

Elemental uptake and distribution of nutrients in avocado mesocarp and the impact of soil quality

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Abstract The distribution of 14 elements (both essential and non-essential) in the Hass and Fuerte cultivars of avocados grown at six different sites in KwaZulu-Natal, South Africa, was investigated. Soils from the different sites were concurrently analysed for elemental concentration (both total and exchangeable), pH, organic matter and cation exchange capacity. In both varieties of the fruit, concentrations of the elements Cd, Co, Cr, Pb and Se were extremely low with the other elements being in decreasing order of $Mg > Ca > Fe > Al > Zn > Mn > Cu > Ni > As$. Nutritionally, avocados were found to be a good dietary source of the micronutrients Cu and Mn. In soil, Pb concentrations indicated enrichment (positive geoaccumulation indices) but this did not influence uptake of the metal by the plant. Statistical analysis was done to evaluate the impact of soil quality parameters on the nutrient composition of the fruits. This analysis indicated the prevalence of complex metal interactions at the soil–plant interface that influenced their uptake by the plant. However, the plant invariably controlled metal uptake according to metabolic needs as evidenced by their accumulation and exclusion.

Keywords Avocado · Elemental distribution · Antagonism · Synergism · Bioavailability · Nutrient uptake

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Introduction

The avocado is a subtropical crop that has 12,000 ha of commercial orchards dedicated to their production in South Africa (Donkin 2011). The cooler climate of the KwaZulu-Natal Province of South Africa permits for the cultivation of such a crop. Peeled whole fruits are consumed primarily for their nutritional and medicinal value. The extracted oils from the fruits find use in the cosmetic industry. Avocado fruits meet the definition of functional foods as outlined by the American Dietetic Association (ADA) Position Statement in that they provide health benefits beyond basic nutrition (American Dietetic Association 1999). The fruits are known to be nutrient dense, cholesterol-free, high in fibre and low in sodium (Pieterse et al. 2003), and they contain high amounts of β -sitosterol, a known anti-cholesterolemic agent (Duester 2001). The medicinal benefits of consuming the avocado fruit arise from intake of the organic constituents. However, this does not preclude intake of the inorganic constituents whose concentrations are dependent on soil quality.

Unlike other contaminants in the environment, heavy metals are non-biodegradable (Kaewsam and Yu 2001). Soil can therefore function as a reservoir for heavy metals, if not regulated. Total soil concentrations of metals are not very useful predictors of availability (Chaudri et al. 2000; Knight et al. 1998); however, exchangeable concentrations better indicate concentrations that are available for uptake by biota. In this study, analysis of the avocado mesocarp and corresponding growth soil yielded information on uptake and distribution of the mineral nutrients in the plant.

Bioaccumulation factors (BFs) are important input variables in the assessment of human health risks in metal-polluted ecosystems (Lock and Janssen 2001; McGrath et al. 2004). BFs also indicate plant essentiality or non-essentiality of elements. This can be determined by obtaining a relative accumulation plot (graph of BF vs. total/exchangeable soil concentrations) and examining the resultant curve (Reddy et al. 2011).

Soil quality is the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation (Karlen et al. 1997). Assessing soil quality involves measuring soil physical, chemical and biological properties and using these measured values to detect changes in soil as a result of land use changes or management practices (Campos et al. 2007). Soil organic matter (SOM), cation exchange capacity (CEC) and pH are important soil properties that affect the capacity of the soil to supply nutrients to the plant (Davis et al. 1995). Soil enrichment or contamination by metals can be assessed by determining the geoaccumulation index (*I*_{geo}). The *I*_{geo} value has been used as a measure of bottom sediment contamination since the 1970s (Muller 1969) and numerous other studies have employed this method to assess for metal contamination in soils (Aikpokpodion et al. 2010; Ahiamadjie et al. 2011). Contamination is determined by comparing existing metal levels in soil with pre-industrial levels (Loska et al. 2003). In this study, geoaccumulation indices were calculated for selected elements in soils to assess for metal enrichment.

The objective of this study was to investigate the elemental composition of the avocado fruit (Hass and Fuerte varieties) and the impact of soil quality on elemental uptake. The 14 elements selectively investigated were Al, As, Ca, Cd, Co, Cu, Cr, Fe, Mg, Mn, Ni, Pb, Se and Zn.

Materials and methods

Sample sites, collection and preparation

The avocado fruits were collected from six different sites in KwaZulu-Natal (Fig. 1). The chosen sites were as follows: Kranskop (A), Seven Oaks (B), Howick (C), Thornville (D), Richmond (E) and Ixopo (F). Generally, phosphoric acid is injected into the stems of avocado

trees to prevent root rot. Leaves are sprayed with copper-based fungicides, B, Ca and Zn, and Ca in soil is enhanced by lime application. The landscape, from which samples were collected, ranged from flat to undulating. Soils were generally sandy or loamy sand in texture. The climate at the sites is humid and subtropical and crops were frequently irrigated. Avocado fruit samples of both Hass and Fuerte varieties with the accompanying growth soil were randomly obtained from each site. Mature fruits were selected based on size recommendations by farm managers. Fruit trees growing near other large trees (wind breakers) were not sampled to reduce the variance in results. All fruits sampled were ripened for 7 days then peeled, deseeded and dried at 45 °C to constant mass. Dried fruits were milled into a fine powder using a food processor (Braun range) and stored in the refrigerator at 4 °C until analysed. Soil samples were collected along the drip line of the tree from the plough depth of about 20 in. The soil fraction obtained after passing through a 2-mm mesh sieve was dried in an oven at 45 °C, overnight. Dry soil samples were crushed with a mortar and pestle, passed through a 75- μ m sieve, stored in plastic zip lock bags and kept at 4 °C until analysed.

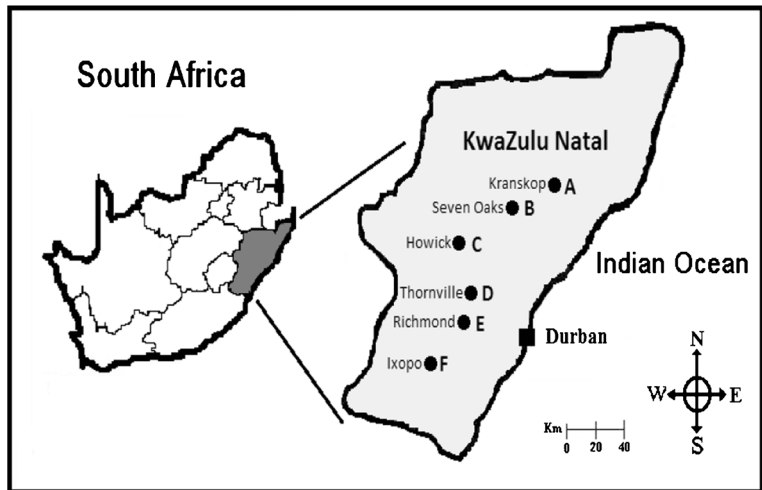
Instrumentation

Before elemental analysis, all plant and soil samples were digested using the CEM MARS Easyprep closed vessel microwave digestion system. Elemental analysis was by inductively coupled plasma–optical emission spectrometry (ICP-OES) using the PerkinElmer Inductively Coupled Plasma–Optical Emission Spectrometer (model Optima 5300 DV, PerkinElmer, Shelton, Conn.) and cold vapour atomic absorption spectroscopy (CVAAS) using the PerkinElmer Analyst 100 Cold Vapour Atomic Absorption Spectrometer Hydride Generator (PerkinElmer: Life and Analytical Science (PTY) Ltd).

Certified reference material analysis

Method validation was performed by analysis of certified reference material (CRM), *lyophilized brown bread* (BCR 191), from the Community Bureau of Reference of the Commission of the European Communities. CRM analysis was performed to confirm complete digestion, optimize instrument parameters and remove calibration errors.

Fig. 1 Map showing selected sampling sites in KwaZulu-Natal, South Africa. (a) Kranskop, (b) Seven Oaks, (c) Howick, (d) Thornville, (e) Richmond, (f) Ixopo



Total metal determination in soil, fruit and CRM

A mass of 0.5 g of dried sample (fruit and soil) was placed in separate perfluoroalkoxy (PFA) vessels. To each vessel, a volume of 10 mL of 70 % nitric acid was added, swirled gently and left to stand for 5 min before sealing. The samples were then subjected to microwave digestion. For digestion, the power was ramped to 1,200 W for 15 min, and then held at 1,200 W for a further 15 min. Digests were filtered by gravity into 50 mL volumetric flasks, brought up to the mark with double-distilled water, transferred into plastic bottles and stored at 4 °C until analysed. The following elements were determined by ICP-OES: Al, Ca, Cd, Co, Cu, Cr, Fe, Mg, Mn, Ni, Pb and Zn. Arsenic and Se were analysed by CVAAS-HG using standard methods. All elemental standards (1,000 ppm) were purchased from Merck. All working standards were prepared in double-distilled water and 70 % HNO₃ to match the sample matrix. Emission lines were chosen based on maximum analytical performance and minimum spectral interferences; lines outside the linear working range were omitted. All determinations were done in triplicate.

Determination of bioavailability

Exchangeable metals in soils were extracted using a solution containing ammonium acetate (1.0 M), ethylenediaminetetraacetic acid (EDTA, 0.05 M) and acetic acid (0.43 M) (Moodley et al. 2007). Approximately 1.0 g of dry soil samples was accurately weighed into plastic bottles and 10 mL of extractant solution added to each bottle. Bottles were shaken for 1 h on an orbital

shaker at 30 m s⁻². The resultant mixtures were filtered through 0.45 µm filters by gravity into 50 mL volumetric flasks and brought up to the mark with double-distilled water. This was transferred immediately into plastic bottles and stored at 4 °C until analysed.

Bioaccumulation factors

The magnitude of the bioavailable or exchangeable fraction relative to total soil concentration for each element is given by the ratio ([Soil]Ex / [Soil]T) × 100. BF_s were obtained by computing the ratio of metal content in plant to total/exchangeable metal content in soil which indicates metal accumulation if >1 and exclusion if <1 (Anton and Mathe-Gaspar 2005). BF_s also indicate essentiality or non-essentiality of elements to the plant. This can be determined by obtaining a relative accumulation plot (graph of BF vs. total/exchangeable soil concentrations) and examining the resultant curve. Essentiality is indicated by a rectangular hyperbola whereas non-essentiality is indicated by a linear plot parallel to the x-axis (Timperly et al. 1970).

Soil quality assessment

Soil pH, soil organic matter and cation exchange capacity

Soil pH was determined using a 2:1 soil–water suspension and pH meter calibrated using standard buffer solutions at pH 4 and pH 7. SOM was estimated using the wet chemistry extraction technique of Walkley and Black (1934). Ammonium acetate at pH 7 was used to

determine the CEC of soil (Chapman 1965). Determination of the concentration of $\text{NH}_4\text{-N}$ in the KCl extract was done by distillation using the Kjeldahl method (Skoog et al. 1992). All determinations were done in triplicate.

Geoaccumulation index (I_{geo})

A common approach to estimating enrichment (contamination) of metal concentrations above background/baseline concentrations in soil is to calculate the geoaccumulation index (I_{geo}) as proposed by Muller (1969). The method assesses the degree of metal pollution in seven grades (Table 1) ranging from uncontaminated to extremely contaminated.

The geoaccumulation index is calculated as follows:

$$I_{\text{geo}} = \log_2\{C_n / 1.5B_n\} \quad (1)$$

Where

- C_n Total concentration of element in soil sample
 B_n Background/baseline concentration of the same element

The factor 1.5 is to minimise variations in the background value due to lithologic (rock composition) variations (Stoffers et al. 1986).

Statistical analysis

The significance of plant–soil relationships was established by computing correlation coefficients (r) for the relationships between the concentrations of the elements in the avocado fruit and the total and exchangeable concentrations in the soil. Pearson's correlation coefficients were obtained using the Statistical

Table 1 Classes with respect to soil quality (Stoffers et al. 1986)

I_{geo} value	Designation of soil quality
0	Uncontaminated
0–1	Uncontaminated to moderately contaminated
1–2	Moderately contaminated
2–3	Moderately to strongly contaminated
3–4	Strongly contaminated
4–5	Strongly to extremely contaminated
>5	Extremely contaminated

Package for the Social Sciences (SPSS) (PASW Statistics, Version 18, IBM Corporation, Cornell, New York). Data generated from analysis were also subjected to one-way ANOVA and Duncan's multiple range tests using the SAS program (Version 6.12, SAS Institute Inc., Cary, NC, USA).

Results and discussion

CRM Analysis

The accuracy of the method for elemental analysis was measured by comparing results obtained with certified results (Table 2). Measured values obtained for the six metals analysed compared well with certified values thereby validating the analytical method and wavelength selection.

Elemental analysis in soils and fruit

The analysis showed all 14 metals to be present in the soil (total and exchangeable), but five metals in the fruit namely Cd, Co, Cr, Pb and Se were found to be below the instrument's detection limits ($<0.0034 \mu\text{g g}^{-1}$ for Cd, $<0.007 \mu\text{g g}^{-1}$ for Co, $<0.0071 \mu\text{g g}^{-1}$ for Cr, $<0.09 \mu\text{g g}^{-1}$ for Pb and $0.1150 \mu\text{g g}^{-1}$ for Se). Total and exchangeable soil concentrations and concentrations in the fruits (Hass and Fuerte varieties) for the 14 elements investigated, at each site, are presented in Table 3. All soils are rich in Al with total concentrations ranging from 49,000 to 80,000 $\mu\text{g g}^{-1}$, followed by Fe (23,000 to 45,000 $\mu\text{g g}^{-1}$), Ca (1,500 to 3,000 $\mu\text{g g}^{-1}$)

Table 2 Comparison of measured and certified values (mean \pm SD; at 95 % confidence interval), based on dry mass, in the certified reference material (*lyophilized brown bread*-BCR 191)

Element	Wavelength	Certified	Measured (MD)
Ca	315.887	0.41 \pm 0.01 mg g ⁻¹	0.40 \pm 0.05 mg g ⁻¹
Cu	324.752	2.6 \pm 0.1 $\mu\text{g g}^{-1}$	2.57 \pm 0.1 $\mu\text{g g}^{-1}$
Fe	259.939	40.7 \pm 2.3 $\mu\text{g g}^{-1}$	39.1 \pm 2.2 $\mu\text{g g}^{-1}$
Mg	280.271	10.0 \pm 0.01 mg g ⁻¹	9.74 \pm 0.40 mg g ⁻¹
Mn	228.616	20.3 \pm 0.7 $\mu\text{g g}^{-1}$	19.64 \pm 0.4 $\mu\text{g g}^{-1}$
Zn	283.563	19.5 \pm 0.5 $\mu\text{g g}^{-1}$	19.42 \pm 0.7 $\mu\text{g g}^{-1}$

Mean replication of experiments ($n=6$), each sample was analysed in triplicate

Table 3 Concentrations of the elements in microgram per gram dry mass [mean ± SD, *n*=3] in soil (total and exchangeable) and avocado mesocarp (Hass and Fuerte varieties)

Element	Site	Soil-total	Igeo	Soil-exchangeable	[Soil]Ex / [Soil]T (%)	Hass total	BF-Hass	Fuerte total	BF-Fuerte
Al	A	49,185±1,360 e	ND	3,295±777 a	6.7	32.5±4.9 a	0.010	37.8±7.4 a	0.011
	B	68,834±6,043 c	ND	2,661±996 bc	3.87	18.5±8.9 c	0.007	25.1±6.1 b	0.009
	C	64,921±3,205 c	ND	3,260±291 a	5.02	18.0±2.5 c	0.006	17.2±4.0 c	0.005
	D	72,366±5,883 b	ND	2,481±596 c	3.43	22.3±4.5 b	0.009	15.3±0.6 c	0.006
	E	79,086±3,037 a	ND	3,143±720 ab	3.13	17.7±6.1 c	0.006	18.3±1.3 c	0.006
	F	56,692±4,498 d	ND	1,399±582 d	2.47	29.1±1.9 a	0.021	36.7±1.5 a	0.026
As	A	8.90±0.92 c	ND	0.89±0.12 b	10.46	2.99±0.07 c	3.34	1.29±0.95 d	1.44
	B	14.5±1.6 b	ND	0.15±0.03 d	1.02	2.80±0.45 c	19.01	3.15±0.72 bc	21.37
	C	14.1±4.6 b	ND	4.22±0.25 a	3.89	4.73±0.62 a	1.12	3.69±0.69 b	0.87
	D	18.1±3.81 a	ND	0.91±0.10 b	4.12	3.97±0.40 b	4.35	2.73±0.27 c	2.99
	E	17.3±2.7 ab	ND	0.67±0.06 c	8.4	4.47±0.54 a	6.66	4.55±0.02 a	6.79
	F	14.8±2.1 b	ND	0.43±0.10 d	2.13	3.75±0.61 b	8.66	3.32±0.75 bc	7.68
Ca	A	1,540±18 e	ND	1,412±286 d	91.67	328.5±16.5 d	0.233	309.5±81.6 c	0.219
	B	1,920±44 c	ND	959±216 e	49.94	534.6±45.1 a	0.557	343.5±36.4 b	0.358
	C	2,104±102 b	ND	1,864±208 b	88.59	466.7±9.65 b	0.250	484.4±21.4 a	0.260
	D	1,196±303 f	ND	1,080±70 e	90.29	451.2±35.6 b	0.418	325.0±10.7 cb	0.301
	E	2,970±103 a	ND	2,445±71 a	82.34	355.3±19.0 c	0.145	312.7±31.3 cb	0.128
	F	1,791±71 d	ND	1,608±95 c	89.78	314.1±24.2 d	0.195	344.0±40.3 b	0.214
Cd	A	2.48±0.36 a	-0.7	1.00±0.08 c	40.38	ND	0	ND	0
	B	1.81±0.10 d	-1.2	0.50±0.02 e	27.7	ND	0	ND	0
	C	2.29±0.11 b	-0.8	1.14±0.11 a	49.97	ND	0	ND	0
	D	1.84±0.01 d	-1.1	0.75±0.12 d	40.95	ND	0	ND	0
	E	1.99±0.04 c	-1.0	1.01±0.08 b	50.58	ND	0	ND	0
	F	2.45±0.05 a	-0.7	0.72±0.16 d	29.37	ND	0	ND	0
Co	A	3.26±0.27 e	-5.0	0.31±0.04 d	9.66	ND	0	ND	0
	B	27.2±1.1 b	-1.9	3.01±0.29 c	11.71	ND	0	ND	0
	C	13.8±1.1 d	-3.0	3.16±0.29 c	15.64	ND	0	ND	0
	D	31.9±1.9 a	-1.7	3.39±0.29 b	10.32	ND	0	ND	0
	E	20.9±0.4 c	-2.3	3.56±0.48 b	13.88	ND	0	ND	0
	F	20.7±1.5 c	-2.3	3.96±0.31 a	18.31	ND	0	ND	0
Cr	A	93.3±2.6 d	-2.5	10.9±1.5 a	11.35	ND	0	ND	0
	B	166.6±7.1 a	-1.7	8.93±0.13 b	5.36	ND	0	ND	0
	C	150.5±10.2 b	-1.8	10.9±1.1 a	7.66	ND	0	ND	0
	D	170.2±3.4 a	-1.6	7.09±0.15 c	4.56	ND	0	ND	0
	E	145.8±5.7 b	-1.9	10.6±1.0 a	5.69	ND	0	ND	0
	F	118.6±7.8 c	-2.2	5.37±1.65 d	4.95	ND	0	ND	0
Cu	A	72.8±4.4 a	-1.3	26.8±0.8 d	36.86	4.91±0.59 c	0.183	5.24±0.33 e	0.183
	B	78.7±1.7 b	-1.2	29.6±1.9 c	37.66	4.61±0.80 c	0.156	9.58±0.26 a	0.156
	C	47.9±1.4 d	-0.6	13.7±1.0 f	28.64	5.07±1.26 c	0.369	5.61±0.76 d	0.369
	D	76.5±6.4 b	-1.2	40.5±1.0 b	52.94	7.10±0.97 b	0.175	7.47±0.10 b	0.175
	E	112.9±1.5 a	-0.6	83.1±0.8 e	73.57	6.54±1.67 b	0.079	5.71±0.04 d	0.079
	F	48.5±0.9 d	-0.9	23.7±0.7 a	48.93	7.37±1.00 a	0.311	6.75±0.21 c	0.311
Fe	A	23,453±3,116 a	ND	2,435±89 a	10.38	8.78±0.53 c	0.004	12.91±1.14 b	0.005
	B	43,397±1,157 a	ND	2,596±200 a	5.98	8.62±1.07 c	0.003	12.36±1.52 b	0.005

Table 3 (continued)

Element	Site	Soil-total	Igeo	Soil-exchangeable	[Soil]Ex / [Soil]T (%)	Hass total	BF-Hass	Fuerte total	BF-Fuerte
Mg	C	36,760±1,866 cb	ND	2,362±159 a	6.43	6.85±1.87 d	0.003	5.10±0.71 c	0.002
	D	41,485±6,026 a	ND	1,690±190 c	4.07	26.01±3.46 b	0.015	12.44±1.25 b	0.007
	E	38,120±1,657 b	ND	2,462±104 a	6.46	9.80±0.32 c	0.004	4.48±0.75 c	0.002
	F	35,545±2,373 c	ND	1,293±121 d	3.64	54.86±2.87 a	0.042	26.86±1.04 a	0.021
	A	1,069±83 e	ND	273±14 e	25.53	954±10 d	3.49	645±17 d	2.36
	B	1,680±109 d	ND	325±29 d	19.34	1,021±62 c	3.14	1,038±81a	3.20
Mn	C	1,908±194 c	ND	604±58 a	31.65	1,102±60 c	1.83	1,093±105 a	1.81
	D	2,034±315 b	ND	494±43 c	24.28	1,334±37 a	2.70	926±99cb	1.87
	E	2,886±66a	ND	540±47 b	18.72	1,223±56 b	2.26	879±43 c	1.63
	F	1,671±23 d	ND	483±29 a	28.89	1,063±87 c	0.65	959±64 b	1.99
	A	123.8±6.1 d	ND	67.9±2.1 e	54.93	14.5±2.4 b	0.21	3.51±0.81 e	0.05
	B	272.3±3.2 a	ND	78.6±4.6 d	28.87	12.2±3.6 a	0.16	6.14±0.13 c	0.08
Ni	C	226.1±7.0 b	ND	125.7±8.5 b	55.58	13.4±0.6 bc	0.11	12.24±0.84 a	0.10
	D	287.8±7.7 a	ND	106.1±4.6 c	36.88	17.2±1.0 a	0.16	7.65±1.35 b	0.07
	E	285.0±8.2 a	ND	182.0±11.8 a	63.88	4.59±0.37 e	0.03	4.93±0.66 d	0.03
	F	206.7±16.2 c	ND	106.2±8.8 c	51.38	7.51±1.53 d	0.07	5.65±0.97 c	0.05
	A	9.30±0.27 f	-4.7	0.63±0.03 c	6.73	4.36±0.36 bc	6.98	1.41±0.72 d	2.26
	B	49.36±0.60 a	-2.3	1.54±1.16 a	3.12	1.94±0.07 d	1.26	5.73±0.35 b	3.72
Pb	C	37.47±0.35 d	-2.7	1.53±0.08 a	4.07	4.99±1.19 b	3.27	7.80±1.26 a	5.11
	D	42.95±1.49 b	-2.5	0.46±0.01 c	1.07	19.40±2.81 a	42.07	2.36±0.17 c	5.12
	E	41.22±2.77 c	-2.5	0.79±0.76 bc	1.90	ND	0.00	ND	0.00
	F	30.15±1.30 e	-3.0	1.14±0.55 ab	3.78	3.61±0.65 c	3.17	2.03±0.83 c	1.78
	A	121.8±10.0 e	0.3	19.19±1.93 b	15.76	ND	0	ND	0
	B	179.9±9.9 b	0.9	13.94±0.76 d	7.75	ND	0	ND	0
Se	C	167.6±12.6 c	0.8	16.36±0.85 c	9.76	ND	0	ND	0
	D	195.8±8.7 a	1.0	24.30±0.51 a	12.41	ND	0	ND	0
	E	198.9±8.1 a	1.0	16.62±0.74 c	8.36	ND	0	ND	0
	F	152.6±10.4 d	0.6	16.46±0.75 c	10.78	ND	0	ND	0
	A	1.82±0.13 d	ND	0.98±0.34 b	53.85	ND	0	ND	0
	B	0.99±0.05 e	ND	0.42±0.05 d	42.19	ND	0	ND	0
Zn	C	3.19±0.13 b	ND	1.19±0.59 ab	37.31	ND	0	ND	0
	D	0.92±0.02 e	ND	0.22±0.03 d	23.35	ND	0	ND	0
	E	3.45±0.73 a	ND	0.69±0.17 c	19.95	ND	0	ND	0
	F	2.10±0.25 c	ND	1.32±0.24 a	62.49	ND	0	ND	0
	A	47.67±1.53 c	-1.9	15.89±1.03 c	33.33	10.28±3.72 c	0.65	16.59±1.30 c	1.04
	B	106.0±3.6 a	-0.7	7.94±0.41 d	7.49	9.69±2.69 c	1.22	27.93±5.01 a	3.52
	C	57.51±1.62 b	-1.6	47.34±2.79 a	82.33	17.66±1.56 b	0.37	20.42±1.05 b	0.43
	D	9.85±1.63 e	-4.1	7.20±1.28 d	73.06	29.25±3.45 a	4.06	13.11±0.92 c	1.82
	E	38.31±0.41 d	-2.2	28.73±1.73 b	75.01	24.06±5.82 a	0.84	19.30±0.26 b	0.67
	F	37.26±5.22 d	-2.2	15.98±1.61 c	42.87	26.94±5.76 a	1.69	8.18±0.97 d	0.51

Mean values in each column followed by different letters are significantly different by Duncan's multiple range test ($P \leq 0.05$). Bioaccumulation factor, BF = [Fruit] / [SoilEx].

ND not detected

aSite: A = Kranskop, B = Seven Oaks, C = Howick, D = Thornville, E = Richmond, F = Ixopo

and Mg (1,000 to 2,900 $\mu\text{g g}^{-1}$). Arsenic was detected in soils at all sites at relatively low concentrations (8 to 18 $\mu\text{g g}^{-1}$). The exchangeable percent ($[\text{Soil}]_{\text{Ex}} / [\text{Soil}]_{\text{T}}$ %) was highest for Ca, with 50–92 % of total soil Ca being exchangeable (Table 3). However, the exchangeable percent did not influence uptake by the plant as BF values were <1 in all cases. Site A had lower total soil concentrations and higher exchangeable concentrations than the other sites for 9 of the 14 metals investigated. The exceptions were Co, Cd, Cu, Se and Zn.

Total soil Cu ranged from 45 to 113 $\mu\text{g g}^{-1}$, with 46.4 % being available for plant uptake, on average (Table 3). For both varieties of avocado, 4 to 10 $\mu\text{g g}^{-1}$ of Cu was taken up. Total soil Fe was high but only 3–10 % of this Fe was available to the plant. Soil Fe is not very mobile as it is fixed within the soil matrix or exists as oxide or hydroxide forms that are sparingly soluble (Schulin et al. 2010). Fe levels in the fruit of both varieties ranged from 4 to 12 $\mu\text{g g}^{-1}$ at all sites except site F, where Fe concentrations in the Hass and Fuerte varieties were 54.86 and 26.86 $\mu\text{g g}^{-1}$, respectively.

Total soil Mg was high and about 18–32 % was exchangeable (Table 3). In both varieties of fruit, Mg concentrations were significantly higher than exchangeable concentrations ($\text{BF} > 1$) indicating that the plant tends to accumulate this nutrient. Plant Mg is dependent on total soil Mg and uptake is controlled by differential absorption to meet physiological needs (Mayland and Wilkinson 1989). The concentrations of elements in both varieties of fruits were generally in decreasing order of $\text{Mg} > \text{Ca} > \text{Al} > \text{Zn} > \text{Fe} = \text{Mn} > \text{Cu} > \text{Ni} = \text{As}$.

BF plots

The relative accumulation plots (BF vs. total or exchangeable soil concentrations) for Hass and Fuerte varieties revealed essentiality for the following metals: Ca, Cu, Fe, Mn, Ni, and Zn. Plots generated using exchangeable soil concentrations better represented plant physiological requirement levels than plots obtained using total soil concentrations. This confirms that exchangeable soil concentrations are better indicators of plant concentrations. The toxic element, As, was shown to function as an essential element (Fig. 2). Arsenic uptake is probably linked to P uptake which is an essential element. Therefore, in the case of As, the produced plot of BF vs. soil concentrations (total and

exchangeable) may indicate the biological similarity in uptake to an essential element (Dixon 1997).

Soil quality assessment

SOM, CEC and pH

The measured soil properties, SOM, CEC and pH for the various sites are represented in Table 4. Soil pH was relatively constant (5.39 to 6.06). Soil management practices ensuring slightly acidic soils promote optimal growth of crops (Wager 1940). The SOM of the soils ranged from 4 to 9 % with site B having the lowest value and site C having the highest. The measured CEC values of soils ranged from 8 to 20 meq/100 g. There seems to be no obvious relationship between the three soil properties. Results from the correlation analysis will therefore confirm any meaningful relationships.

Geoaccumulation index

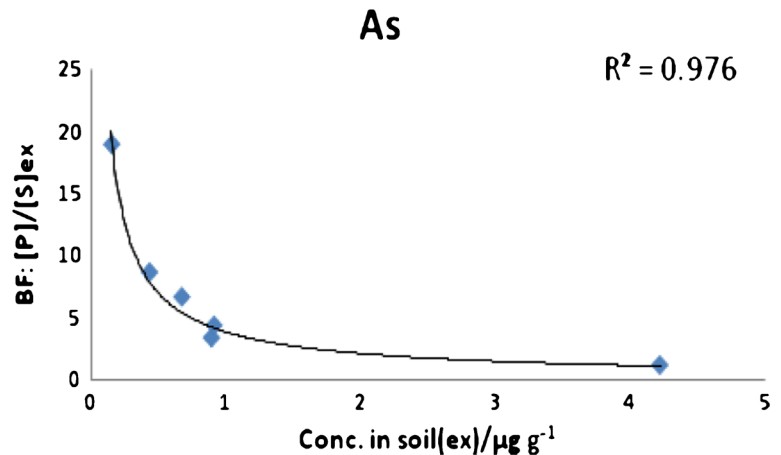
The background concentration conveys an idea of the natural range in concentration that can be expected prior to contamination and it can be used to assess for pollution. Herselman et al. (2005) derived background/baseline metal concentrations in South African soils from 4,500 top soils; soil samples were analysed for their total metal concentration using aqua regia (EPA 3050). Background concentrations are 2.7 $\mu\text{g g}^{-1}$ for Cd, 69 $\mu\text{g g}^{-1}$ for Co, 353 $\mu\text{g g}^{-1}$ for Cr, 117 $\mu\text{g g}^{-1}$ for Cu, 159 $\mu\text{g g}^{-1}$ for Ni, 65.8 $\mu\text{g g}^{-1}$ for Pb and 115 $\mu\text{g g}^{-1}$ for Zn.

The status of heavy metal enrichment/pollution at the various sampling sites was determined by examining the geoaccumulation index (I_{geo}) (Table 3). Negative I_{geo} values, as for Cd, Co, Cr, Cu, Ni and Zn, indicate non-contamination. Positive I_{geo} values, as for Pb, indicate enrichment of soil by the metal. However, the degree of enrichment at all sites is moderate since I_{geo} values for Pb are less than or equal to unity.

Statistical analysis

A composite correlation matrix for the concentrations of the elements in the fruit (Hass and Fuerte varieties) with soil concentrations (total and exchangeable) are presented in Table 5. The correlation matrix shows the positive and negative correlations that exist between the cations in the soil and fruits. Relationships with correlation

Fig. 2 Relative accumulation plot for arsenic showing essentiality in avocado fruit (Hass variety)



coefficients >0.8 are strongly synergistic, between 0.7 and 0.8 are positive, <-0.8 are strongly antagonistic and between -0.7 and -0.8 are antagonistic.

A perusal of Table 5 shows various significant positive and negative correlations between soil properties SOM, CEC and pH with elemental concentrations in plant. A strongly positive correlation ($r=0.8$) is observed in soil between pH and exchangeable Ca. However, a strong negative correlation ($r=-0.8$) is observed between soil pH and Ca concentration in fruit (Hass). As soil pH increases, exchangeable Ca increases but uptake by the plant is reduced. This effect is not observed in Fuerte varieties. SOM is shown to have a strongly positive correlation with exchangeable Ni concentrations. CEC correlates positively with Ca, Mg, Mn and Ni concentrations in the fruit. There are no observed inter-correlations amongst the three soil properties measured except between pH and CEC which shows an unexpected negative correlation ($r=-0.7$).

The phenomenon of synergism between elements occurs when two elements compete for the same soil

adsorption site (Prasad et al. 2006). A synergistic relationship is observed when an increase in total soil concentration of one element increases availability of another. (Kalavrouziotis et al. 2008). Synergistic relationships in soil are represented in Fig. 3. Arrows represent a synergy between total and exchangeable (in boxes) soil concentrations of the two elements with their respective r values indicating the degree of synergy. Figure 3 shows exchangeable Mn to have strong synergistic relationship with total Mg ($r=1.0$), Al, As and Ca while exchangeable Cu is synergistic with total Mg, Al and Ca. A synergy between Ni and Zn ($r=0.8$) was observed. The correlation analysis also revealed exchangeable Ca and Cu to be significantly correlated to their total soil concentrations.

Antagonism amongst elements occurs when the plant takes up two different elements by the same mechanism (Kalavrouziotis et al. 2008). A negative relationship exists when an increase in exchangeable soil concentration of one element reduces uptake of the other. Research with coffee has shown antagonism to be cultivar dependant. Since the mechanisms of uptake may be different between dissimilar varieties of fruits, antagonistic relationships observed for Hass and Fuerte varieties, represented in Fig. 4, were compared. Figure 4 shows statistical evidence of a strongly antagonistic correlation for Al with Fe and Cu in the Hass variety indicating high exchangeable soil Al reduces Fe and Cu uptake. Antagonistic relationships exist for Fe with Cu and Zn, Ca with Mn, and Mg with itself in the Hass variety. The only common antagonistic relationship between Hass and Fuerte varieties was observed for Al and Mg. Exchangeable soil Ca and As both negatively influence the uptake of Cu into the Fuerte variety and the

Table 4 pH, soil organic matter (SOM), and cation exchange capacity (CEC) of soil samples from each site ($n=3$)

Site	Soil pH	SOM (%)	CEC(meq/100 g)
A	6.05±0.04	5.70±0.01	13.53±0.12
B	5.39±0.03	4.64±0.07	17.31±2.02
C	5.97±0.03	8.28±0.01	19.59±1.03
D	5.97±0.02	6.20±0.08	21.82±1.78
E	5.45±0.02	6.70±0.26	9.33±0.54
F	5.99±0.02	5.18±0.01	8.02±0.36

Table 5 Correlation matrix for concentrations of elements in Soil [Total (T) and Exchangeable (E)] and mesocarp of Hass (H) and Fuerte (F)

	AIT	AIE	AIH	AIF	AST	ASE	ASH	ASF	CatT	CaET	CaHT	CaFT	CuT	CuE	CuH	CuF	FeT	FeE	FeH	FeF	MgT	MgE	MgH	MgF	MnT	MnE	MnH	MnF	NiT	NiE	NiH	NiF	ZnT	ZnE	ZnH	ZnF	pH	SOM
AIE	-0.1																																					
AIH	0.9	-0.1																																				
AIF	0.9	-0.3	0.9																																			
AST	0.9	-0.5	0.7	0.7																																		
ASE	0.3	0.2	-0.1	0.3	0.1																																	
AH	0.5	0.0	-0.6	0.7	0.5	0.2																																
AH	0.8	-0.2	0.8	0.7	0.7	0.2	0.8																															
CatT	0.3	0.0	-0.4	-0.3	0.2	0.5	0.5	0.8																														
CaE	0.1	0.0	-0.1	-0.2	0.1	0.6	0.7	0.6	0.7																													
CaH	0.4	0.3	0.7	-0.6	0.3	-0.5	0.1	0.2	-0.1	-0.5																												
CaF	0.0	0.3	-0.4	-0.4	0.0	-0.3	0.7	0.3	0.1	0.3	0.4																											
CuT	0.6	0.1	-0.4	-0.3	0.3	0.6	-0.2	0.3	0.5	0.0	0.1	-0.6																										
CuE	0.8	0.0	-0.5	-0.6	0.6	0.8	0.3	0.6	0.7	0.5	-0.1	-0.3	0.8																									
CuH	0.2	-0.8	0.1	0.0	0.6	0.2	0.2	0.2	-0.1	0.2	-0.5	-0.3	-0.1	0.3																								
CuF	0.1	-0.3	-0.2	-0.1	0.3	-0.8	-0.3	-0.1	-0.5	0.8	0.7	0.0	-0.1	-0.4	0.0																							
FeT	0.8	-0.3	0.8	-0.7	0.8	-0.3	0.4	0.7	0.2	-0.3	0.7	0.1	0.2	0.3	0.2	0.7																						
FeE	0.0	0.9	-0.3	-0.3	-0.4	0.2	0.1	0.0	0.2	0.1	0.4	0.5	0.1	0.0	0.9	-0.3	-0.2																					
FeH	-0.2	-0.9	0.4	0.4	0.2	-0.3	0.0	-0.1	-0.3	0.0	-0.5	-0.2	-0.4	-0.3	0.8	0.2	0.1	-0.9																				
FeF	-0.5	-0.7	0.7	0.7	-0.1	-0.5	-0.4	-0.4	-0.5	-0.3	-0.4	-0.3	-0.5	-0.5	0.5	0.4	-0.1	-0.8	0.9																			
MgT	0.9	-0.3	0.7	0.7	0.8	0.5	0.6	0.9	0.7	0.5	0.0	0.0	0.5	0.9	0.4	-0.2	0.6	-0.2	0.0	-0.4																		
MgE	-0.2	-0.9	0.3	0.4	0.2	-0.3	0.2	0.1	0.0	0.2	-0.5	0.0	-0.5	-0.2	0.7	0.0	0.0	-0.8	0.9	0.8	0.1																	
MgH	0.6	0.6	-0.6	-0.8	0.3	0.5	0.2	0.2	0.1	-0.1	0.5	0.0	0.5	-0.3	-0.1	0.3	0.6	-0.7	-0.9	0.4	-0.8																	
MgF	0.6	0.6	-0.8	-0.8	0.3	0.0	0.3	0.4	0.2	-0.1	0.8	0.4	0.3	0.2	-0.6	0.2	0.5	0.7	-0.8	-0.8	0.3	-0.8	0.8															
MnT	0.9	-0.3	0.9	-0.8	0.9	0.0	0.4	0.7	0.3	-0.1	0.5	0.0	0.5	0.6	0.3	0.4	0.9	-0.2	0.0	-0.3	0.8	-0.1	0.5	0.5														
MnE	0.8	-0.3	-0.6	-0.6	0.8	0.6	0.7	0.9	0.7	0.7	-0.2	0.1	0.4	0.8	0.5	-0.4	0.4	-0.2	0.0	-0.4	1.0	0.2	0.3	0.2	0.6													
MnH	0.3	0.5	0.1	-0.1	-0.2	-0.3	-0.3	-0.6	0.8	-0.7	0.5	0.2	-0.3	-0.5	-0.3	0.4	-0.1	0.3	-0.2	-0.1	-0.6	-0.5	0.4	0.3	-0.2	-0.6												
MnF	0.2	0.3	-0.6	-0.6	0.3	-0.3	0.8	0.4	0.0	0.2	0.5	0.9	-0.5	-0.2	-0.1	0.1	0.4	0.3	-0.2	-0.4	0.1	-0.1	0.2	0.6	0.3	0.2	0.3											
NiT	0.8	-0.2	0.9	0.7	0.8	-0.2	0.4	0.7	0.3	-0.2	0.7	0.2	0.3	0.3	0.1	0.6	1.0	0.0	-0.1	-0.3	0.6	-0.1	0.4	0.6	0.9	0.5	-0.1	0.4										
NiE	0.1	-0.2	-0.3	0.0	0.0	-0.7	0.1	0.4	0.3	-0.1	0.5	0.4	-0.1	-0.3	-0.3	0.5	0.5	0.1	0.0	0.1	0.0	0.2	-0.4	0.2	0.2	-0.1	-0.3	0.3	0.5									
NiH	0.1	0.0	-0.1	-0.3	0.4	-0.1	0.0	-0.3	0.7	-0.5	0.2	-0.1	-0.2	-0.1	0.4	0.4	0.2	-0.3	0.2	0.1	-0.1	-0.1	0.4	0.1	0.2	0.0	0.7	0.3	0.1	-0.5								
NiF	0.0	0.4	-0.4	-0.3	-0.1	-0.7	0.3	0.1	-0.1	-0.2	0.7	0.8	-0.5	-0.5	-0.6	0.4	0.3	0.5	-0.3	-0.2	-0.3	-0.2	0.1	0.6	0.1	-0.3	0.4	0.8	0.4	0.6	0.0							
ZnT	-0.1	0.3	-0.2	0.1	-0.3	-0.5	-0.3	0.0	0.2	-0.3	0.6	0.2	0.1	-0.4	-0.8	0.4	0.2	0.5	-0.4	-0.1	-0.3	-0.3	-0.1	0.3	0.0	-0.5	0.0	0.0	0.2	0.8	-0.6	0.6						
ZnE	0.1	0.4	-0.3	-0.4	0.0	0.3	0.8	0.5	0.6	0.8	0.0	0.8	-0.3	0.1	-0.2	-0.6	-0.1	0.5	-0.3	-0.5	0.3	0.0	0.1	0.3	-0.1	0.4	-0.2	0.6	0.0	0.1	-0.4	0.4	0.0					
ZnH	0.4	-0.6	-0.2	-0.3	0.8	0.2	0.5	0.4	0.0	0.3	-0.3	-0.1	-0.1	0.4	0.9	0.0	0.3	-0.7	0.6	0.2	0.6	-0.1	-0.3	0.5	0.7	-0.2	0.1	0.3	-0.3	0.5	-0.4	-0.8	0.0					
ZnF	0.3	0.6	-0.6	-0.4	-0.1	-0.1	-0.1	0.3	0.4	-0.2	0.7	0.2	0.5	0.1	-0.8	0.2	0.3	0.8	-0.8	-0.6	0.0	-0.7	0.5	0.8	0.3	-0.1	0.1	0.2	0.4	0.5	-0.4	0.5	0.8	0.1	0.7			
pH	-0.4	-0.1	0.5	0.4	-0.4	0.3	0.3	0.1	0.4	0.8	-0.8	0.2	-0.3	0.0	0.1	-0.8	-0.6	0.0	0.2	0.1	0.0	0.4	-0.5	-0.6	0.2	-0.6	-0.1	-0.6	-0.1	-0.6	-0.2	0.6	0.0	-0.4				
SOM	0.3	-0.6	-0.3	-0.1	0.4	-0.5	0.3	0.6	0.4	0.1	0.3	0.3	-0.1	-0.1	0.1	0.4	0.6	-0.3	0.3	0.3	0.3	0.5	-0.5	0.0	0.4	0.2	-0.6	0.2	0.6	0.9	-0.5	0.3	0.5	0.1	0.2	0.0		
CEC	0.2	0.5	-0.4	-0.5	0.1	-0.3	0.1	-0.1	-0.5	-0.5	0.8	0.4	-0.2	-0.2	-0.4	0.5	0.3	0.4	-0.4	-0.4	-0.2	-0.6	0.6	0.7	0.3	-0.2	0.9	0.6	0.3	-0.1	0.7	0.6	0.1	0.0	-0.1	0.3	0.7	0.3

AIT - [Soil As]_{Total}
 AIE - [Soil As]_{Exchangeable}
 AIH - [As]_{Hass}
 AIF - [As]_{Fuerte}
 SOM - Soil Organic Matter
 CEC - Cation Exchange Capacity

same effect is shown with exchangeable soil Al and Fe on uptake of Fe.

Dietary Reference Intakes

An average serving of fresh avocado fruit pulp (one and a half fruits) is equivalent to 270 g fresh weight and 100 g dry weight (DW). The results in Table 6 show the estimated contribution of 100 g (DW) of avocado mesocarp (average serving size) to the RDA. One serving

of avocado is estimated to contribute more than 3, 66, 10, 29, 34 and 18 % towards the RDA for Ca, Cu, Fe, Mg, Mn and Zn, respectively in most adults. None of the elements have concentrations in the fruit exceeding the upper intake levels (UL) and even consumption of twice the average serving size is still considered safe.

The results suggest that an individual deficient in Cu should consume avocados frequently, especially the Fuerte variety which can contribute approximately 75 % towards the RDA for this element. Individuals with Mn deficiency should also consume avocados,

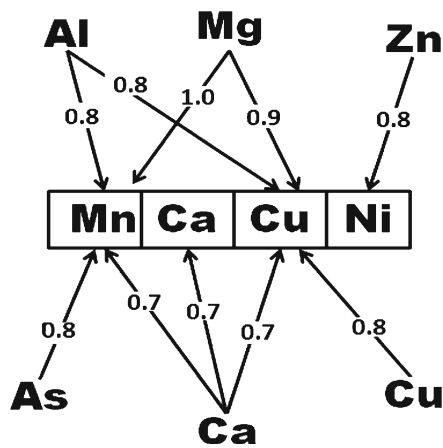


Fig. 3 Synergistic relationships in soil

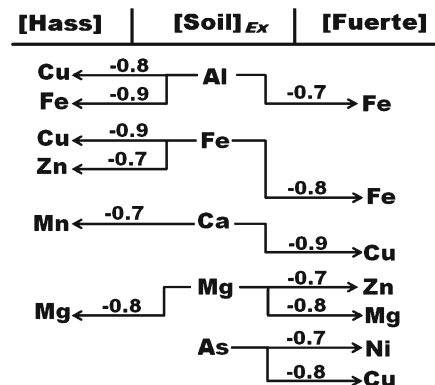


Fig. 4 Antagonistic relationships between exchangeable elemental concentrations and concentrations in fruit (Hass and Fuerte varieties)

Table 6 Dietary Reference Intake (DRIs), Recommended Dietary Allowance (RDA), and tolerable upper intake levels (UL) of elements for most individuals (Institute of Medicine of the Nation-al Academies: Dietary Reference Intakes, 2001) and average concentration of elements ($n=6$) in mesocarp of avocado (Hass and Fuerte varieties)

Element	Average Concentration (mg/100 g dry mass) Hass	Average Concentration (mg/100 g dry mass) Fuerte	DRI (mg/day)		Estimated Contribution to RDA (%) Hass	Estimated Contribution to RDA (%) Fuerte
			RDA	UL		
As	0.38	0.31	ND	ND	ND	ND
Ca	40.84	35.32	1,000–1,300	2,500	4	3
Cu	0.59	0.67	0.9	8	66	75
Fe	1.92	1.24	8–18	45	14	10
Mg	99.13	92.32	310–320	350	32	29
Mn	1.16	0.67	1.6–2.3	9	58	34
Ni	0.69	0.39	ND	1.0	ND	ND
Zn	1.96	1.76	8–11	34	20	18

ND not determined due to lack of data

especially the Hass variety. For the remaining nutrients, there is no marked difference in estimated contribution to the RDA. The maximum limit for metals in fruits and vegetables set by the Department of Health, South Africa, is $0.1 \mu\text{g g}^{-1}$ for Pb (Department of Health 2004). Avocado flesh contained Pb concentrations below the instruments detection levels of $0.09 \mu\text{g g}^{-1}$ and therefore is considered safe. The maximum limit for As in fruits is not listed by the Department of Health, South Africa, per se; however, the maximum limit for As in foodstuff is $0.1 \mu\text{g g}^{-1}$ as listed for edible fats and oils and $0.5 \mu\text{g g}^{-1}$ as listed for fish (Department of Health 2004). Arsenic concentrations found in the avocado fruit show no cause for concern in terms of toxicity.

Conclusion

Avocado fruit is shown to have negligible concentrations of Cd, Co, Cr, Pb and Se; hence, it is not an accumulator of these metals. The concentration of elements in both varieties of fruit was, generally, in decreasing order of $\text{Mg} > \text{Ca} > \text{Fe} > \text{Al} > \text{Zn} > \text{Mn} > \text{Cu} > \text{Ni} > \text{As}$. Soils are moderately enriched by Pb as shown by positive geoaccumulation indices but is not shown to influence uptake of Pb into the fruit. Statistical analysis revealed the influence of complex metal interactions in the soil–plant interface on the uptake of Fe into both varieties of fruits. The plant displayed controlled uptake as evidenced by the accumulation and exclusion

of elements to meet its physiological requirement levels. Locally grown avocado fruit is a good dietary source of the micronutrients Cu and Mn. It should be noted that the results obtained in this study are indicative and are limited to the number of samples and sites that were analysed.

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