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Heavy metals in the irrigation water, soils and vegetables in the Philippi horticultural area in the Western Cape Province of South Africa

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Abstract

The aims of this study were to investigate the extent of heavy metal contamination in the Philippi horticultural area in the Western Cape Province, South Africa. Concentrations of Cd, Cr, Cu, Mn, Ni, Pb and Zn were determined in the irrigation water, soils and vegetables in both winter and summer cropping seasons with an ICP-AES and tested against certified standards. Differences were found in heavy metal concentrations between the winter and summer cropping seasons in the irrigation water, soils and vegetables. Certain heavy metals exceeded the maximum permissible concentrations in the irrigation water, soils and vegetables produced in South Africa. These toxic concentrations were predominantly found in the summer cropping season for the soils and in the crops produced in winter. It is thus suggested that further studies are carried out in the Philippi horticultural area to determine the sources of the heavy metals to try and mitigate the inputs thereof and therefore reduce the amount of heavy metals entering the human food chain.

Introduction

Heavy metals are naturally occurring in the environment due to the natural weathering of bedrock. These naturally released heavy metals are usually contained in forms that are not readily available to plant roots (Tyler et al. 1989; Nellessen and Fletcher 1993; Prasad 2004). However, in recent years, this has changed due to the increase in anthropogenic activities which release more biologically available forms of heavy metals into the environment (Prasad 2004; Benavides et al. 2005; Islam et al. 2007; Arora et al. 2008). Agriculture is one of the most significant anthropogenic activities contributing to the release of bioavailable heavy metals into the environment (Martin et al. 2006). Mortvedt (1996) suggested that both organic (depending on the parent material) and inorganic/ chemical fertilizers are major sources of heavy metals, while Kabata-Pendias (2011) suggested that other agro-chemicals could also be significant sources of heavy metals to agricultural soils. Several researchers have subsequently shown that the continuous applications of both organic and inorganic/chemical fertilizers, as well as other agrochemicals such as pesticides, herbicides, fungicides, waste water and sewage sludge, allow for bioaccumulation of heavy metals and other chemical residues in agricultural soils (Reuss et al. 1976; Ayuso et al. 1996; Mortvedt 1996; Ihnat and Fernandes 1996; Harmon et al. 1998; Haroun et al. 2009; Worthington 2001; Goi et al. 2006; Cai et al. 2007; Arora et al.

2008; Chen et al. 2008; Müller et al. 2014).

Because plants form one of the major sinks for both essential and toxic elements in the terrestrial environment, an increase in heavy metal concentrations in agricultural soils would thus also lead to an increase in the uptake of these heavy metals by the crops grown on these soils and, this in turn, would result in an increase in heavy metals in the human diet (Pinamonti et al. 1997; Cole et al. 2001; Martin et al. 2006; Casadovela et al. 2007; Islam et al. 2007; Kidd et al. 2007; Bose and Bhattacharyya 2008; Odlare et al. 2008; Achiba et al. 2009; Delbari and Kulkarni 2011). Arora et al. (2008) indicated that using wastewater to irrigate agricultural soils resulted in significantly higher concentrations of heavy metals in the edible portions of the crops grown on these soils. These authors concluded that both adults and children consuming the vegetables grown on the wastewater-irrigated soils ingested significant amounts of iron, manganese, copper and zinc. Müller et al. (2014) found that at the end of a 9-year growing period, organic and inorganic/chemical fertilizer applications to a Cripps Pink/M7 apple orchard resulted in higher aluminium and iron concentrations in the inorganically/chemically treated soils and cadmium, lead and zinc concentrations that were higher in the organically treated soils. The same authors indicated that the increased cadmium concentrations found in the soils under organic fertilizer applications also resulted in cadmium concentrations in the apples to exceed the maximum permissible concentrations for fresh produce grown in South Africa.

Heavy metals enter the human body mainly through inhalation or ingestion (Islam et al. 2007). The intake of heavy metals through vegetable consumption is a problem that has been reported globally. It is receiving increasing attention not only from governments but also from the public, who are becoming increasingly concerned about the possible health risks associated with the higher concentrations of heavy metals found in the human food chain (Islam et al. 2007). It is estimated that nearly half of the mean ingestion of heavy metals is of plant origin (Türkdogan et al. 2002; Järup 2003; Islam et al. 2007). Ingestion of large amounts of heavy metals could result in various illnesses and toxicities due to the disruption of several biochemical processes within the human body (Prasad 2004; Anhwange et al. 2013). Thus, bioaccumulation of heavy metals in vegetables and fruits could pose a direct threat to human health (Islam et al. 2007).

The aims of the current study were therefore to investigate the extent of heavy metal (Cd, Cr, Cu, Mn, Ni, Pb, and Zn) contamination of the irrigation water, soils and fresh produce grown in both winter and summer cropping seasons in the Philippi horticultural area, a major supplier of fresh produce in the Cape Town area in the Western Cape Province of South Africa.

Materials and Methods

Study area

The Philippi horticultural area (latitudes 34° 00′ S and 36° 00′ S and longitudes 18° 31′ E and 18° 35′ E) is situated on the sandy Cape Flats and lies approximately 14 km from Cape Town City centre. The area spans over approximately 3500 ha with a topography typical of coastal plains and dune fields (DWAF 2007; AzaGnandji et al. 2013). The area used for agricultural purposes has however diminished considerably over the last decade due to urbanisation, both formal and informal. The remaining land is predominantly used for vegetable farming; however, pig, poultry and cattle farming also exist to a lesser extent (AzaGnandji et al. 2013). The main vegetable crops that are grown in the Philippi horticultural area include carrots, cabbages, potatoes, lettuce, onions, peppers, beans, cauliflowers, spinach and broccoli in both winter and summer cropping seasons (AzaGnandji et al. 2013). This continuous production all year round makes the Philippi horticultural area a major source of fresh produce to the surrounding areas which are faced with high levels of food insecurity (Battersby-Lennard and Haysom 2012). However, due to past problems such as illegal dumping, ground water pollution and informal settlements, along with the current intense agricultural practices, the quality of the crops produced in the Philippi horticultural area could be negatively impacted (Meerkotter 2012).

Sample collection, preparation and analyses

Water, soil and vegetable samples were collected from 34 sampling locations in the Philippi farming area during the months of February (summer) and July (winter). Water samples were collected from the irrigation ponds at the sampling locations, and soil and vegetable samples were collected from the cropping sites adjacent to the irrigation ponds. After the water was collected, the pH was determined using an Orion 2-star benchtop pH meter (KCl), after which, the samples were preserved by adding 1–2 ml of 32 % hydrochloric acid (HCl) and stored at 4 °C for heavy metal determination. At each sampling location, ten soil samples were randomly collected from the surface to a depth of approximately 15 cm. These ten samples were thereafter added together and thoroughly mixed, creating one composite sample at each sampling location. After collection, the soil samples were air-dried for approximately 3 weeks, after which, the soil pH was determined using an Orion 2-star benchtop pH meter (KCl) using the sticky point method as described by Jackson (1962). Different vegetable samples were collected based on their availability from the same areas where soil samples were collected. As with the soil, ten vegetable samples were collected from random locations on the cropping site after which these ten samples were added together to create a single composite sample for each vegetable crop species from each sampling location. After collection, the vegetables were rinsed with deionised water and oven-dried at 70 °C until a constant mass was reached. Once dried, the samples were milled and stored for heavy metal determination. Soil samples were digested using an Aqua Regia digestion method (Chen and Ma 2001) for 2 h on a hot plate, while the vegetable samples were ashed at 450 °C for 2 h, except for selenium analyses, for which the samples were digested using a mixed acid digestion mixture (Moore and Chapman 1986). At each digestion and dry ashing, three blank samples were also prepared for quality assurance. Analyses of Cd, Cr, Cu, Mn, Ni, Pb and Zn in the water, soil and vegetable samples were performed using an ICP-AES and regularly tested against certified standards (Bemlab Ltd.).

Statistical analyses

The Statistical Package for the Social Sciences version 21 (SPSS Inc., Chicago, IL) was used to test the data for normality using a Shapiro-Wilk test, after which, a Kruskal-Wallis analysis

(H) was performed to determine whether there were statistically significant differences ($P < 0.05$) in the heavy metal concentrations in the irrigation water, soil and vegetable crops between the winter and summer cropping periods.

Results and discussion

Water

The pH of the irrigation water from the Philippi horticultural area did not differ significantly ($P \geq 0.05$) between the winter and summer cropping seasons. The results obtained indicated that the pH of the irrigation water ranged from 6.4 to 8.6 (mean = 7.5) and 6.5 to 8.5 (mean = 7.3) in the winter and summer cropping seasons, respectively. These pH ranges indicate that in both winter and summer cropping seasons, at certain of the sampling locations, the pH of the irrigation water was either marginally below or above the targeted range of 6.5 to 8.4 for water used for irrigation in South Africa (DWAF 1996; Aza-Gnandji et al. 2013).

Differences in cadmium, copper and zinc concentrations in the irrigation water were observed between the winter and summer cropping seasons (Table 1). Cadmium and copper concentrations were marginally higher in the winter cropping season, while zinc concentrations were higher in the summer cropping season. Cadmium concentrations in the irrigation water collected from certain sampling locations were found to marginally exceed or were at the maximum permissible concentrations of 0.05 mg Cd/L in water used for irrigation in South Africa in both winter and summer cropping seasons (DWAF 1996). The Philippi horticultural area receives a significant amount of winter rainfall which is used to fill irrigation ponds; however, in the summer months, groundwater is often used as the main water source for irrigation of crops. The groundwater is pumped and stored in irrigation ponds from where it is re-pumped to irrigate croplands. These irrigation ponds, however, not only serve as reservoirs to contain rain and groundwater but also significant amounts of irrigation return flow and channel water (Aza-Gnandji et al. 2013). This could be the reason for the high heavy metal content in the irrigation water at certain sampling locations. This corresponds to Ross (1994) who suggested that contamination of agricultural soils with heavy metals through irrigation water is primarily due to irrigation water sourced from deep wells or polluted rivers, lakes and channels.

Soils

The pH of the soils in the Philippi horticultural area ranged from 6.7 to 8.3 (mean=7.7) and 6.9 to 8.5 (mean = 7.8) in the winter and summer cropping seasons, respectively.

Table 1 Heavy metal concentrations in irrigation water collected in both winter and summer cropping seasons from the Philippi horticultural area

	Heavy metal concentration (mg/kg)						
	Cd Mean±SE Range	Cr Mean±SE Range	Cu Mean±SE Range	Mn Mean±SE Range	Ni Mean±SE Range	Pb Mean±SE Range	Zn Mean±SE Range
Winter	0.01±0.002b	0.06±0.009a	0.02±0.003b	0.02±0.002a	0.02±0.002a	0.04±0.006a	0.02±0.003a
	0–0.06[a]	0–0.16	0–0.09	0–0.07	0–0.05	0–0.12	0–0.07
Summer	0.009±0.002a	0.06±0.009a	0.01±0.002a	0.02±0.004a	0.02±0.002a	0.05±0.008a	0.05±0.002b
	0–0.05[a]	0–0.23	0–0.07	0–0.10	0–0.05	0–0.14	0.02–0.08
H	3.929	>0.05	6.808	>0.05	>0.05	>0.05	23.016
P	0.047		0.009				<0.001

Mean heavy metal concentrations with the same letters indicate no difference ($P \geq 0.05$) between the winter and summer concentrations

[a] Concentrations above the legal limit in South Africa

The soil pH ranges in both winter and summer cropping seasons observed in this study met the targeted pH ranges of 6.5 to 8.5 for agricultural soils in South Africa (WRC 1997). Soil pH plays an important role in the bioavailability of heavy metals to plants. An increase in soil pH, i.e. the soil environment becomes more alkaline, results in a decrease in the availability of heavy metals to plants (Prasad 2004). However, under more alkaline soil conditions, the heavy metals are more tightly bound in the soil, resulting in the accumulation of these metals in the soil over time (Prasad 2004). This in turn could become problematic when large quantities of heavy metals have accumulated in agricultural soils over time, and for any reason, the soil becomes even slightly more acidic, making large quantities of metals more bioavailable for the uptake by plants (Prasad 2004).

In this study, significant differences ($P < 0.05$) in copper, manganese, nickel and zinc concentrations were observed between the winter and summer cropping seasons. These heavy metals were found to be significantly higher in the soils collected in the summer cropping season (Table 2). Soils collected from certain sampling locations were also found to contain cadmium, chromium, copper, lead and zinc at concentrations which exceed the maximum permissible concentrations of 2, 80, 6.6, 6.6 and 46 mg/kg, respectively for soils used for agriculture in South Africa (WRC 1997). However, cadmium and chromium were only found to exceed the maximum permissible concentrations in the winter cropping season (Table 2).

Table 2 Heavy metal concentrations in the agricultural soil collected in both winter and summer cropping seasons from the Philippi horticultural area

	Heavy metal concentration (mg/kg)						
	Cd Mean±SE Range	Cr Mean±SE Range	Cu Mean±SE Range	Mn Mean±SE Range	Ni Mean±SE Range	Pb Mean±SE Range	Zn Mean±SE Range
Winter	0.74±0.18a	30.13±3.93a	14.53±2.02a[a]	96.74±12.29a	1.71±0.40a	19.24±2.91a[a]	72.71±8.49a[a]
	0.004–4.72[a]	2.04–107.70[a]	2.68–53.96	16.43–360.98	0–8.50	0.55–80.86	18.59–184.38
Summer	0.48±0.07a	37.52±4.10a	22.68±2.38b[a]	134.31±17.50b	3.12±0.44b	22.21±2.90a[a]	99.20±10.72b[a]
	0009–1.77	2.84–6.44	2.58–72.95	31.42–631.32	0–9.91	0–61.56	30.29–352.29
H	>0.05	>0.05	10.659	4.566	6.113	>0.05	4.566
P			0.001	0.033	0.013		0.033

Mean heavy metal concentrations with the same letters indicates no difference ($P \geq 0.05$) between the winter and summer concentrations

[a] Concentrations above the legal limit in South Africa

Although copper and zinc are considered essential micronutrients to plants for their roles as activators of many enzymes and cofactors for oxidative enzymes (Hopkins and Hüner 2004), excessive uptake of these metals could inhibit many metabolic functions which lead to growth retardation and injury to the plants which, in turn, leads to yield reductions (Van Assche et al. 1988; Stadtman and Oliver 1991; Somasekharaiah et al. 1992; Cakmak and Marshner 1993; Ebbs and Kochian 1997; Thomas et al. 1998; Prasad et al. 1999; Hegedus et al. 2001; Lewis et al. 2001; Romero-Puertas et al. 2004). Cadmium, chromium and lead on the other hand are well-known plant toxins. Despite the selectivity of plant roots to the uptake of mineral elements, these toxic elements are also taken up and incorporated into plant tissues (Hopkins and Hüner 2004; Prasad 2004). The uptake of cadmium, lead and chromium in excessive amounts by plants has adverse effects on both morphology as well as biochemical processes within plants (Baker 1972; Gruenhage and Jager 1985; Stiborova et al. 1987; Sharma and Dubey 2005).

Vegetables

The vegetable crops collected from the Philippi horticultural area were found to contain varying concentrations of the focus heavy metals (Table 3).

Table 3 Heavy metal concentrations in the vegetable crops collected in both winter and summer cropping seasons from the Philippi horticultural area

		Heavy metal concentration (mg/kg)						
		Cd Mean±SE Range	Cr Mean±SE Range	Cu Mean±SE Range	Mn Mean±SE Range	Ni Mean±SE Range	Pb Mean±SE Range	Zn Mean±SE Range
Cabbage	Winter	0.22±0.09b[a]	2.68±0.52b	5.55±0.57b	41.64±5.21b	0.34±0.25a	2.32±0.91a[a]	54.12±9.24a[a]
		0.01–0.55	1.32–4.75	3.93–7.83	26.20–58.38	0.02–1.60	0.06–5.12	28.90–82.02
	Summer	0±0a	1.02±0.11a	3.07±0.53a	24.50±2.44a	0.19±0.07a	0.07±0.03a	44.16±0.80a[a]
		0–0	0.84–1.29	1.62–4.08	20.12–31.46	0–0.31	0.05–0.10	43.17–45.75
	H	*6.968*	*6.545*	*5.500*	*4.545*	*>0.05*	*>0.05*	*>0.05*
	P	*0.008*	*0.011*	*0.019*	*0.033*			
Cauliflower	Winter	0.38±0.06b[a]	1.41±0.26a	5.77±1.53a	30.25±3.46a	0.22±0.09a	0.77±0.34b[a]	63.71±5.94a[a]
		0.18–0.57	0.48–2.36	3.45–13.23	24.43–46.97	0.02–0.56	0.05–2.20	50.62–89.10
	Summer	0.001±0.001a	0.80±0.21a	7.05±2.13a	27.23±1.92a	0.10±0.07a	0.01±0.01a	64.42±3.96a[a]
		0–0.004	0.31–1.51	4.66–15.56	20.87–32.39	0–0.33	0–0.05	54.75–78.43
	H	*7.857*	*>0.05*	*>0.05*	*>0.05*	*>0.05*	*6.844*	*>0.05*
	P	*0.005*					*0.009*	
Carrots	Winter	0.23±0.08b[a]	2.46±0.40a	4.22±0.29a	8.50±0.52a	0.46±0.18a	3.79±0.93b[a]	30.55±4.31a
		0.01–0.73	0.88–5.40	2.91–5.55	6.12–11.08	0.03–2.01	0.03–9.96	18.43–57.20[a]
	Summer	0.06±0.02a	4.48±1.34a	7.30±0.66b	15.96±4.64a	1.66±0.50b	0.14±0.04a	35.67±3.51a
		0.02–0.13	0.85–14.50	4.70–9.79	6.56–55.69	0.15–5.16	0.02–0.35	22.43–53.26[a]
	H	*4.624*	*>0.05*	*11.763*	*>0.05*	*6.96*	*10.227*	*>0.05*
	P	*0.032*		*0.001*		*0.008*	*0.001*	
Lettuce	Winter	0.51±0.16b[a]	4.21±1.57a	9.90±1.74a	40.18±10.96a	3.39±1.39a	4.14±1.50a[a]	73.52±10.59a[a]
		0.05–0.85	1.28–8.88	5.73–16.14	16.28–79.85	0.03–6.98	0.05–9.40	39.66–100.40
	Summer	0.06±0.02a	3.71±0.59a	9.24±1.55a	28.57±2.07a	1.66±0.44a	0.09±0.04a	57.25±6.23a[a]
		0.002–0.17	1.84–5.06	4.18–14.84	23.26–35.47	0.29–2.62	0.05–0.27	32.22–71.50
	H	*5.633*	*>0.05*	*>0.05*	*>0.05*	*>0.05*	*>0.05*	*>0.05*
	P	*0.018*						

Mean heavy metal concentrations with the same letters indicates no difference ($P \geq 0.05$) between the winter and summer concentrations

[a] Comparisons were made within crop species and concentrations above the legal limit in South Africa

In certain of these vegetable crops, significant differences were found in heavy metal concentrations between the winter and summer cropping seasons. However, where these differences were observed, heavy metal concentrations were generally higher in the vegetables harvested in the winter cropping season, with the exception of copper and nickel concentrations in carrots which were higher in the summer cropping season (Table 3).

According to South African Legislation and regulations made under the Foodstuffs, Cosmetics and Disinfectant Act, Act number 54 of 1972, fresh produce containing the metals cadmium, copper, lead, tin and zinc in amounts greater than what is stipulated in the act will be deemed harmful or damaging to human health (Government Gazette 1994). In the current study, cadmium, lead and zinc concentrations in each of the vegetable crops exceeded these limits of 0.1, 0.3–0.5 and 40 mg/kg, respectively (Government Gazette 1994). These harmful concentrations of cadmium and lead were only observed during the winter cropping season while zinc concentrations exceeded the legal limits in both winter and summer cropping seasons (Table 3).

This result is of serious concern. Prolonged exposure to these toxic heavy metals through the consumption of vegetables could lead to the disruption of several biochemical processes within the human body (Anhwange et al. 2013). Although zinc is an essential nutrient to humans necessary for the functioning of a large number of metalloenzymes, excess uptake of zinc can alter cholesterol metabolism, weaken blood vessels, induce vomiting and diarrhoea, as well as damage the kidneys (DuPuy and Mermel 1995; Hallberg et al. 1993). Cadmium and lead on the other hand have no beneficial effects on human health. Cadmium has been classified by the International Agency for Research on Cancer (IARC) as a human carcinogen that can be implicated in various cancers (Järup 2003), while high levels of lead have been found to affect an array of human physiological systems, including renal function, neurological functions and immunological functions (Gidlow 2004).

From these results, it is clear that the irrigation water, soils, as well as the fresh produce produced in the Philippi horticultural area contains varying concentrations of certain heavy metals. Due to the integral role that the Philippi horticultural area plays in the acquisition of mineral nutrients to the communities surrounding the Philippi horticultural area, which are also suffering from food insecurity (Battersby-Lennard and Haysom 2012), it is suggested that further studies are conducted in the Philippi horticultural area in order to determine the major agronomic sources of heavy metals to the irrigation water and soils in the area. Further work is also needed not only to try and mitigate the inputs of these heavy metals but also to remove already existing metals from the irrigation water and soils to mitigate the uptake of these metals by the crops grown in the Philippi horticultural area. This in turn would result in a reduction in heavy metals entering the human food chain in this area.

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