

Accumulation of Essential Mineral and Toxic Trace Elements in Crops and Soils of Vegetable Cropping Systems in Central Highlands of Sri Lanka

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Research Article

Keywords: Heavy metals, Leaching, Metalloids, Nutrition, Pollution

Posted Date: July 2nd, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-660623/v1>

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Abstract

Background and Aims Vegetables are widely cultivated in high rainfall and mountainous regions in Sri Lanka with poor soil conservation practices. Accumulation of essential mineral and toxic trace elements in these soils and widely cultivated vegetable crops are not known.

Methods One hundred soil and vegetable (*i.e.* cabbage, carrot and potato) samples were collected at the time of harvest and analysed for element concentrations.

Key Results Soils contained very high concentrations of essential mineral and toxic trace elements. When compare edible parts, cabbage contained the highest concentrations of mineral and toxic trace elements, and potato contained lowest. Irrespective of the crop, edible parts contained high concentrations of N, P, K, (14-35, 2-6, 15-24 g kg⁻¹, respectively), Cu, Zn, Mn (2.5-6.7, 11-30, 8-147 mg kg⁻¹, respectively). Vegetables also contained As, Cd and Pb (0.04-1, 0.02-0.15, 0.02-0.26 mg kg⁻¹, respectively), but didn't exceed the maximum permissible limits. Irrespective of the crop 36-64 kg N, 6-11 kg of P, 35-45 kg K per ha were removed with the harvest. According to the current rate of vegetable consumption by a Sri Lankan adult (*i.e.* 240 g FW per day), per capita consumption of 0.05-0.2 mg Cu, 0.45-0.65 mg Zn and 0.5-2 mg Mn day⁻¹ through these vegetables was observed, *i.e.* 5-23% Cu, 7.5-11% Zn and 22-87% Mn of the recommended daily intake.

Conclusion Vegetables grown in the region served as a key source of essential mineral elements. However, agronomic mitigation strategies are needed to improve soil health and sustainability of these cropping systems.

Introduction

Crop productivity has increased over the past 50–60 years as a result of green revolution (Pingali 2012). With the development and use of high-yielding crop varieties, demand for fertilizers has also been increased. Therefore, farmers apply high doses of both organic and inorganic sources of nutrients aiming to reach higher crop productivities (Weerakkody and Mawalagedara 2020). However, continuous overdosing of fertilizers without following the recommendations has led to problems such as soil degradation, soil nutrient imbalances, nutrient toxicities to plants, and pollution of water bodies (Khai et al. 2007; Bandara et al. 2010; Weerakkody and Mawalagedara 2020). As a result, the sustainability of those agricultural systems has been threatened.

Intensive vegetable cultivation systems exhibit a significant contribution to the present vegetable
Loading [MathJax]/jax/output/CommonHTML/fonts/TeX/fontdata.js farmer fields in Nuwara Eliya (6.9497° N,

80.7891° E) and Welimada (6.9019° N, 80.9079° E) regions provide classic examples for commercial and intensive vegetable cultivation in open field conditions. High-value crops are grown, in rotation, three to four times per year without following the land aiming to reach high income per unit of land and time (Sirisena and Suriyagoda 2018; Weerakkody and Mawalagedara 2020). Therefore, farmers mobilize all available and affordable inputs, including agrochemicals and manures, without considering the environment sustainability or profit margins (Sirisena and Suriyagoda 2018). Major vegetable crops cultivated in these regions include; carrot (*Daucus carota* L.), cabbage (*Brassica oleracea* L.), beetroot (*Beta vulgaris* L.), bean (*Phaseolus vulgaris* L.), leeks (*Allium porrum* L.) and potato (*Solanum tuberosum* L.).

Even though vegetables act as a key source of mineral elements its contribution to human nutrition is largely neglected in Asia (Ali and Tsou 1997; Weerakkody and Mawalagedara 2020). The quality of vegetable crops produced is influenced by the amount and type of mineral elements available in soil and the amount taken up by the crop. However, the nutritional quality of vegetables is not valued by these farmers. Therefore, they frequently apply inorganic sources of nitrogen (N), phosphorus (P) and potassium (K) to soil, and micro-nutrients such as zinc (Zn), sulfur (S), manganese (Mn), molybdenum (Mo), and copper (Cu) through fertilizer mixers either to soil in the solid form or foliage in the liquid form. They also apply organic manures such as compost, cattle manure and poultry manure. As a result of this continuous practice, plant available P and K concentrations have reached sufficiency even for the succeeding crops (Wijewardana and Amarasiri 1997; Sirisena and Suriyagoda 2018). Moreover, the main watersheds in the country are situated around these vegetable cultivating regions, risking the pollution of a wide range of water sources (Diyabalanage et al. 2017; Sirisena and Suriyagoda 2017).

Micro-nutrients are essential dietary requirements for plants and animals. Daily intake/uptake of those are essential for the basic functioning of plants or animals (Abeywickrama et al. 2018). Deficiencies in micro-nutrients are known as “hidden hunger” as those deficiencies cannot be clinically identified till the last stages (Abeywickrama et al. 2018). Recent reviews suggested the prevalence of iron (Fe), Zn and calcium (Ca) deficiencies among Sri Lankans (Akhtar et al. 2013; Abeywickrama et al. 2018). Even though both macro- and micro-nutrients are frequently been applied to these intensive agricultural systems, the availability of those mineral elements in soils and accumulation in major vegetable crops grown are largely unknown (Ali and Tsou 1997; Weerakkody and Mawalagedara 2020). Moreover, according to the WHO/FAO recommendation, the per capita vegetable and fruit intake should be a minimum of 400 g or five servings per day to prevent the occurrence of chronic diseases (Kanungsukkasem et al. 2009). However, in the year 2015 the per capita fruit and vegetable consumption in Sri Lanka was 240 g or three servings per day by an adult (Jayawardena et al. 2020). Therefore, it is important to study the contribution of major vegetables when supplying essential mineral elements to local communities.

It is reported that mineral fertilizers such as phosphates, and organic manures are sometimes contaminated with toxic trace elements such as arsenic (As), cadmium (Cd) and lead (Pb) (Dissanayake 20). Continuous and excessive application of

these mineral sources may result in increasing the bioavailability of those toxic trace elements in soil and accumulate in the food chain causing chronic health problems to humans (Premarathna et al. 2005; Dissanayake and Chandrajith 2009; Suriyagoda et al. 2018). However, the accumulation of these toxic trace elements in widely cultivated Sri Lankan vegetable crops has not been studied. Therefore, it is essential to study the concentrations of plant available forms of essential mineral elements and toxic trace elements in soil, accumulation in edible plant parts, and the amount removed by the crops with the harvest. Therefore, the objectives of this study were to evaluate the (i) concentrations of essential mineral and toxic trace elements in soils and crops, and (ii) amount removed with the harvest of widely cultivated vegetable crops from Nuwara Eliya and Welimada regions of Sri Lanka.

Materials And Methods

Vegetable crop and soil samples were collected from Nuwara Eliya and Welimada regions in Sri Lanka during the period from October to December 2019. Basic soil and climate characteristics of the two study regions are given in Table 1. Vegetable cultivation in these sloppy lands has been a major land use for decades. Temperature is optimal for the cultivation of most of the vegetable crops and receives a year-round abundant rainfall. Farmers also practice supplementary irrigation as required from natural waterways.

Table 1
Soil and climate characteristics in the two vegetable cultivating regions

Parameter	Nuwera Eliya	Welimada
Agro-climatic zone	Up-country Wet zone	Up-country Intermediate zone
Main soil types	Red-yellow podzolic soils, wet mountain regosols, and red-yellow podzolic soils with prominent A1 horizon	Reddish brown latasolic soils with mountain regosols, and immature brown loams
Topography	Very steep, hilly and rolling	Mountainous, hilly and rolling
Average temperature	20°C	25°C
Annual rainfall for the 75% expectancy	1800 mm – 3100 mm	1400 mm – 2400 mm
Major crops	tea, vegetables	vegetables, rice
Minor land usage	paddy, perennial crops, natural forests, forest plantations, scrub lands and grass lands	tea, natural forests, forest plantations and export agricultural crops
Sources: General Soil Map, 1967; DOA, 2003		

Three widely grown vegetable crops in the region; cabbage, carrot and potato were selected for the study (AgStat 2018). The number of soil and plant samples to be collected from each region and crop was determined proportionately based on their extent (AgStat 2018). When collecting plant samples at least four sampling points from one field were selected considering the crop and topographical heterogeneities in the field. One square meter land area was selected for harvesting at each point. Harvested plants from those four points in a field were combined and mixed to make a composite sample. Both the above and below-ground plant parts of carrot and potato were harvested while only the shoots of cabbage were harvested from the base. Harvesting was done by pulling both carrot and potato plants after losing the soil around the base of the plant using a fork without damaging the below-ground plant parts by a skilled labourer. Cabbage plants were cut from the base using a harvesting knife to obtain the shoot. Fresh weights of shoots and roots harvested from each sample were recorded. Samples were collected on the days when farmers harvested their crops to be sent to markets. Therefore, eight visits were made to Nuwara Eliya and Welimada regions to collect those samples.

Soil samples were collected from the fields used to collect vegetable samples. When collecting soil samples at least four individual samples from the top 15 cm were collected. Samples from one field were combined and mixed to make a composite sample. Soil samples from nearby undisturbed forest patches, representing unfertilized native vegetation in the region, were also collected. One hundred soil and vegetable samples from intensively vegetable cultivated fields, and nine soil samples from forest patches were collected (Table 2). Soil samples were collected at the time of plant sample collection, and also within the quadrat of plant samples collected.

Table 2
Description of the soil and plant (only from crop fields) samples collected

District	Crop fields			Forest patches	Total
	Carrot	Cabbage	Potato		
Nuwara Eliya	36	17	9	6	68
Welimada	10	4	24	3	41
Total	46	21	33	9	109

Both soil and plant samples were transported to the Department of Crop Science, Faculty of Agriculture, University of Peradeniya for processing and laboratory analyses. Apart from the soil and vegetable samples, compost, cattle manure and poultry manure samples were also collected from farmer fields or retail traders in the region to measure nutrient concentration in those samples.

Soil samples were air-dried and sieved through one mm sieve before estimating mineral element and toxic trace element concentrations. Total N concentration was estimated using the Kjeldahl method (Anderson and Ingram 1993). Ammonium acetate-extractable K was extracted with a 1 M ammonium acetate (NH₄OAc) solution buffered to pH 7 and testing in a flame atomic absorption spectrophotometer

(GBC model 932AA, Hampshire, USA) (Van Ranst et al. 1999). Available P concentration was measured using Olsen method (Olsen et al. 1954). Soil solution concentrations of N, P and K were measured using the column displacement procedure (Adams et al. 1980; Somaweera et al. 2017). Organic matter, pH (1:5 ratio of soil: water) and EC of the soil samples were also measured (Anderson and Ingram 1993). Plant available concentrations of other mineral elements (*i.e.* Ca, Mg, Mo, Cu, Mn, Fe, Ni and Zn) and toxic trace elements (*i.e.* As, Pb and Cd) in soil samples were determined after extracting in 0.01 M CaCl₂ solution. For this, approximately 4 g of air-dried, sieved and homogenised soil sample was weighed into 60 mL centrifuge tube, filled with 40 mL of 0.01 M CaCl₂, centrifuged at a 130 rpm in an end-to-end shaker for two hours (Houba et al. 2000). Thereafter, those tubes were centrifuged at 3,600 rpm for four minutes and the supernatant was filtered through a cellulose acetate syringe filter with a pore size of 0.45 µm. The supernatant was diluted seven times using deionized water and element concentrations were determined using ICP-MS (Thermo iCapQ, Bremen, Germany).

To determine the dry weight (*i.e.* moisture content) and element concentrations (macro- and micro-nutrients, and toxic trace elements) in plant samples, a representative sub sample with a minimum of 500 g fresh weight from each sample was prepared. The fresh weight of the sample was obtained and oven-dried until a constant weight was reached (*i.e.* minimum of four days) at 70°C. For this root and shoot samples of carrot and potato, and shoot samples of cabbage were used. The difference between fresh and dry weight was considered as the moisture content and expressed as a percentage of fresh weight. Oven-dried samples were ground to make a powder using a steel ball mill and stored in the oven at 60°C. Care was taken to clean the equipment after processing of each sample. An approximately 100 mg subsample was taken and digested in nitric-perchloric mix acid and analyzed using the vanado-molybdo-phosphate yellow colorimetric method for the determination of tissue P concentration. Tissue K concentration was determined as explained by Van Ranst et al. (1999) and N concentration using Kjeldahl method (Anderson and Ingram 1993). For the determination of other elements in plant tissues (*i.e.* Cu, Zn, Mn, As, Cd and Pb), approximately 200 mg subsample was digested in 2 mL hydrogen peroxide/4 mL nitric acid (160°C for 40 minutes) using Milestone microwave digestion system (EthosEASY, Sorisole (BG), Italy). All the chemicals used were analytical grade. Plant tissue elemental concentrations were quantified using ICP-MS method. Regent blanks, in-house standard sample (Bg450) and an international reference material, IRMM-804 (Institute for Reference Materials and Measurements (IRMM), Geel, Belgium) were used for analytical quality control. This allowed the comparison of data within and among digestion cycles. While collecting soil and plant samples farmers were interviewed by filling a short-structured questionnaire to understand their current fertilizer application plan. Concentrations of mineral and toxic trace elements, moisture content, and fresh weights of cabbage shoots, potato tubers and carrot roots were used when estimating the removal of mineral and toxic trace elements with harvest.

Data were analysed using SAS statistical software (SAS 2005) as a factorial ANOVA to study the effects of regions (*i.e.* Nuwara Eliya and Welimada), crops (*i.e.* cabbage, carrot, and potato) and their interactions on tested variables. All the interpretations were made at a significance level of $\alpha = 0.05$.

Results

Types of fertilisers applied

Majority of vegetable farmers used both inorganic and organic fertilisers (Table 3). Out of the farmers who used inorganic fertilizers, majority preferred mixed fertilizers than straight fertilizers. Farmers used different types of organic manures simultaneously with inorganic fertilizers. Application of compost and poultry manure was more common than applying either cattle manure or charcoal. The number of farmers who applied lime or dolomite was lower, and none of the farmers have applied green manure or crop residues.

Table 3
Types of fertilizers applied by vegetable farmers in Nuwara Eliya and Welimada regions (n = 94)

Fertilizer type	Percentage of farmers used the practice (%)
Inorganic fertilizers	81.1
i. Mixed fertilizers	79.7
ii. Straight fertilizers	32.4
Organic manures	64.9
i. Compost	39.2
ii. Poultry manure	32.4
iii. Cattle manure	24.3
iv. Charcoal	20.3
v. Lime/dolomite	6.8
vi. Green manure/crop residue	0

Concentration of mineral elements in soils and manures

Irrespective of the crops grown, soils in Nuwara Eliya contained 2.2, 1.4 and 2.6-times higher concentrations of total N, available P and organic matter, respectively than that observed in Welimada region (Fig. 1). Fields used to cultivate carrot and potato in Nuwara Eliya contained higher exchangeable K concentrations than those crop fields in Welimada. The highest EC value was observed in potato fields in Welimada. Concentrations of P and K reported in crop fields were higher than the levels required for optimal growth of crops. Plant available P, exchangeable K and EC values reported in crop fields were 18, 6.7 and 3.4-times higher, respectively while N, pH and organic matter levels were comparable to those observed in forest soils. Soil solution concentrations of N, P and K were higher than those reported in forest soils (Fig. 2).

The concentration of CaCl_2 extracted mineral elements in soil between the two cultivating regions and crop fields were similar except for the higher Mg and lower Mn concentrations in Welimada region than those observed in Nuwara Eliya (Table 4). Moreover, a higher Cu concentration was reported in potato fields in Nuwara Eliya and carrot fields in Welimada than other crop fields in those regions.

Table 4

Micro nutrient concentrations (mg kg^{-1}) in the soils of two cultivating regions when extracted using 0.01 M CaCl_2 , mean \pm SE, sample size is as stated in Table 2

Region	Crop	Ca mg g^{-1}	Mg mg kg^{-1}	Mn mg kg^{-1}	Fe mg kg^{-1}	Ni mg kg^{-1}	Zn mg kg^{-1}	Mo $\mu\text{g kg}^{-1}$	Cu $\mu\text{g kg}^{-1}$
Nuwara Eliya	Cabbage	3.1 \pm 0.94	183 \pm 24	48 \pm 13	2.1 \pm 0.42	5.7 \pm 0.2	0.8 \pm 0.1	29 \pm 2	248 \pm 96
	Carrot	3.9 \pm 0.49	158 \pm 15	33 \pm 8	2.1 \pm 0.22	5.6 \pm 0.1	1.1 \pm 0.3	37 \pm 12	144 \pm 17
	Potato	3.7 \pm 0.85	175 \pm 10	45 \pm 10	2.3 \pm 0.12	6.0 \pm 0.2	1.4 \pm 0.4	30 \pm 3	718 \pm 86
Welimada	Cabbage	3.3 \pm 0.56	226 \pm 16	29 \pm 9	2.4 \pm 0.08	5.9 \pm 0.1	1.3 \pm 0.3	31 \pm 2	480 \pm 117
	Carrot	3.8 \pm 0.39	224 \pm 10	19 \pm 3	2.3 \pm 0.03	6.1 \pm 0.1	1.2 \pm 0.2	31 \pm 1	728 \pm 86
	Potato	3.4 \pm 0.56	194 \pm 14	28 \pm 9	2.2 \pm 0.17	5.7 \pm 0.1	1.0 \pm 0.3	40 \pm 2	148 \pm 17

Soils in both regions and crop fields contained high concentrations of CaCl_2 extracted As, Cd and Pb (Fig. 3). Concentrations of Pb and Cd between the two regions and crop fields were similar, except for the lower concentration of Pb reported in the cabbage fields in Welimada. Moreover, a relatively lower concentration of As was reported in Nuwara Eliya soils than that reported in Welimada.

Cattle manure contained a higher concentration of Mg, Zn and Pb while poultry manure contained higher concentrations of Mo, As and Cd than other sources of organic manure (Table 5). The concentration of elements in cattle manure varied widely than that observed in poultry manure and compost. Compost contained the lowest concentrations of Zn, Cu, Mo, As and Cd than those in cattle manure and poultry manure.

Table 5
Element concentration in the organic matter applied when
extracted using 0.01 M CaCl₂, (mean ± SE, n = 6)

Element	Cattle manure	Compost	Poultry manure
N- mg g ⁻¹	13.7 ± 1.5	12.3 ± 0.9	33.8 ± 1.8
P- mg g ⁻¹	5.1 ± 0.9	4.2 ± 0.5	24.3 ± 1.5
K- mg g ⁻¹	3.4 ± 1.3	3.7 ± 0.8	17.6 ± 3.5
Ca- mg g ⁻¹	2.9 ± 0.92	3.7 ± 0.36	1.5 ± 0.19
Mg- mg kg ⁻¹	500 ± 181	273 ± 39	258 ± 12
Mn- mg kg ⁻¹	30 ± 24	14 ± 5.7	5.7 ± 0.3
Fe- mg kg ⁻¹	3.6 ± 1.8	2.9 ± 0.33	1.9 ± 0.01
Ni- mg kg ⁻¹	4.9 ± 1.9	5.8 ± 0.6	2.1 ± 0.1
Zn- mg kg ⁻¹	10.7 ± 8.6	1.3 ± 0.35	5.2 ± 0.2
Cu- mg kg ⁻¹	2.7 ± 1.5	0.6 ± 0.02	1.7 ± 0.11
Mo- µg kg ⁻¹	209 ± 89	64 ± 9	598 ± 35
As- µg kg ⁻¹	111 ± 27	58 ± 19	274 ± 17
Cd- µg kg ⁻¹	35 ± 11	10 ± 3	62 ± 4
Pb- µg kg ⁻¹	207 ± 176	120 ± 60	35 ± 2.4

Yield and dry matter content

The harvested fresh weights of cabbage, carrot roots and potato tubers were 2.6 ± 0.3, 2.2 ± 0.7 and 1.7 ± 0.5 kg m⁻², respectively and those were similar between the two regions. Dry matter content of the shoot samples of cabbage, carrot and potato were 7.5, 12 and 16.5%, respectively while that of carrot roots and potato tubers were 9 and 13.9%, respectively.

Concentration of mineral elements in shoots and roots

Nitrogen concentration in both roots and shoots of the three crops was similar between the two cultivating regions (Fig. 4). Carrot and potato shoots had higher N concentrations than that in their roots. When compare crops, cabbage recorded the highest shoot N concentration in both regions. Nitrogen concentration in carrot roots was higher than that in potato tubers in Nuwara Eliya while it was similar

between the two crops in Welimada. When compare edible parts, cabbage shoots contained 1.8 and 2.1-times higher N concentrations than in carrot roots and potato tubers, respectively.

Crops grown in Welimada had a higher shoot and root concentrations of P than that in Nuwara Eliya (Fig. 4). When compare crops, shoot P concentration was the highest in cabbage while that in potato shoots was the lowest in both the regions. Carrot roots contained more P than in potato tubers in both regions. When compare edible parts, cabbage shoots contained 1.7 and 2.2-times higher concentrations of P than in carrot roots and potato tubers, respectively.

Shoot K concentration of the three crops was higher in Nuwara Eliya than that in Welimada while root K concentration between the two regions was similar (Fig. 4). Potato shoots had the highest K concentration while in cabbage shoots was the lowest in both regions. Carrot roots contained more K than in potato tubers. When compare edible parts, carrot roots contained 1.2 and 1.5-times higher concentration of K than in cabbage shoots and potato tubers, respectively.

Apart from higher N, P and K, shoots of carrot and potato contained higher concentrations of Cu, Mn and Zn than that in their roots or tubers (Table 6). Among shoots, cabbage contained the lowest concentrations of Mn, Cu and Zn while potato contained the highest concentrations of those elements. When compare edible parts, cabbage shoots contained higher concentrations of all the tested micronutrients than that in carrot roots and potato tubers (Table 6).

Table 6
Micro nutrient concentrations (mg kg⁻¹) in the shoots and roots of three crops from two cultivating regions, mean ± SE, sample size is as stated in Table 2

Region	Crop	Plant part	Cu	Mn	Zn
Nuwara Eliya	Cabbage	Shoot	3.3 ± 0.58	57 ± 5.3	30 ± 5.8
		Carrot	Shoot	10.0 ± 0.58	195 ± 22
		Root	6.7 ± 0.33	41 ± 4.6	25 ± 2.1
	Potato	Shoot	15.8 ± 1.20	529 ± 193	153 ± 7.1
		Tuber	4.2 ± 0.42	8 ± 2.8	11 ± 2.8
	Welimada	Cabbage	Shoot	2.5 ± 0.25	147 ± 30
Carrot		Shoot	5.8 ± 0.50	383 ± 107	50 ± 12.6
		Root	5.8 ± 0.67	57 ± 13	21 ± 2.9
Potato		Shoot	16.6 ± 1.25	904 ± 95	110 ± 9.3
		Tuber	6.7 ± 0.33	24 ± 3.3	14 ± 1.5

Irrespective of the region, carrot and potato shoots contained higher concentrations of As, Cd and Pb than those in their roots/tubers (Fig. 5). The concentration of Pb in potato shoots was higher than the other two crops in Welimada, while that in Nuwara Eliya was similar. The lowest and highest shoot Cd concentrations were recorded in cabbage and potato, respectively. The concentration of As in carrot shoots was lower than that in cabbage and potato shoots. When compare edible parts, cabbage shoots contained the highest concentrations of As, Cd and Pb *i.e.* 6 and 27-times higher concentration of As, 1.2 and 1.8-times higher concentration of Cd, and 16 and 3-times higher concentration of Pb than that in carrot roots and potato tubers, respectively.

Irrespective of the crop, the mean quantity of mineral and toxic trace elements contained in 240 g of fresh edible parts of the three crops were 0.4–0.6 g N, 0.06–0.1 g of P, 0.3–0.5 g K, 0.05–0.2 mg Cu, 0.5–2 mg Mn and 0.45–0.65 mg Zn (Fig. 6). Additionally, 0.001–0.02 mg As, 0.001–0.002 mg Cd, 0.0004–0.003 mg Pb were also contained in 240 g FW of those vegetables. The amount of mineral and toxic trace elements removed with the harvest from one ha land also had a similar pattern, *i.e.* 36–64 kg N, 6–11 kg of P, 35–45 kg K, 6–13 g Cu, 37–199 g Mn, 44–53 g Zn, 0.1–1.9 g As, 0.12–0.18 g Cd and 0.04–0.32 g Pb per ha were removed (Fig. 6).

Discussion

Soils were heavily fertilized and rich in minerals and toxic trace elements

Vegetable fields in both Nuwara Eliya and Welimada regions of Sri Lanka have frequently and heavily been fertilized using both inorganic and organic sources of nutrients for decades (Dissanayake and Chandrajith 2009; Sirisena and Suriyagoda 2018; Dandeniya and Caucci 2020). Therefore, soil fertility levels have been built up to very high levels (*i.e.* to the levels higher than that required for optimal plant growth), *e.g.*, organic matter, N, P and K concentrations and EC levels were very high. As far as authors are aware this much higher available P and exchangeable K concentrations have not been previously reported from any agricultural fields. This situation has caused soil solution to retain very high concentrations of N, P and K as observed in the leaching column experiment.

Apart from the application of straight fertilizers such as urea (N), triple superphosphate (P) and muriate of potash (K), the use of organic matter and inorganic fertilizer mixtures available in the market has resulted in the development of micronutrient levels, and inevitably, the toxic trace element concentrations due to their poor quality (Tables 3,4,5) (Premarathna et al. 2005; Dissanayake and Chandrajith 2009; Bandara et al. 2010; Jayasumana et al. 2015). The concentrations of micro nutrients and toxic trace elements made available to crops through the application of organic matter varied depending on the type of organic matter applied and region, *e.g.*, the organic matter added to soil in this region contained a lower concentration of As than that reported in rice cultivating regions of Sri Lanka (Jayasumana et al. 2015). Moreover, the same authors reported that the inorganic fertilizers contained a higher concentration of toxic trace elements than those found in organic matter. Despite these heterogeneities, due to the continuous application of fertilizers and manures concentrations of micronutrients and toxic trace

elements have been built up to very high levels. Similar to the findings of this experiment, the presence of high micronutrient and toxic trace element concentrations in the soils from the same region and intensively cultivated cropping fields in North China have previously been reported (Premarathna et al. 2005; Ju et al. 2007).

Farmers in these vegetable cultivated fields have not adopted adequate soil conservation practices despite located in mountainous areas exposed to heavy rainfall (Samarakoon and Abeygunawardena 1996; Diyabalanage et al. 2017; Weerakkody and Mawalagedara 2020). It is also reported that the disturbed and damaged soil structures with high organic matter content can no longer be protected by microbial decomposition and aggregation (Kobierski et al. 2020). These conditions have aggravated the risk in erosion and leaching, polluting aquatic ecosystems downstream which are important tributaries and reservoirs in Sri Lanka (Samarakoon and Abeygunawardena 1996; Bandara et al. 2010; Diyabalanage et al. 2017; Sirisena and Suriyagoda 2018). This highlights the importance of revising (*e.g.*, cutting down) fertilizer application plans and adopting soil conservation methods urgently in this region.

Soils in the region were rich in organic matter, particularly at Nuwara Eliya. The addition of organic matter is the cause of the development of high organic matter content in agricultural soils while the senesced biomass contributed to the accumulation of organic matter in natural forests. Application of poultry manure and cattle manure has become popular among vegetable farmers in this region as it increases productivity than applying inorganic fertilizers alone (Table 2) (Wijewardena and Amarasiri 1997; Wijewardena 2000). Greater accumulation of organic matter in Nuwara Eliya than that in Welimada would also be due to the cooler temperatures in Nuwara Eliya slowing down the decomposition of organic matter and mineralization (Table 1). Moreover, as farmers practice crop rotation in their fields, a significant difference in mineral element concentrations among fields within a region was not observed. As a result, irrespective of the crop grown, Nuwara Eliya soils retained more organic matter than that in Welimada.

Vegetables as a source of essential mineral elements

Among the edible parts of the crops studied, element concentrations were the highest in cabbage and lowest in potato. Similar pattern was observed in the amounts of mineral and toxic trace elements removed with the harvest from one ha land, except for K and Cu. However, the amounts of mineral element intake through these crops in a daily ration (*i.e.* 240 g FW) did not follow the same pattern due to the difference in their dry matter content (*i.e.* cabbage < carrot < potato) (Fig. 6).

Even though these soils have been heavily fertilized, only some of the essential mineral elements showed high concentrations in plant tissues such as P and K. Moreover, none of the crops displayed deficiency or toxicity symptoms of mineral elements. Therefore, vegetables produced in this region can be considered as a major source of mineral elements to the local community and used to minimize mineral malnutrition (*i.e.* hidden hunger). However, people suffering from chronic disorders such as kidney disease may reduce the consumption of vegetables such as cabbage and carrot produced in this region as those vegetables

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When compare mineral accumulation, N concentration in green leaves of a range of vegetables from different parts of the country was lower than that reported in the present study (Liyanage et al. 2000). Similarly, potatoes produced in Canada and the Czech Republic, and cabbage produced in Turkey also contained lower concentrations of essential mineral elements in their edible parts and in the soil solution than reported in this experiment (Kiziloglu et al. 2008; Bártořá et al. 2013; Liang et al. 2019). However, Takahashi et al. (2018) and Wen et al. (2019) reported similar concentrations of N, P and K in cabbage and lettuce tissues when grown in soils well fertilized with N, P and K. Therefore, higher tissue N, P and K concentrations reported in the crops grown in this region would also be due to heavy N, P and K fertilization.

Vegetables act as a key source of micronutrients in the human diet. Mineral elements such as Zn, Mn and Cu are either components in the large number of enzymes or essential for enzymatic reactions in both plants and animals (Abeywickrama et al. 2018). According to the current rate of vegetable consumption by a Sri Lankan adult (*i.e.* 240 g per day), per capita consumption of 0.05–0.2 mg Cu, 0.45–0.65 mg Zn and 0.5–2 mg Mn day⁻¹ through these vegetables was observed. These amounts represent only 5–23% Cu, 7.5–11% Zn and 22–87% Mn of the recommended daily intake (IMNA 2001), and thus, these vegetables contributed as a key source of mineral elements requirement to the local community. It is reported that the residents of almost all South Asian countries consume extremely low quantities of fruit and vegetables, lower than the World Health Organization recommendation (Dizon et al. 2019; Jayawardena et al. 2020). Therefore, in terms of quantity, vegetable consumption has to be increased, particularly for vegetable-based diets to increase the provision of a mineral element through vegetables. Moreover, the identification of vegetables rich in minerals and methods that can be used to enrich/fortify vegetables with minerals need to be investigated (Dobosy et al. 2020).

Carrot and potato shoots contained high concentrations of mineral elements and toxic trace elements than those present in their roots/tubers, and higher than those present in cabbage shoots. Despite nutritional excellence, carrot and potato shoots are not generally consumed as vegetables but used in making compost. Even though the chance of contaminating with toxic trace elements is lower in shoots than that in roots or tubers (Setiyo et al. 2020), an opposite response was observed in the present study. As samples were carefully washed using running water before drying for element analysis, the observed concentration of mineral elements would have not been due to surface accumulation, but represent the amount accumulated in leaf tissues. This could be due to the heavy use of foliar fertilizers and pesticides for these crops in this region (Shahid et al. 2017). However, this needs further testing and confirmation.

Although mineral elements are essential, excessive and long-term intake, higher than the required amount may cause complications *e.g.*, long-term intake of Zn higher than the recommended level would cause problems in the metabolism of Cu (FAO/WHO 2001).

However, according to the findings of this study the available concentrations of essential mineral elements would not cause a serious threat to its consumers as the tissue concentrations have not been built up to toxic levels, but would cause detrimental impacts to the environment. Therefore, it is important

to reduce the rate of fertilizer application, implement soil conservation methods, educate farmers on good agricultural practices (GAP), avoid the flow of agricultural residues and wastewater directly to natural waterways to minimize environmental pollution and increase the health, safety and wellbeing of these vegetable growers and consumers (Weerakkody and Mawalagedara 2020). In this process, evaluation and monitoring of nutrient levels in soils and vegetables and implementation of policy and regular measures by the responsible organizations is required.

Accumulation of toxic trace elements in vegetables

According to the FAO/WHO (2019) guidelines established for human consumption, the maximum permissible limit of Pb in *Brassica* vegetables, and root and tuber crops is 0.1 mg kg^{-1} . Similarly, the maximum permissible limit of Cd in *Brassica* vegetables is 0.05 mg kg^{-1} , and in root and tuber crops is 0.1 mg kg^{-1} . European Commission (EU 2006) has set the permissible levels of Cd and Pb in potato tubers as 0.05 and 0.1 mg kg^{-1} , respectively. Moreover, the maximum permissible levels of Cd, Pb and As set for leafy vegetables and root crops in China are 0.05 , 0.1 and 0.5 mg kg^{-1} , respectively (GAIN 2014). All the above limits have been given on a fresh weight basis. When comparing those limits with the values observed in the present experiment (*i.e.* concentration of toxic trace elements in dry weight basis \times dry matter content/100), the concentrations of As, Cd and Pb observed in edible parts of these crops on fresh weight basis did not exceed the maximum permissible limits established. However, Premerathna et al. (2005) reported the presence of high Cd in cabbage shoots from the same region exceeding maximum permissible limits. Similarly, the leafy vegetable Mukunuwenna (*Alternanthera sessilis* L.) samples collected from different urban regions in Sri Lanka also contained similar or higher concentrations of Cd and Pb than observed in the present study (Kananke et al. 2014, 2016). It is also reported that irrigation of agricultural lands with wastewater leads to the accumulation of toxic trace elements in soils and crops grown (Kiziloglu et al. 2008; Sharma et al. 2016). Therefore, the concentration of toxic trace elements in vegetable crops depend on the variation in soil characteristics such as soil pH, clay and organic matter contents, crop management practices such as quality of irrigation water and fertilizer applied, and crop adaptations (Tack, 2014; Khan et al. 2015; Setiyo et al. 2020). It is also suggested that P fertilizers induced immobilization of heavy metals such as Pb, Cd, and Zn in soil (Wang et al. 2008; Yang et al. 2019) and decrease translocation from roots to shoots in cabbage (Qiu et al. 2011). However, this response depends on the concentration of P and other competing elements in soil (Suriyagoda et al. 2018). As there is a risk of accumulating high concentrations of toxic trace elements in vegetables grown in the region, agronomic mitigation strategies need to be implemented in order to ensure the sustainability of these cropping systems and the health of consumers.

Concluding Remarks

Intensive vegetable cultivating lands in Nuwara Eliya and Welimada regions of Sri Lanka are owned by small-scale (< 0.5 ha) farmers. They apply heavy doses of agrochemicals to maximize their crop productivity per land per year. Due to this practice, soil nutrient and toxic trace element concentrations

have been built up to high concentrations, risking the contamination of streams and groundwater through leaching and runoff. Three major vegetable crops grown in the region; cabbage, carrot and potato also contained high concentrations of mineral elements and toxic trace elements. However, the concentrations of As, Cd and Pb did not exceed the maximum permissible limits. Improving the awareness of farmers on their malpractices, and the introduction of good agricultural practices (GAP) are urgently needed to conserve soil and ensure the sustainability of these cropping systems.

Declarations

Declarations

Authors declare no conflicts of interest.

Acknowledgements

The authors acknowledge the technical assistance given by the officers in the Department of Crop Science, Faculty of Agriculture, Mr. Anurashantha and Agriculture Instructors (AI) in the region for field assistance. Financial support was provided by the University of Peradeniya.

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Figures

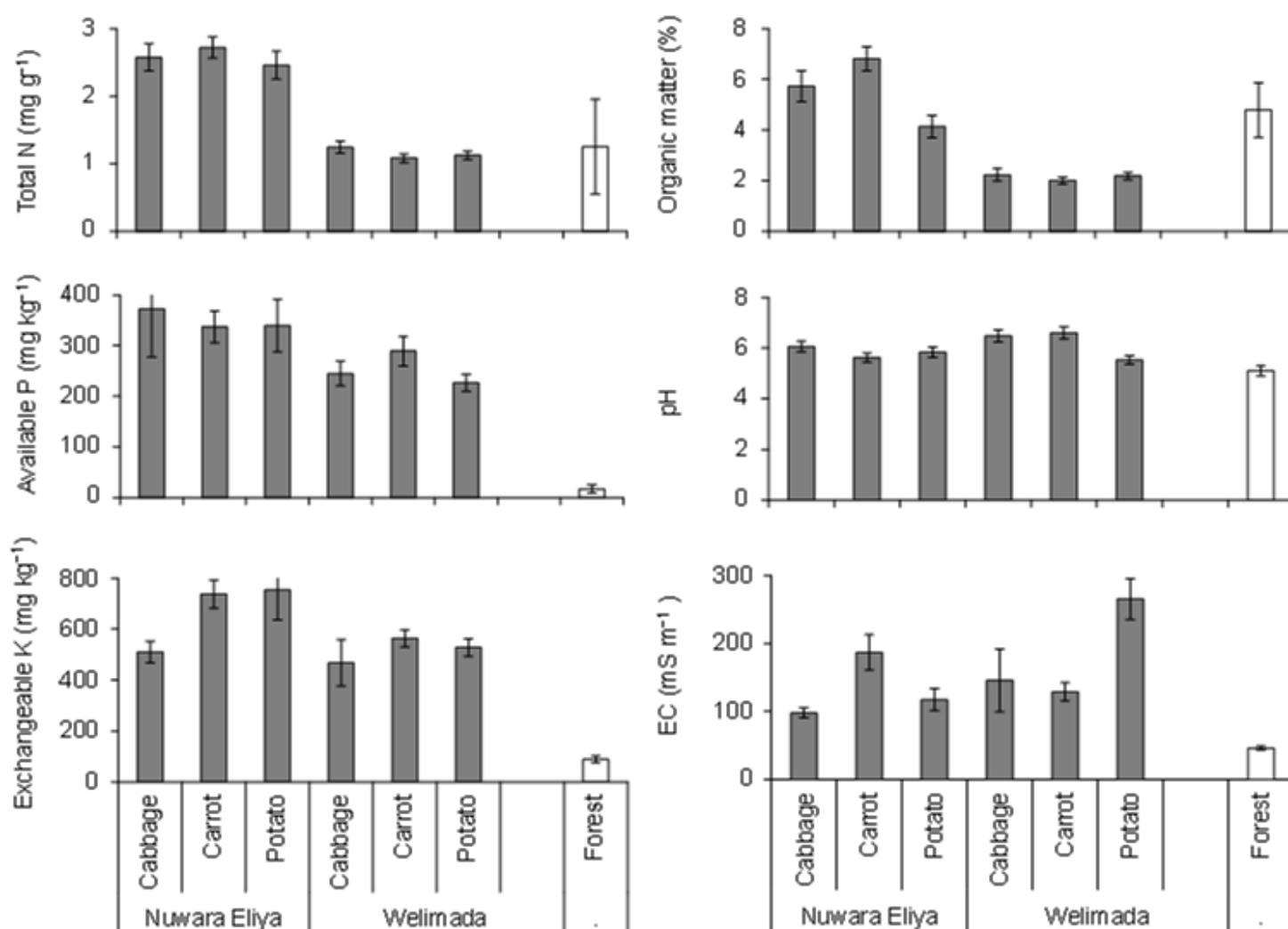


Figure 1

Concentrations of total nitrogen (N), available phosphorus (P), exchangeable potassium (K), organic matter, pH and electrical conductivity in the crop and forest fields in the two study regions (mean±SE,

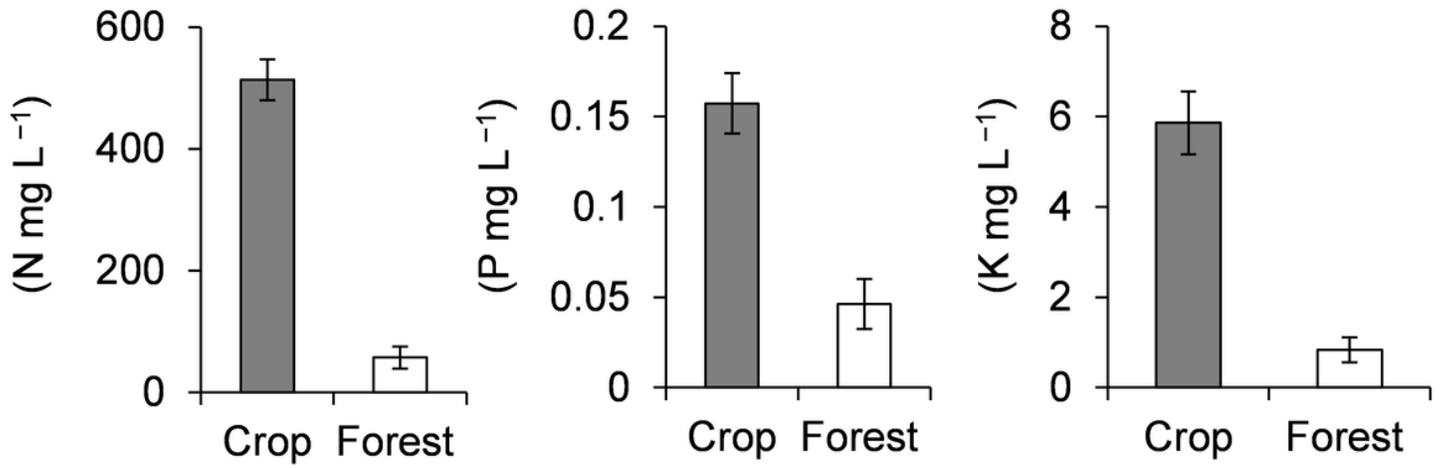


Figure 2

Concentrations of soil solution nitrogen (N), phosphorus (P) and potassium (K) in the crop and forest fields (mean±SE, sample size is as stated in Table 2).

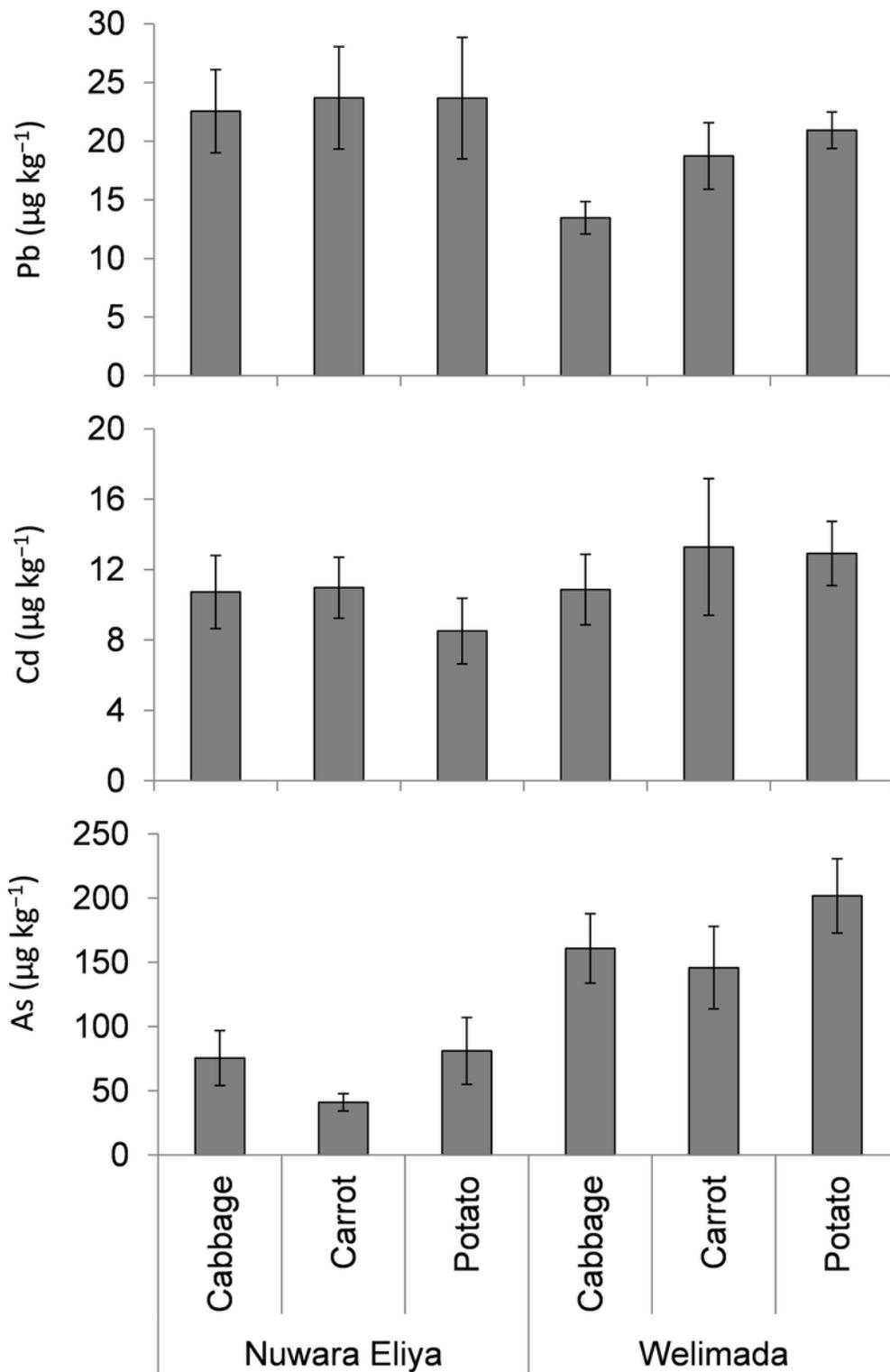


Figure 3

Concentrations of lead (Pb), cadmium (Cd) and arsenic (As) in the crop fields from two cultivating regions (mean \pm SE, sample size is as stated in Table 2).

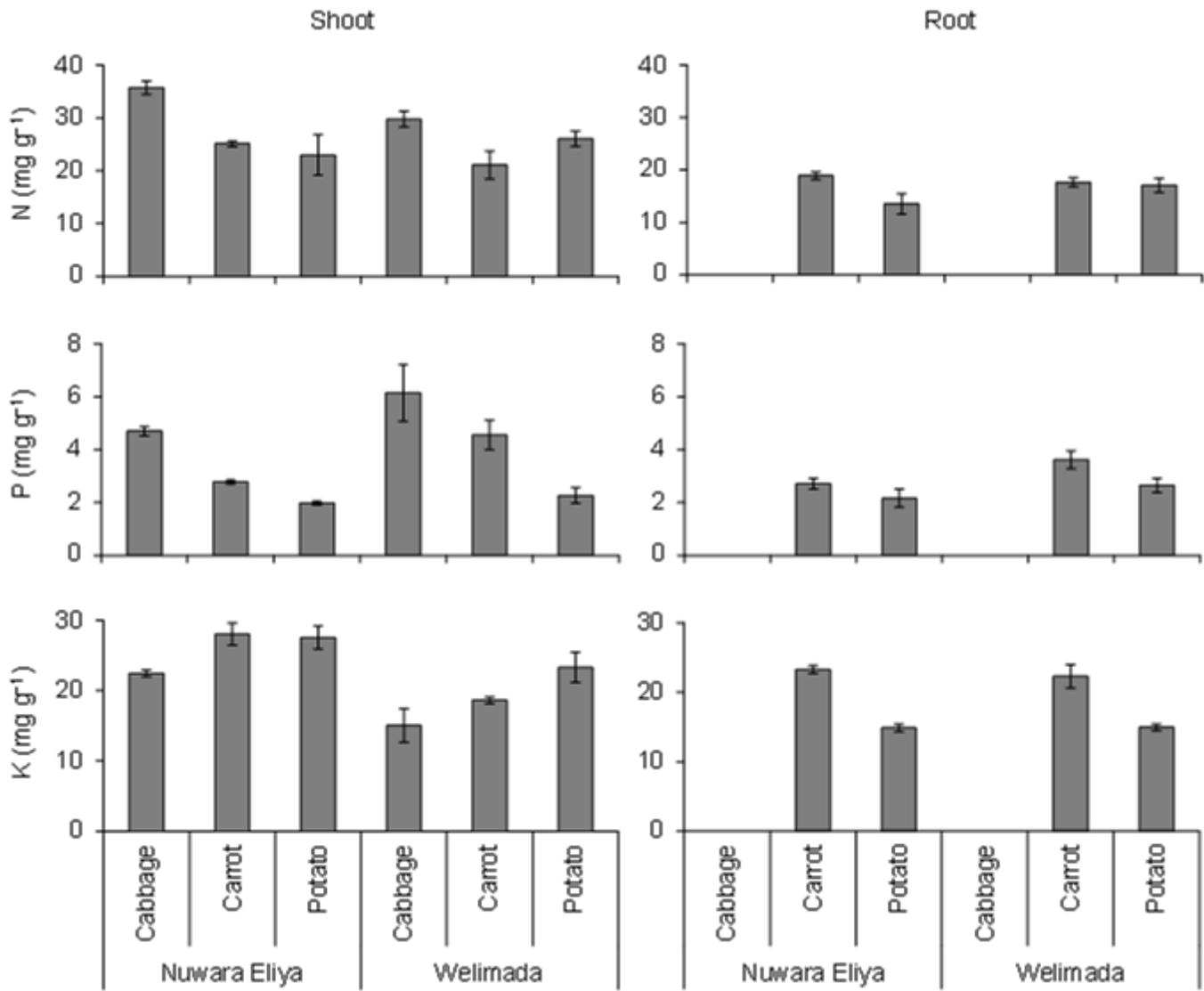


Figure 4

Tissue concentrations (on dry weight basis) of nitrogen (N), phosphorus (P) and potassium (K) grown in the two regions (mean±SE, sample size is as stated in Table 2)

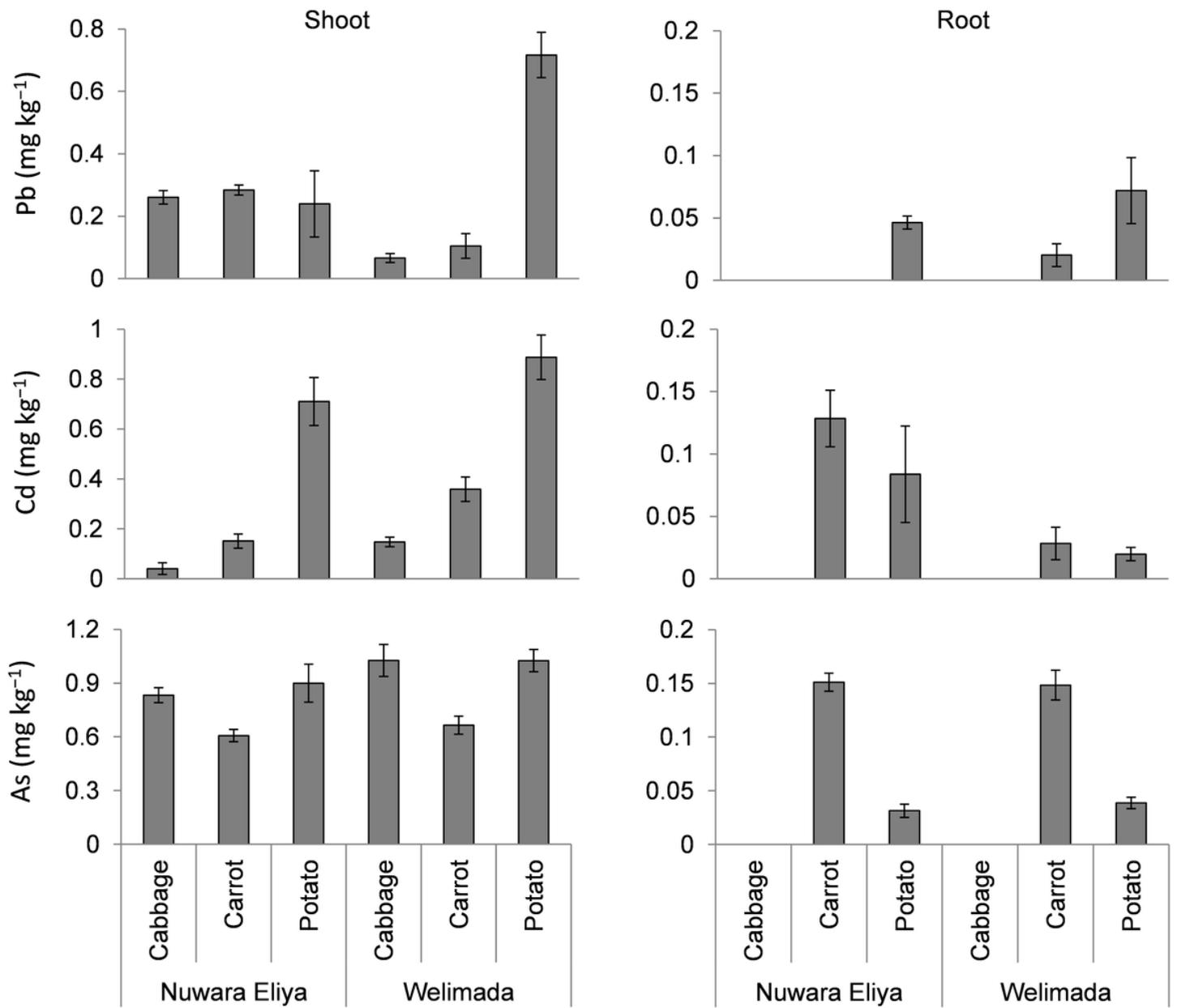


Figure 5

Tissue concentrations (on dry weight basis) of lead (Pb), cadmium (Cd) and arsenic (As) grown in two cultivating regions (mean±SE, sample size is as stated in Table 2). Note: the difference in Y-axis scale in the two panels.

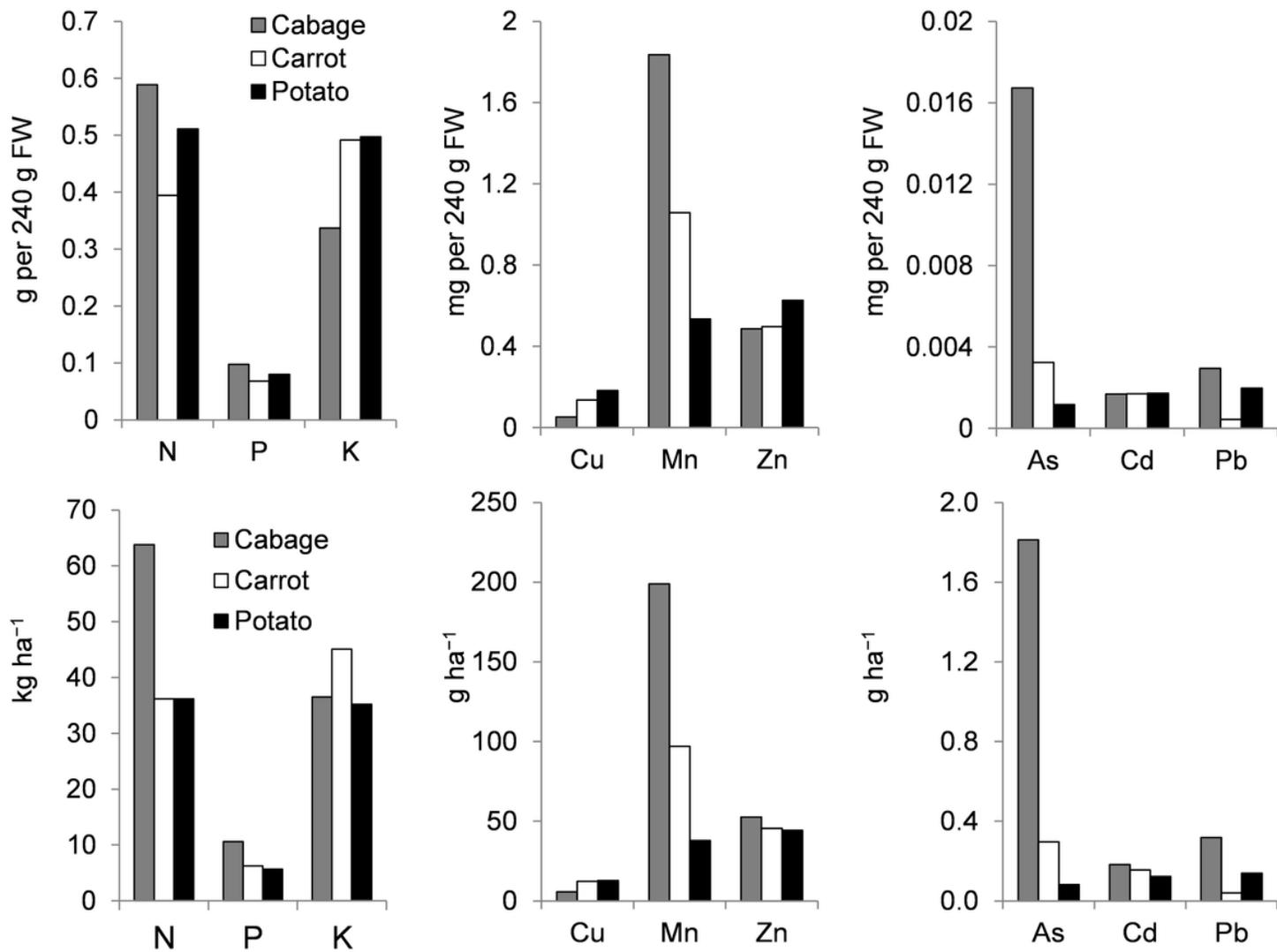


Figure 6

The mean amounts of essential mineral and toxic trace elements- present in 240 g (FW basis) of edible portion (upper panel), and removed with the harvest from one ha land (lower panel) of cabbage, carrot and potato.