carrot (<i>n</i> = 2)	3.0	0.2 ± 0.02	110 ± 10	0.5	300.0
Zungeru	Amaranthus (<i>n</i> = 6)	3.5	0.3 ± 0.13	47 ± 11	0.7	100.0
	Parsley (<i>n</i> = 3)	1.7	0.2 ± 0.08	79 ± 5	0.3	100.0
Kwakwaci	Amaranthus (<i>n</i> = 10)	28.1	0.1 ± 0.03	87 ± 12	2.0	1,700.0
	Carrot (<i>n</i> = 2)	1.8	0.1 ± 0.02	12 ± 2	0.2	50.0
Gada	Amaranthus (<i>n</i> = 6)	25.8	0.2 ± 0.03	67 ± 25	3.0	1,700.0
	Lettuce (<i>n</i> = 4)	6.4	0.2 ± 0.07	61 ± 27	1.0	500.0
Katsina road	Parsley (<i>n</i> = 4)	8.1	0.1 ± 0.01	112 ± 27	1.0	900.0
	Lettuce (<i>n</i> = 2)	4.3	0.2 ± 0.01	164 ± 91	1.0	600.0

Data show means ± one standard error

yields of 1.8 and 3.0 t ha⁻¹ in Kwakwaci and Koki, respectively (Table 6). The corresponding Cd and Zn export was equally low. Leaching of Cd estimated from resin extraction was 200–300 g ha⁻¹ and of Zn 1,100–2,800 g ha⁻¹.

Input–output balances

High inputs of nutrients through wastewater irrigation have been reported for several studies from West African cities. Diogo et al. (2010) showed large nitrogen (N) surpluses as a result of N rich wastewater irrigation in Niamey, Niger. Similarly, Khai et al. (2007) reported large Zn inputs into vegetable gardens of Hanoi, Vietnam through wastewater irrigation. The net surplus of 9,200–39,700 g Zn

ha⁻¹ year⁻¹ (Table 5) observed in our amaranthus gardens by far exceeded the 650–7,700 g ha⁻¹ reported by Khai et al. (2007). This largely reflects the level of contamination of the wastewater used for irrigation in Kano. With 9,200 g ha⁻¹ Zn surplus was lowest in the garden under parsley and amaranthus. Gardens under amaranthus and carrot production, however, had highest values with 39,700 g Zn ha⁻¹ and 4,200 g Cd ha⁻¹ (Table 5). In the present study, leafy vegetables seemed to accumulate more HM than fleshy vegetables despite the fact that the fleshy vegetable (carrot) had a longer growing cycle (Table 6). The significance of correlations between the concentration of HMs and HM balances decreased with soil depth (Table 7) reflecting the effects of anthropogenic activities. The close and

Table 7 Relationship between profile distribution of Cd and Zn with HM balances in wastewater irrigated vegetable gardens in Kano, Nigeria

Soil depth (cm)	Cd balance		Zn balance	
	Equation	r ² value	Equation	r ² value
0–15	y = 8E–10x ² –1E–05x + 4.02	0.99	Y = –6E–07x ² + 0.03x + 3.36	0.98
15–25	y = 2E–09x ² –5E–05x + 3.89	0.99		0.51
25–35	y = –7E–10x ² –5E–05x + 3.45	0.93		0.32
35–45	y = –6E–10x ² –6E–05x + 3.03	0.80		0.26
45–75	y = –2E–09x ² –5E–05x + 3.72	0.99		0.48
75–100		0.33		0.56
100–150		0.43		0.17

Equations were only presented for significant relationship (*P* ≤ 0.05)

significant relationships observed between HM balance and soil depth largely indicated superficial enrichment of Cd and Zn. HM accumulation and balance can thus be predicted by changes in HM concentration over a defined length of time. Furthermore, the higher relationship observed for Cd can be attributed to higher Cd loading and ease of Cd movement and translocation in the soil profile as compared with Zn. Such accumulations may in the long term cause environmental and human health risks even if at present those risks seem to be limited except for Cd and Zn.

Conclusions

Our study shows Cd and Zn accumulation in surface soils of vegetable gardens in Kano (Nigeria). Soil HM concentrations followed the sequence Kano >> Sikasso > Bobo-Dioulasso. Garden-based flux measurements of HM revealed that the major sources of Cd and Zn in Kano are wastewater irrigation, atmospheric deposition and NPK fertilizer wherever it was applied. Cadmium and Zn loads may lead to elevated concentrations in marketed vegetables and leach to the groundwater with negative consequences for human health. Legislation is needed to restrict HM loads to soils by limiting HM discharges from industries into wastewater that will continue to be used to irrigate urban vegetable gardens.

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