The dual-purpose use of orange-fleshed sweet potato (*Ipomoea batatas* var. Bophelo) for improved nutritional food security

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Highlights

- Sweet potato leaves could provide almost the entire daily-recommended vitamin A intake to children aged 4–18 years.
- Vine harvesting improved iron nutritional yield, but reduced zinc and β-carotene nutritional yield.
- Less water was needed to meet daily-recommended intakes with sweet potato grown as a dual-purpose crop.
- There is scope of utilising sweet potato as a dual-purpose crop.

Abstract

Orange-fleshed sweet potato (OFSP) leaves can be utilised as a fresh green leafy vegetable, in addition to the traditional use of storage root; therefore, OFSP can be seen as a "dual-purpose'' crop. We hypothesized that no vine harvesting combined with fertiliser application and irrigation will improve the storage root yield and selected plant parameters (water productivity, leaf and storage root nutrient concentrations, nutritional yield, and nutritional water productivity). The objectives of the study were to (i) evaluate the effect of vine harvesting on the selected plant parameters, and, (ii) assess the effect of irrigation regimes and soil fertilisation on these selected parameters. Field experiments were conducted at ARC-VOP, Pretoria, South Africa, during the 2013/14 and 2014/15 seasons. Treatments included irrigation regimes [well-watered (W1) and supplemental irrigation (W2)], soil fertilisation [well-fertilised (F1) and no fertiliser application (F2)], and vine harvesting [no vine harvesting (H1) and vine harvesting (H2)]. For the 2014/15 season, the well-watered regime improved total storage root yield (W1 = 13.0 t DM ha^{-1}; W2 = 7.5 t DM ha^{-1}). Under the practice of vine harvesting, soil fertility treatments did not affect (total dry storage root yield and dry marketable storage root yield) storage root production. Our results further revealed that vine harvesting reduced storage root nutrient concentrations (23% for iron; 14% for zinc; 12% for β-carotene). Nevertheless, total nutritional yields increased; the highest total nutritional yields for iron, zinc, and β-carotene were found under the water and nutrient input regime (W1F1). Assessments showed that boiled orange-fleshed sweet potato aboveground edible biomass could potentially contribute to the daily-recommended nutritional requirement of iron and vitamin A for a family of six people. More water was needed to meet the daily-recommended nutrient intake (iron, zinc, and vitamin A) with OFSP grown as a storage root crop only than when grown as a dual-purpose crop. Our results indicated that there is an opportunity to utilise OFSP as a dual-purpose crop for rural resource-poor households because total nutritional yields (iron, zinc, and β-carotene) and total nutritional water productivities (iron, zinc, and β-carotene) were improved. More research is needed to assess the effect of vine harvesting on a range of OFSP varieties and should be conducted on the farm. Rural resource-poor households are encouraged to produce OFSP for their own consumption and the surplus could be sold at the local market.

Keywords: Micronutrient deficiency; Nutritional water productivity; Vitamin A; Green leafy vegetable; Water stress

1. Introduction

In sub-Saharan Africa, micronutrient deficiencies (known as “hidden hunger”) are a major problem, affecting rural resource-poor households (RRPHs). The most common deficiencies in some sub-Saharan Africa countries are iron, zinc and vitamin A (Harika et al., 2017). Harika et al. (2017) assessed the prevalence of micronutrient deficiencies in Ethiopia, Kenya, Nigeria, and South Africa. Their findings revealed that the prevalence of iron deficiency stands at 28% in South Africa. Moreover, in South Africa, vitamin A deficiency is more prevalent (22%) than in Ethiopia (4%) or Nigeria (4%). This highlights that nutritional food insecurity is pervasive in rural areas of South Africa. Several approaches are being followed in combating micronutrient deficiencies; these include supplementation through the distribution of capsules that are rich in micronutrients, fortification of staple foods with micronutrients, and through changing diets to achieve adequate intake of micronutrient-rich foods (Mitra, 2012). In South Africa, food-based approaches are preferred because 34% of rural resource-poor households rely on agriculture; therefore, this is the main vehicle to address nutritional food insecurity (Nyathi et al., 2018b). Through plant breeding, several orange-fleshed sweet potato varieties (A-15, Beauregard, Bophelo, Excel, Jewel, Resisto, and W-119) were developed. These varieties are rich in β-carotene, which the body converts into vitamin A. In addition, orange-fleshed sweet potato varieties contain significant quantities of iron and zinc (Laurie et al., 2012a,b; 2015; 2018).

Previous studies (Claessens et al., 2008; Larbi et al., 2007; Megersa et al., 2012; Mussoline and Wilkie, 2017) evaluated the potential of using sweet potato as a dual-purpose crop, i.e. harvesting the aboveground biomass as fodder for livestock feed and harvesting the storage root for human consumption. Sweet potato is not a staple crop in South Africa; its estimated overall consumption is 1.1 kg fresh mass per person per year (Laurie et al., 2018). The practice of using sweet potato as a dual-purpose food crop is not common in South Africa, despite the high levels of micronutrient deficiencies (Schönfeldt et al., 2017). The leaves can be used as a green leafy vegetable during the summer season and could potentially alleviate food shortages (Sun et al., 2014). In the northern parts of South Africa and other frost-free areas, sweet potato can be cultivated throughout the year. We presume that if rural resource-poor households were to utilize sweet potato as a dual-purpose food crop (green leafy vegetable and storage root for human consumption) in South Africa, the consumption rate per person per year might increase. Boiling, roasting, or baking (Laurie et al., 2018) are some of the methods used to prepare sweet potato for consumption. Studies by Gomes and Carr (2001, 2003a,b) and Van An et al. (2003) showed that increasing the frequency of vine harvesting improved leaf yield, but total storage root yield decreased. Several studies (Gomes and Carr, 2001, 2003a; Laurie et al., 2012a; Motsa et al., 2015) reported that sweet potato is a drought tolerant crop. However, water stress reduces canopy growth, which causes a reduction in light interception and thus in storage root yield. Laurie et al. (2012a) showed that a well-watered treatment resulted in a two to four-fold increase in total storage root yield compared with a water-stressed treatment. However, the well-watered treatment showed a lower β-carotene concentration than the water-stressed treatment. Applying fertiliser at 50% of the recommended rate increased total storage root yield two-fold, whereas fertiliser application at 100% of the recommended rate, increased storage root yield three-fold, relative to no fertiliser application. In addition, fertiliser application improved the β-carotene concentration of the storage root, from 134 µg g^{-1} for the unfertilised treatment, to 151 µg g^{-1} for the treatment receiving fertiliser (Laurie et al., 2012a,b). This shows that irrigation and fertiliser application are essential for improving orange-fleshed sweet potato storage root yield and β-carotene concentration.

Studies by Laurie et al. (2012a,b) evaluated the effect of water regimes and soil fertility in different environments (Roodeplaat, Giyani, Hazyview and Empangeni) on water productivity, nutrient concentrations (iron, zinc), and β-carotene nutritional yield of different sweet potato varieties. However, the effect of vine harvesting on these crop parameters was not considered. To the best of our knowledge, this study is the first to assess the potential use of orange-fleshed sweet potato (var. Bophelo) as a dual-purpose food crop (green leafy vegetable and as a storage root for human consumption) in South Africa. The objectives of the study were: (1) to evaluate the effect of vine harvest on selected plant parameters [total storage root yield, marketable storage root yield, nutrient concentrations (iron, zinc, and β-carotene), nutritional yield, water productivity, and nutritional water productivity], and, (2) to assess the effect of irrigation regimes and soil fertilisation on these selected plant parameters. We selected orange-fleshed sweet potato (var. Bophelo) because it is popular in the informal markets of South Africa, it is highly productive and has acceptable levels of β-carotene (6708 µg 100 g^{-1} on a fresh mass basis) (Laurie et al., 2018). We imposed two irrigation regimes, two soil fertilisation levels, and two vine-harvest treatments. Our hypotheses were that (1) Vine harvesting of orange-fleshed sweet potato will reduce storage root yield and the other selected plant parameters (water productivity, nutrient concentration, nutritional yield, and nutritional water productivity). (2) No vine harvesting combined with fertiliser application and irrigation will improve storage root yield and the selected plant parameters.

2. Materials and methods

2.1. Site description, experimental setup, environmental conditions and irrigation regimes

Field experiments were conducted at ARC-VOP, Roodeplaat, Pretoria (25° 59′ S; 28° 35″ E; 1168 m.a.s.l.), in the Gauteng Province of South Africa, during two summer seasons: 2013/14 (December-May), and 2014/15 (November-May). The soil was classified (Soil classification working group, 1991) as a yellow-brown Oakleaf form, Buchuberg family (Oa 1120), with a depth of 0.65 to 0.85 m and clay content of 20%. The field capacity of the soil was 292 mm m^{-1} and the permanent wilting point was 55 mm m^{-1}. Table 1 presents the chemical properties of the soil for the top 0.3 m layer.

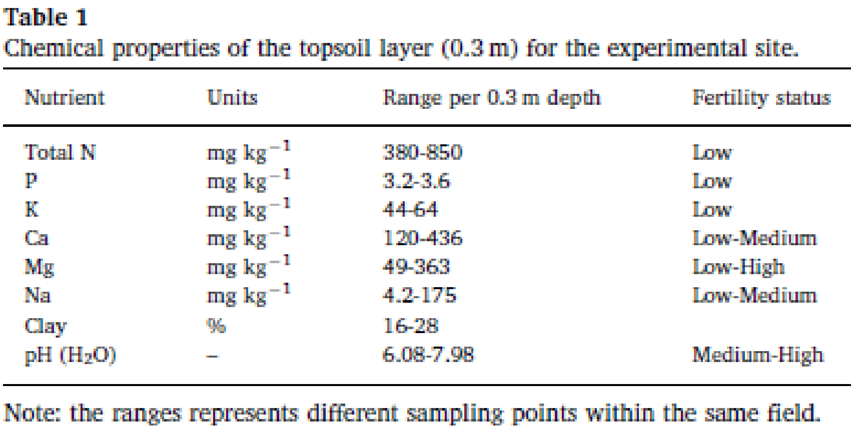

Table 1
Chemical properties of the topsoil layer (0.3 m) for the experimental site.

Nutrient	Units	Range per 0.3 m depth	Fertility status
Total N	mg kg^{-1}	380-850	Low
P	mg kg^{-1}	3.2-3.6	Low
K	mg kg^{-1}	44-64	Low
Ca	mg kg^{-1}	120-436	Low-Medium
Mg	mg kg^{-1}	49-363	Low-High
Na	mg kg^{-1}	4.2-175	Low-Medium
Clay	%	16-28	
pH (H_2O)	–	6.08-7.98	Medium-High

Note: the ranges represents different sampling points within the same field.

The experiment had a 2 × 2×2 factorial design; factors were irrigation regime [well-watered (W1) and supplemental irrigation (W2)], soil fertilisation [recommended N, P, and K application (F1) and no fertiliser application (F2, control)], and vine harvest [no vine harvesting (H1) and vine harvesting every 4 weeks (H2)]. The W1 treatment aimed to keep soil water content above 30% of plant available water and the W2 treatment was supplemental irrigation; if it did not rain for 4 weeks and soil water content reached a depletion of 80%, we irrigated back to 50% of plant available water. The experiment was a randomised complete block design, replicated three times (24 plots of 9 m^2 each). Nyathi et al. (2018a) presented the long-term weather data [rainfall amount (mm), maximum and minimum temperatures (°C)] of the study site. Table 2 presents the meteorological conditions [maximum and minimum temperatures (°C), total solar radiation (MJ m^{-2}), total rainfall (mm), cumulative reference evapotranspiration (mm), and vapour pressure deficit (kPa)] during the two growing seasons. Prior to planting, aluminium access tubes were installed in the middle of each plot to a depth of 1 m. A neutron water meter (CPN, 503 DR Hydroprobe, USA) calibrated for the site with measurements from a wet and dry profile was utilised to measure soil water content. Compensating non-leaking (CNL) Urinam dripper lines, with a discharge dripper rate of 2.3 l h^{-1} were used for irrigation. Irrigation scheduling was based on irrigation regimes (W1 and W2). The soil water balance was estimated using Equation 1 (Table 3).

Table 2

Monthly meteorological data for the 2013/14 (S1) and 2014/15 (S2) growing seasons.

Month	T_{max}[a]		T_{min}[b]		Radiation		Rainfall		ET_0[c]		VPD[d]	
	S_1 °C	S_2 °C	S_1 °C	S_2 °C	S_1 MJ m^{-2}	S_2 MJ m^{-2}	S_1 mm	S_2 mm	S_1 mm	S_2 mm	S_1 kPa	S_2 kPa
November	30.3	27.8	14.6	14.3	768	631	88	95	159	131	1.4	1.1
December	27.9	28.7	16.3	16.3	697	731	186	175	140	147	0.9	1.0
January	30.8	30.2	16.9	16.5	798	789	25	136	163	161	1.3	1.1
February	30.5	31.9	17.4	16.0	616	744	31	33	128	152	1.1	1.4
March	26.4	30.2	15.9	14.7	479	686	115	72	94	135	0.6	1.2
April	25.2	27.4	9.2	10.8	516	537	26	44	95	101	0.7	0.9
May	25.6	27.6	5.3	6.1	479	545	3	0	89	95	0.8	1.1
					4354	**4663**	**474**	**554**	**869**	**923**		

The reported values are monthly means of daily climatic data during the two growing seasons; from day of transplanting to end of harvest.

[a] T_{max}- maximum temperature.

[b] T_{min}-minimum temperature.

[c] ET_0- reference evapotranspiration.

[d] VPD- vapour pressure deficit; bold values are cumulative values.

Table 3
Equations used to calculate the selected parameters.

Equations	Description	Number
$ET_a = I + P \pm \Delta W$	Where ET_a (mm) is the actual evapotranspiration, I is the irrigation amount (mm), ΔW is the change in soil water content (mm). Deep percolation (mm) was considered negligible because irrigation was done to supplement rain-received back to field capacity.	(1)
$HI = [(Y_{Tsr})/(Y_{Tsr} + AGB)]$	HI is the harvest index (unit-less); Y_{Tsr} is total storage root yield (t ha^{-1}); AGB is above ground biomass (t ha^{-1}).	(2)
$WP_{Total} = [(Y_{Tsr} + AGB)/(ET)] \times 1000$	WP_{Total} is water productivity for the total biomass (kg ha^{-1} mm^{-1}); ET is actual evapotranspiration (mm).	(3)
$NY_{AGEB\ (Fe,\ Zn,\ and\ \beta)} = [(MC \times AGEB)/100]$	NY_{AGEB} is the above ground biomass nutritional yield (NY, kg ha^{-1}) for iron (Fe), zinc (Zn), and β-carotene; MC is mass concentrations of Fe, Zn, and β (mg 100 g^{-1}); AGEB is the above ground edible biomass (t ha^{-1}).	(4)
$NY_{Tsr\ (Fe,\ Zn,\ and\ \beta)} = [(MC \times Y_{TSr})/100]$	NY_{Tsr} is the total storage root NY (g ha^{-1}) for Fe, Zn, and β; MC of Fe, Zn, and β (mg 100 g^{-1}); Y_{Tsr} (t ha^{-1}).	(5)
$NY_{Total} = [(MC \times AGEB)/100] + [(MC \times Y_{TSr})/100]$	NY_{Total} (kg ha^{-1}) is total nutritional yield	(6)
$NWP_{Tsr} = WP_{Tsr} \times MC \times 10$	Where NWP_{Tsr} is nutritional water productivity (mg m^{-3}) of the total storage roots; WP_{Tsr} is water productivity of the T_{sr} (kg m^{-3}); MC (mg 100 g^{-1}) of Fe, Zn, and β.	(7)
$NWP_{Total} = [(AGEB \times MC \times 1000) + (T_{sr} \times MC \times 1000)]/ET$	Where NWP_{Total} is total nutritional water productivity (mg m^{-3}); AGEB (t ha^{-1}); T_{sr} (t ha^{-1}); MC (mg 100 g^{-1}) of Fe, Zn, and β; ET (mm).	(8)

2.2. Soil fertilisation and crop management

For both seasons, fertilisers [limestone ammonium nitrate (28% N), Calsiphos (12% P and 14% Ca), potassium chloride (50% K), and calcium nitrate Ca $(NO_3)_2$ (24% Ca and 15.5% N)] were applied providing N, P, K and Ca based on the soil analysis and target yields as recommended by ARC-VOP. The application rates for full fertilisation (F1) were 150 kg N ha^{-1}, 74 kg P ha^{-1}, 200 kg K ha^{-1} and 160 kg Ca ha^{-1}, of which half was applied at planting and the remaining half top dressed in equal portions at 14 and 30 days after planting. Orange-fleshed sweet potato (var. Bophelo) cuttings were obtained from the ARC-VOP plant breeding division. The cuttings were planted on ridges (0.3 m high and 0.2 m wide) at a spacing of 1 m between ridges and 0.3 m within ridges (33 333 plants ha^{-1}). At planting, three nodes above and below ground were maintained to allow the cuttings to develop roots from the nodes. The newest five well-developed leaves were plucked at 4, 8, 12, and 16 weeks after planting in the vine harvesting treatments.

2.3. Sampling procedure, plant parameters, and potential contribution to human nutrition

Orange-fleshed sweet potato aboveground edible biomass (AGEB) were separated into leaf blades and petioles; leaf blades were sampled (500 g) at 4 and 12 weeks after planting and thoroughly washed with distilled water to remove debris. Thereafter, samples were put in transparent airtight plastic polythene bags and immediately sent to NviroTek laboratories to be analysed for iron and zinc mass concentrations. At the end of the growing seasons (2013/14 and 2014/15), total storage root yield (small + mechanically damaged + long-curved + sprouts + groves + cracked + marketable) and marketable storage root yield were measured fresh and oven dried. Three marketable medium-sized storage roots were sampled from each plot for nutritional analysis and weighed fresh. Thereafter, these samples were washed with distilled water to remove debris and analysed for iron and zinc by NviroTek Laboratories. Analysis of β-carotene concentration of AGEB and storage roots was conducted at the ARC-VOP biotechnology laboratory. Storage roots were peeled and dried with a paper towel. Two opposite quarters from the longitudinal storage root were combined, homogenised, aliquots weighed, and stored at −80 °C for a week before freeze-drying. Details of the equipment, reagents, and extraction methods used in determining iron, zinc, and β-carotene concentrations were as described by Nyathi et al. (2018b).

β-carotene concentration was converted into vitamin A [(µg RAEs (retinol activity equivalents)] based on Trumbo et al. (2003) (1 µg RAE = 1 µg retinol = 12 µg of β-carotene). The daily-recommended nutrient intakes (DRNI) for iron, zinc and β-carotene were sourced from Uusiku et al. (2010). Percentage contribution to the DRNI was calculated [nutrient concentrations (iron, zinc, and β-carotene in mg 100 g^{-1}) divided by nutrient requirements in mg $day^{-1} \times 100$]. The potential nutritional contribution (iron, zinc, and vitamin A) from one hectare for a family of six (one male adult; one female adult; two 1–3 year infants; two 4–9 year old children) was calculated using nutritional yield (NY) data [iron, zinc and β-carotene NYs (kg ha^{-1}) divided by the DRNI (mg 100 g^{-1}). We assumed that 30% of β-carotene is lost during cooking (boiling) as mentioned by Laurie et al. (2012a) and Van Jaarsveld et al. (2006). For iron and zinc, around 50% is lost; 5% due to boiling and 45% due to bioavailability inside human bodies (Amagloh et al., 2017; Gupta et al., 2006).

2.4. Statistical analysis

Two models of the generalised linear mixed model procedures for GenStat (version 14, VSN, UK) were used for data analysis. We used Model 1 to assess the fixed effects (irrigation regime, soil fertilisation level, harvesting and season) and random effects (block/plot) on the studied variables. Model 2 was used to assess the fixed effects (irrigation regime, soil fertilisation and season) and random effects (block/plot) on the vines harvested during growing seasons (4, 8, 12, and 16 weeks after planting) and nutrient concentrations (iron, zinc, β-carotene) of the AGEB. Checks for normality and homogeneity of variance were carried out using Shapiro Wilk's and Bartlett's tests, respectively. Post-hoc mean separation was done using Fischer’s least significance difference test at a 5% significance level. Table 3 presents the equations used to calculate selected plant parameters.

3. Results

3.1. Rainfall and irrigation amount

Total rainfall was 474 mm during the 2013/14 season, whereas for the 2014/15 season, total rainfall was 554 mm. The total irrigation amount was 495 mm (W1) and 210 mm (W2) in the 2013/14 season. During the 2014/15 season, total irrigation amount was 338 mm (W1) and 218 mm (W2) (Fig. 1a). The similarity in irrigation of W2 treatments for both seasons resulted from the difference in the duration of the growing period; during season 1, orange-fleshed sweet potato storage root was harvested 130 days after planting, and for season 2, storage root was harvested 180 days after planting.

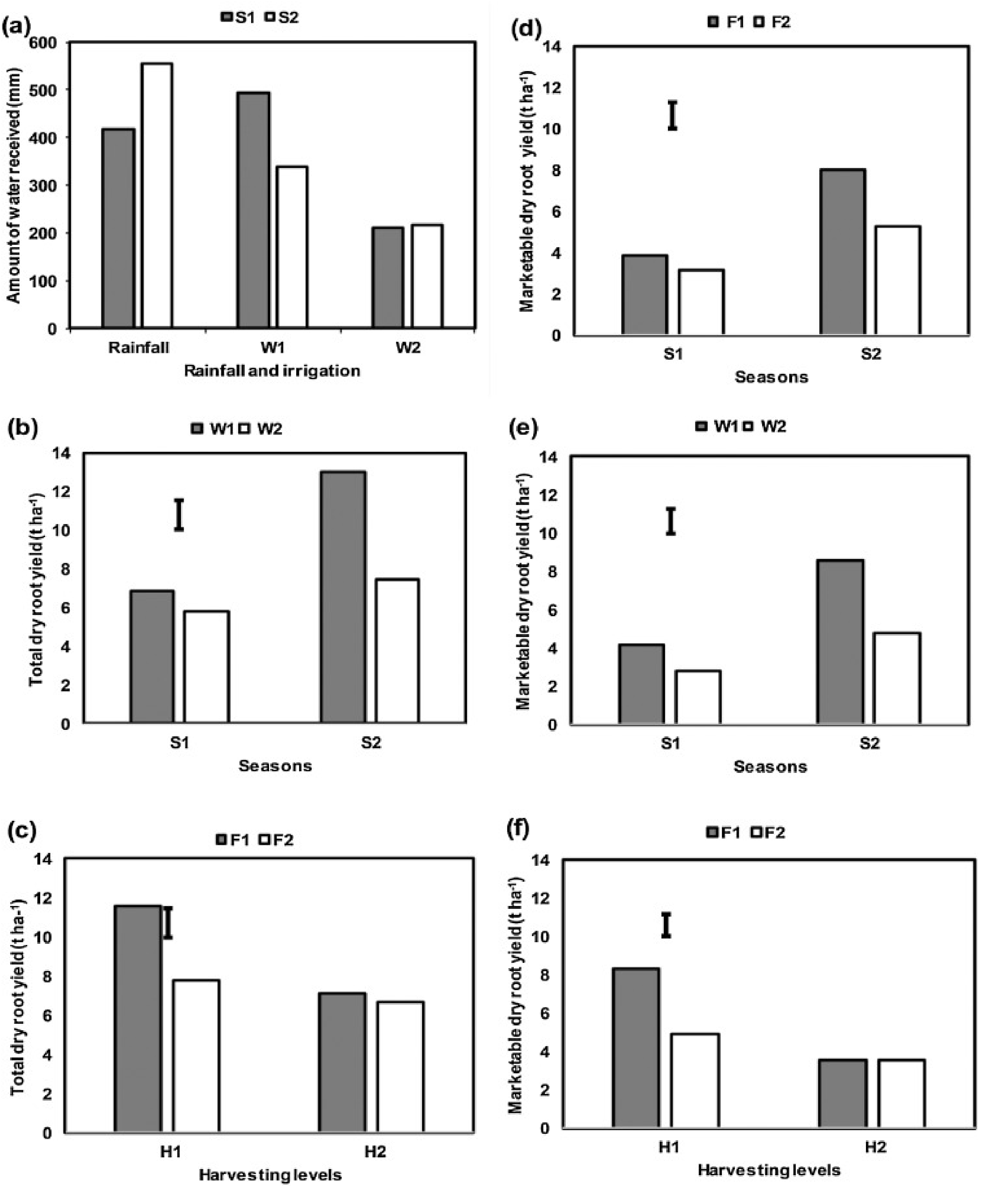

Fig. 1. Total rain and irrigation amount (**a**). Treatment effect on total dry storage root yield (**b, c**) and on marketable storage root yield (**d, e, and f**). Total storage root yield includes marketable storage roots yield and unmarketable storage roots yield (small + mechanical damage + long-curved + groves + cracked). W1- well-watered regime; W2- supplemental regime; F1- 100% N, P, and K application; F2- 0% N, P, and K application (control); H1-no vine harvesting; H2- vine harvesting; S1-2013/14 season; S2-2014/15 season. Values are averaged over the treatments that are not mentioned, for instance in pane b, yields are averaged over fertilisation and vine harvesting levels. Bars represent the $LSD_{0.05}$.

3.2. Total storage root yield, marketable storage root yield, and aboveground edible biomass

The four-way and three-way interactions between irrigation regime, soil fertilisation, vine harvesting, and season were not significant ($P > 0.05$). However, there was a significant ($P < 0.05$) interaction between irrigation regime and season for total storage root yield and marketable storage root yield (Fig. 1b, e). For the 2013/14 season, irrigation regimes did not affect ($P > 0.05$) both storage root yields. In contrast, the 2014/15 results revealed that the well-watered regime significantly ($P < 0.05$) increased both storage root yield over the supplemental regime; for total storage root yield, it was higher by ≈ 42%, whereas for marketable storage root yield, it was higher by ≈ 44%. Correspondingly, the soil fertilisation by vine harvesting interaction significantly ($P < 0.05$) affected total storage root yield and marketable storage root yield (Fig. 1c, f). Without vine harvesting, applying fertiliser increased total storage root yield (≈33%) and marketable storage root yield (≈41%) compared to the control (no fertiliser application). Interestingly, with vine harvesting, soil fertilisation had no effect ($P > 0.05$) on total storage root yield and marketable storage root yield. With no fertiliser applied, both storage root yields were comparable whether vines were harvested or not. There was a significant ($P = 0.04$) interaction effect between season and soil fertilisation for marketable storage root yield (Fig. 1d). In the 2013/14 season, soil fertilisation did not affect ($P > 0.05$) marketable storage root yield. On the contrary, the well-fertilised treatment improved marketable storage root yield by ≈ 44% compared to the control in the 2014/15 season. There were no significant effects ($P > 0.05$) of irrigation regimes and soil fertilisation for the aboveground edible biomass harvested during the growing seasons; yet, our results revealed that between 0.9–1.1 t DM (dry matter) ha^{-1} (2013/14 season) and between 1.2–1.5 t DM ha^{-1} (2014/15 season) were harvested (Table A1).

3.3. Micronutrients, β-carotene, nutritional yield, and potential contribution to human nutrition

There were no significant ($P > 0.05$) interactions for main effects on moisture content; this implies that moisture did not compromise differences in mass concentrations reported here and established on a fresh mass basis. For the aboveground edible biomass, moisture content ranged from 0.78 to 0.80 and for the storage root, moisture content ranged from 0.74 to 0.81 (Fig. A1). Similarly, irrigation regime, soil fertilisation, and the season had no effect ($P > 0.05$) on iron, zinc, and β-carotene mass concentrations in the aboveground edible biomass and storage roots. The aboveground edible biomass was superior in micronutrient concentrations [grand means (50 mg Fe 100 g^{-1}; 2.8 mg Zn 100g^{-1})] compared to the storage root [grand means (4.6 mg Fe 100 g^{-1}; 1.2 mg Zn 100 g^{-1})]. However, the storage root was rich in β-carotene, with mean values ranging from 173 to 229 mg β-carotene 100 g^{-1} (Table 4). In addition, the mean results (2013/14 and 2014/15) for micronutrient and β-carotene mass concentrations illustrated that without vine harvesting, low input management (supplemental irrigation regime and no fertiliser application treatments) improved storage root concentrations by ≈ 79% for iron and ≈ 22% for β-carotene, whereas for zinc, it remained the same, in comparison to the highest input regime (well-watered and well-fertilised treatments). In contrast, vine harvesting reduced storage

Table 4

Nutrient concentrations (iron, zinc, and β-carotene) of orange-fleshed sweet potato var. Bophelo for the aboveground edible biomass (AGEB) and storage roots (Tubers) for 2013/14 (S1) and 2014/15 (S2) seasons.

Treatments	Iron		Zinc		β-carotene	
	AGEB mg 100 g^{-1}	Tubers mg 100 g^{-1}	AGEB mg 100 g^{-1}	Tubers mg 100 g^{-1}	AGEB mg 100 g^{-1}	Tubers mg 100 g^{-1}
No vine harvesting (H1)						
W1F1S1	n.d	3.9 (0.1)	n.d	1.7 (0.2)	n.d	235 (0.3)
W1F1S2	n.d	4.5 (0.2)	n.d	1.3 (0.1)	n.d	221 (0.1)
W1F2S1	n.d	5.1 (0.2)	n.d	1.4 (0.1)	n.d	185 (0.3)
W1F2S2	n.d	7.0 (0.1)	n.d	1.1 (0.2)	n.d	221 (0.2)
W2F1S1	n.d	2.9 (0.1)	n.d	1.4 (0.3)	n.d	182 (0.1)
W2F1S2	n.d	8.7 (0.2)	n.d	1.2 (0.1)	n.d	248 (0.3)
W2F2S1	n.d	3.8 (0.1)	n.d	1.7 (0.2)	n.d	214 (0.2)
W2F2S2	n.d	11.2 (0.1)	n.d	1.3 (0.1)	n.d	293 (0.1)
Grand means	**n.d**	**6.0**	**n.d**	**1.4**	**n.d**	**225**
Vine harvesting (H2)						
W1F1S1	53 (4.0)	4.6 (0.4)	3.2 (0.8)	1.6 (0.4)	43 (4.7)	214 (0.8)
W1F1S2	48 (3.4)	3.5 (0.1)	2.5 (1.0)	0.9 (0.2)	37 (4.3)	173 (0.1)
W1F2S1	69 (3.4)	4.8 (0.2)	3.0 (0.1)	1.6 (0.3)	63 (3.5)	182 (0.2)
W1F2S2	44 (11)	7.0 (0.1)	2.0 (6.3)	1.0 (0.2)	38 (17)	173 (0.2)
W2F1S1	45 (6.7)	4.3 (0.2)	3.1 (0.3)	1.3 (0.1)	44 (6.5)	203 (0.2)
W2F1S2	48 (20)	6.2 (0.1)	2.6 (3.1)	1.0 (0.3)	48 (23)	218 (0.5)
W2F2S1	45 (4.7)	2.7 (0.3)	3.0 (1.0)	1.4 (0.1)	47 (5.5)	193 (0.4)
W2F2S2	46 (24)	3.8 (0.1)	2.6 (6.4)	1.1 (0.1)	48 (31)	229 (0.1)
Grand means	**50**	**4.6**	**2.8**	**1.2**	**46**	**198**

W1 is the well-watered regime; W2 is the supplemental regime; F1 is 100% N, P, and K fertiliser application; F2 is the 0% N, P, and K fertiliser application. Numbers in brackets represent the standard deviations of the mean. Moisture content values for the AGEB and storage roots for fresh mass are presented by Fig. A1. n.d means there are no data values for the no vine harvesting since the leaves are not consumed.

root concentrations by ≈ 20% for iron and 2% for zinc, whereas for β-carotene concentration, it was improved by ≈ 9%, compared to the highest input regime.

W1 is the well-watered regime; W2 is the supplemental regime; F1 is 100% N, P, and K fertiliser application; F2 is the 0% N, P, and K fertiliser application. Numbers in brackets represent the standard deviations of the mean. Moisture content values for the AGEB and storage roots for fresh mass are presented by Fig. A1. n.d means there are no data values for the no vine harvesting since the leaves are not consumed.

For both seasons (2013/14 and 2014/15), there was no significant ($P > 0.05$) interaction effect between soil fertilisation and vine harvesting for iron nutritional yields [storage root and total biomass (storage root plus the aboveground edible biomass)] (Table 5). However, the main effects (vine harvesting and season) were highly significant ($P < 0.001$) for total iron nutritional yield. Our results displayed that vine harvesting (0.73 kg Fe ha^{-1}) improved total iron nutritional yield compared to no vine harvesting (0.39 kg Fe ha^{-1}). For the 2014/15 season, total iron nutritional yield (0.72 kg Fe ha^{-1}) was higher than for the 2013/14 season (0.41 kg Fe ha^{-1}). Zinc nutritional yields (storage root and total biomass) and β-carotene nutritional yields (storage root and total biomass) were affected ($P < 0.05$) by the interaction of soil fertilisation and vine harvesting (Table 5). Our results illustrated that vine harvesting reduced zinc and β-carotene nutritional yields for the storage root, relative to no vine harvesting. Generally, the reductions were larger under the well-fertilised treatment (zinc = 43%; β-carotene = 43%) compared to the control (zinc = 11%; β-carotene = 19%). Similarly, vine harvesting reduced total nutritional yields (storage root plus aboveground edible biomass) for zinc and β-carotene under the well-fertilised treatment. Without fertiliser, vine harvesting improved total β-carotene nutritional yield. For the same season (2013/14), there was a significant ($P < 0.05$) interaction between irrigation regime and soil fertilisation for β-carotene nutritional yields; mean values ranged from 11 to 18 kg β-carotene ha^{-1} (Table 5). Under well-watered conditions, total β-carotene nutritional yield declined from 18 to 11 kg β-carotene ha^{-1} when fertiliser was withheld, whereas under the supplemental irrigation regime, soil fertility had no effect on total β-carotene nutritional yield.

During the 2014/15 season, only zinc nutritional yields (storage root and total biomass) were affected ($P < 0.05$) by the interaction of soil fertilisation and vine harvesting (Table 5). However, the main effects (irrigation regime, fertilisation, and vine harvesting) were significant ($P < 0.05$) for β-carotene nutritional yields (storage root and total biomass). The well-watered regime improved both β-carotene nutritional yields (storage root = 25.3 kg ha^{-1}; total biomass = 25.5 kg ha^{-1}) compared to the supplemental irrigation regime (storage root = 18.6 kg ha^{-1}; total biomass = 18.9 kg ha^{-1}). Correspondingly, applying fertiliser enhanced both β-carotene nutritional yields (storage roots = 24.4 kg ha^{-1}; total biomass = 24.7 kg ha^{-1}) compared to no fertiliser application (storage roots = 19.5 kg ha^{-1}; total biomass = 19.7 kg ha^{-1}). Our results further revealed that vine harvesting reduced storage root β-carotene nutritional yield (from 28.1 to 15.8 kg ha^{-1}) and total biomass β-carotene nutritional yield (from 28.1 to 16.3 kg ha^{-1}). Zinc nutritional yields (storage root and total biomass) were affected ($P < 0.05$) by the interaction between soil fertilisation and vine harvesting; mean values ranged from 0.09 to 0.17 kg ha^{-1} for the storage root and 0.11 to 0.17 kg ha^{-1} for the total biomass. The 2014/15 results (for the effects of soil fertilisation and vine harvesting) were similar to the 2013/14 results. Firstly, vine harvesting reduced zinc nutritional yields (storage roots and total biomass) relative to no vine harvesting. Secondly, reductions were larger under well-fertilised conditions. In the 2014/15 season, iron nutritional yield for the storage root and iron nutritional yield for total biomass were not affected ($P > 0.05$) by the irrigation regime (Table 5). In contrast, zinc nutritional yield and β-carotene nutritional yield were affected ($P < 0.05$) by irrigation regime; the well-watered regime increased zinc nutritional yields (storage roots ≈ 43%; total biomass ≈ 38%) and β-carotene nutritional yields (≈ 26% for storage roots and total biomass) compared to the supplemental irrigation regime.

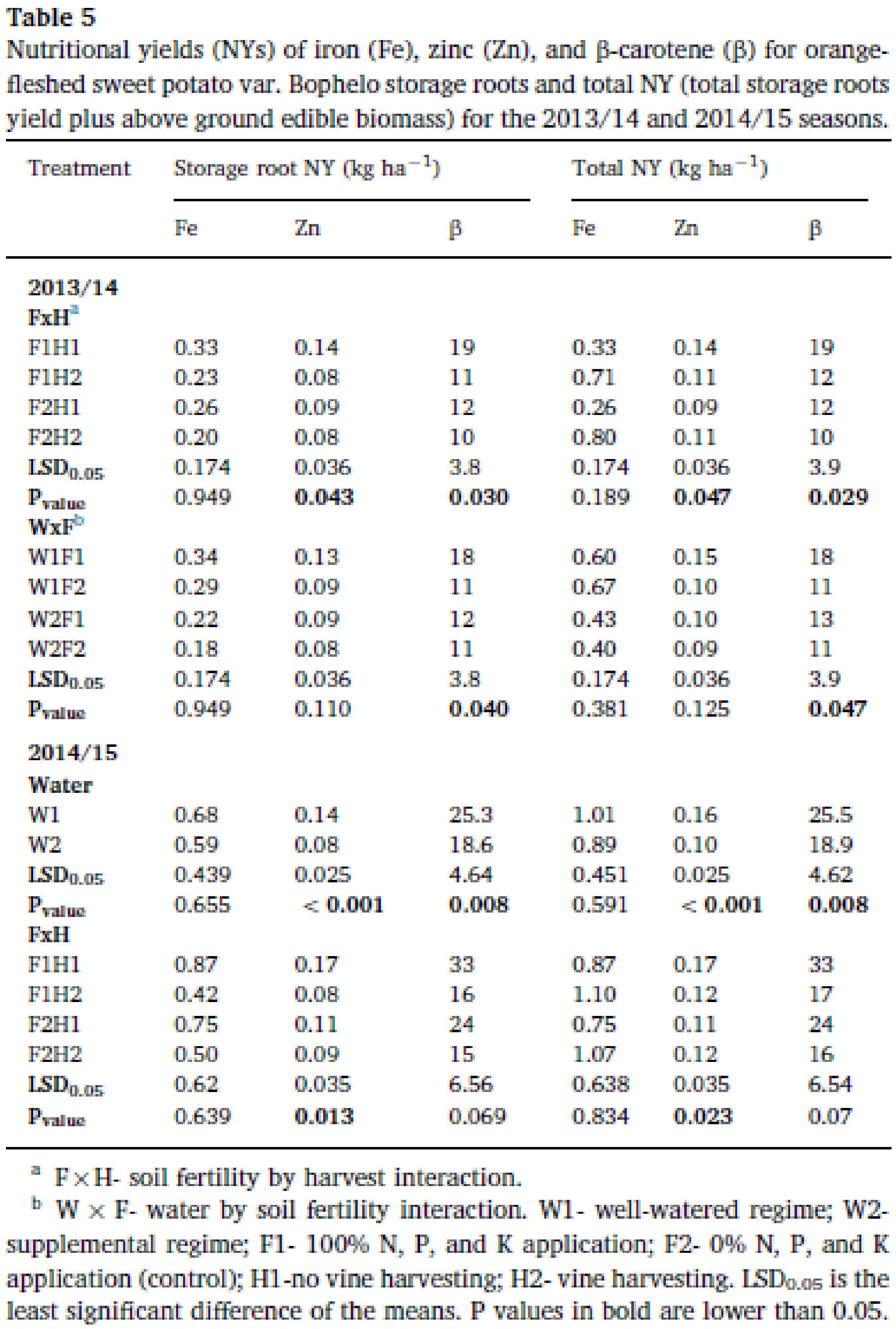

Table 5

Nutritional yields (NYs) of iron (Fe), zinc (Zn), and β-carotene (β) for orange-fleshed sweet potato var. Bophelo storage roots and total NY (total storage roots yield plus above ground edible biomass) for the 2013/14 and 2014/15 seasons.

Treatment	Storage root NY (kg ha^{-1})			Total NY (kg ha^{-1})		
	Fe	Zn	β	Fe	Zn	β
2013/14						
FxH[a]						
F1H1	0.33	0.14	19	0.33	0.14	19
F1H2	0.23	0.08	11	0.71	0.11	12
F2H1	0.26	0.09	12	0.26	0.09	12
F2H2	0.20	0.08	10	0.80	0.11	10
LSD$_{0.05}$	0.174	0.036	3.8	0.174	0.036	3.9
P$_{value}$	0.949	**0.043**	**0.030**	0.189	**0.047**	**0.029**
WxF[b]						
W1F1	0.34	0.13	18	0.60	0.15	18
W1F2	0.29	0.09	11	0.67	0.10	11
W2F1	0.22	0.09	12	0.43	0.10	13
W2F2	0.18	0.08	11	0.40	0.09	11
LSD$_{0.05}$	0.174	0.036	3.8	0.174	0.036	3.9
P$_{value}$	0.949	0.110	**0.040**	0.381	0.125	**0.047**
2014/15						
Water						
W1	0.68	0.14	25.3	1.01	0.16	25.5
W2	0.59	0.08	18.6	0.89	0.10	18.9
LSD$_{0.05}$	0.439	0.025	4.64	0.451	0.025	4.62
P$_{value}$	0.655	**< 0.001**	**0.008**	0.591	**< 0.001**	**0.008**
FxH						
F1H1	0.87	0.17	33	0.87	0.17	33
F1H2	0.42	0.08	16	1.10	0.12	17
F2H1	0.75	0.11	24	0.75	0.11	24
F2H2	0.50	0.09	15	1.07	0.12	16
LSD$_{0.05}$	0.62	0.035	6.56	0.638	0.035	6.54
P$_{value}$	0.639	**0.013**	0.069	0.834	**0.023**	0.07

[a] F × H- soil fertility by harvest interaction.

[b] W × F- water by soil fertility interaction. W1- well-watered regime; W2- supplemental regime; F1- 100% N, P, and K application; F2- 0% N, P, and K application (control); H1-no vine harvesting; H2- vine harvesting. LSD$_{0.05}$ is the least significant difference of the means. P values in bold are lower than 0.05.

Fig. A2 presents mean values of the amount of boiled orange-fleshed sweet potato (var. Bophelo) aboveground edible biomass harvested during the growing season to meet iron, zinc, and vitamin A daily-recommended nutrient intakes. Assessments showed that orange-fleshed sweet potato aboveground edible biomass could potentially contribute to the daily-recommended nutrient intake for iron and vitamin A, whereas it cannot meet the daily-recommended nutrient intake for zinc. This is mainly because of the large amounts of orange-fleshed sweet potato that are needed to be consumed. For example, under the highest input regime (well-watered and well-fertilised treatments), a family of six people would need to consume 2465 g per day (≈ 411 g per day for an individual) to meet iron nutritional requirements and 616 g per day (≈ 103 g per day for an individual) to meet vitamin A requirements. For zinc nutritional requirements, a family of six would need to consume an impossible 22096 g per day (≈ 3682 g per day for an individual) of boiled orange-fleshed aboveground edible biomass. It was interesting to realise that under the low input regime (water stressed and no fertiliser application growing conditions), daily iron and vitamin A nutritional requirements for a family of six people could still be met [≈ 2694 g per day for iron (449 g per day for an individual) and 642 g per day for vitamin A (107 g per day for an individual)].

3.4. Evapotranspiration, water productivity, and nutritional water productivity

For the 2013/14 and 2014/15 seasons, there was no significant interaction ($P > 0.05$) between irrigation regime, soil fertilisation, and vine harvesting for actual evapotranspiration (ET_a) (Fig. 2). However, ET_a values for different treatment combinations (Box 1) ranged from 427 to 491 mm for the well-watered treatment (2013/14 season) and from 592 to 658 mm for the 2014/15 season (Table A1). For the supplemental regime, ET_a of different treatment combinations ranged from 219 to 257 mm (2013/14 season) and from 439 to 467 mm for the 2014/15 season. There was no significant effect ($P > 0.05$) on water productivity of the treatments (irrigation regime, fertilisation, and vine harvesting) during both seasons (Table A1). For the 2013/14 season, two main effects (irrigation regime and soil fertilisation) were significant ($P < 0.05$) for water productivity. Our results showed that supplemental irrigation (35 kg DM ha^{-1} mm^{-1}) improved water productivity compared to the well-watered regime (22 kg DM ha^{-1} mm^{-1}). Correspondingly, the well-fertilised treatment (31 kg DM ha^{-1} mm^{-1}) had superior water productivity compared to the control (26 kg DM ha^{-1} mm^{-1}). For the 2014/15 season, all main effects (irrigation regime, soil fertilisation, and vine harvesting) were significant ($P < 0.05$) for water productivity. The results of the study illustrated that water productivity values were similar regardless of the main effect (W1 = 25 kg DM ha^{-1} mm^{-1} and W2 = 21 kg DM ha^{-1} mm^{-1}; F1 = 25 kg DM ha^{-1} mm^{-1} and F2 = 21 kg DM ha^{-1} mm^{-1}; and H1 = 25 kg DM ha^{-1} mm^{-1} and H2 = 21 kg DM ha^{-1} mm^{-1}). However, water productivity for irrigation regime displayed contradicting results compared to the 2013/14 season; the well-watered regime indicated water productivity superior to that of the supplemental regime. In addition, our results displayed that vine harvesting reduced water productivity.

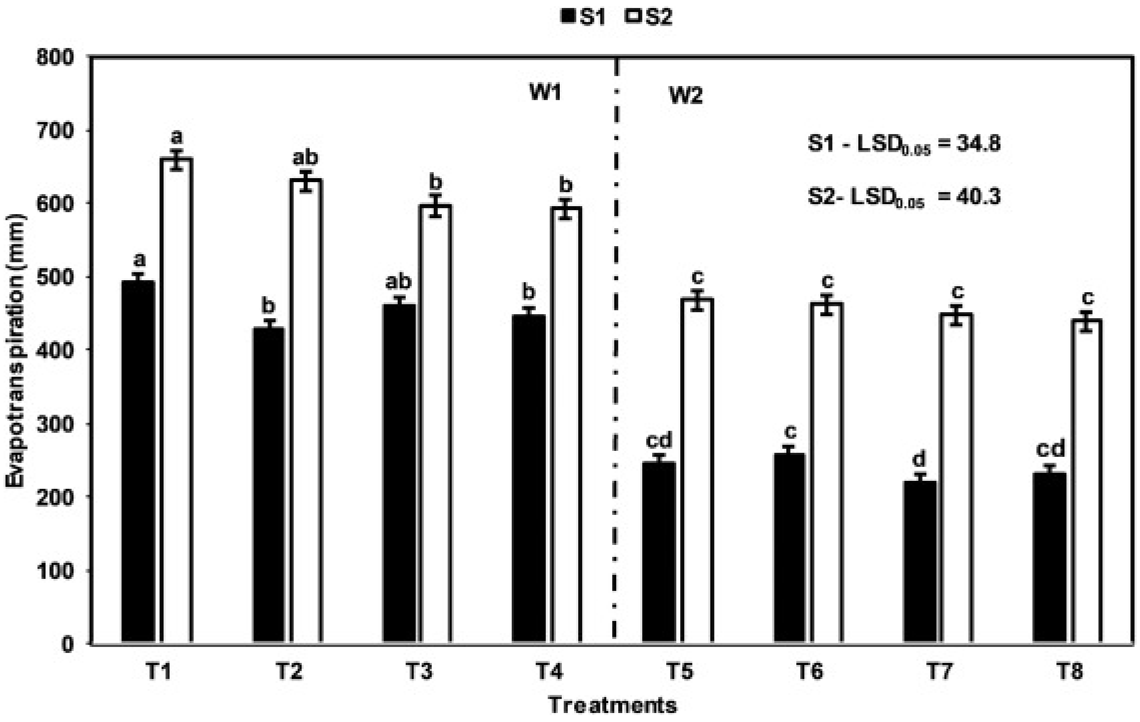

Fig. 2. Actual evapotranspiration for S1 (2013/14 season) and S2 (2014/15 season); T1 to T8 represents treatment combinations (Box 1); W1- well-watered regime, W2- supplemental regime, F1- 100% N, P, and K application, F2- 0% N, P, and K application (control), H1- no vine harvesting; H2- vine harvesting. Averages within a season accompanied by the same letter are not significantly different.

Box 1
Treatments combinations for Fig. 2.

T1- W1F1H1; T2-W1F1H2; T3-W1F2H1;T4-W1F2H2; T5-W2F1H1; T6-W2F1H2; T7- W2F2H1; T8- W2F2H2

Table 6 presents iron, zinc, and β-carotene nutritional water productivities for both storage root and total biomass (storage root plus the aboveground edible biomass) (2013/14 and 2014/15 seasons). Irrigation regime did not affect ($P > 0.05$) iron nutritional water productivities (storage root and total biomass); however, zinc and β-carotene nutritional water productivities were affected ($P < 0.05$) by irrigation regime (2013/14 season). Our results showed that the supplemental irrigation regime improved storage root nutritional water productivity (≈ 50% for zinc and ≈ 56% for β-carotene) and total biomass nutritional water productivity (≈ 52% for zinc and ≈ 56% for β-carotene), relative to the well-watered regime. Vine harvesting affected ($P < 0.05$) iron and β-carotene nutritional water productivities for the storage root and total biomass, except for zinc total biomass nutritional water productivity ($P = 0.383$). Generally, vine harvesting reduced nutritional water productivity for both storage root and total biomass [except for the huge increase shown by total biomass iron nutritional water productivity [60%)) compared to no vine harvesting (2013/14 season)]. In the 2014/15 season, water regimes affected only zinc nutritional water productivity for the storage root ($P = 0.045$) significantly; there was no effect ($P > 0.05$) for other storage root nutritional water productivities (iron and β-carotene) and total biomass nutritional water productivities (iron, zinc, and β-carotene). Our results showed that storage root zinc nutritional water productivity decreased under the supplemental irrigation regime, relative to the well-watered regime. Iron nutritional water productivities (storage root and total biomass) were not affected ($P > 0.05$) by vine harvesting, whereas zinc and β-carotene nutritional water productivity were affected ($P < 0.05$) by vine harvesting. The results of this study showed that the vine harvesting treatment reduced both nutritional water productivities for zinc (storage roots = 63% and total biomass = 18%) and β-carotene (storage roots = 72% and total biomass = 66%), relative to the no vine harvesting treatment.

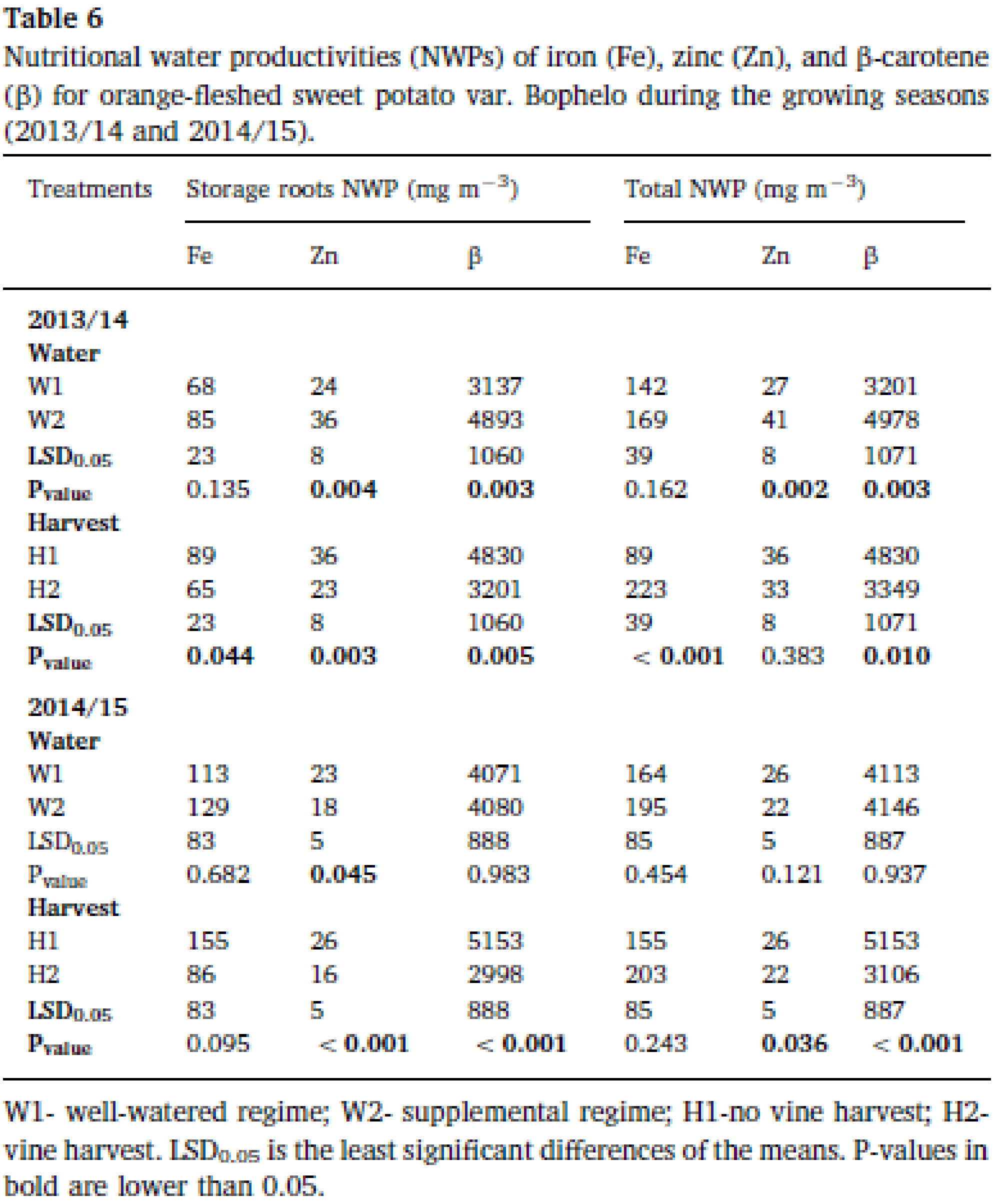

Table 6

Nutritional water productivities (NWPs) of iron (Fe), zinc (Zn), and β-carotene (β) for orange-fleshed sweet potato var. Bophelo during the growing seasons (2013/14 and 2014/15).

Treatments	Storage roots NWP (mg m^{-3})			Total NWP (mg m^{-3})		
	Fe	Zn	β	Fe	Zn	β
2013/14						
Water						
W1	68	24	3137	142	27	3201
W2	85	36	4893	169	41	4978
$LSD_{0.05}$	23	8	1060	39	8	1071
P_{value}	0.135	**0.004**	**0.003**	0.162	**0.002**	**0.003**
Harvest						
H1	89	36	4830	89	36	4830
H2	65	23	3201	223	33	3349
$LSD_{0.05}$	23	8	1060	39	8	1071
P_{value}	**0.044**	**0.003**	**0.005**	**< 0.001**	0.383	**0.010**
2014/15						
Water						
W1	113	23	4071	164	26	4113
W2	129	18	4080	195	22	4146
$LSD_{0.05}$	83	5	888	85	5	887
P_{value}	0.682	**0.045**	0.983	0.454	0.121	0.937
Harvest						
H1	155	26	5153	155	26	5153
H2	86	16	2998	203	22	3106
$LSD_{0.05}$	83	5	888	85	5	887
P_{value}	0.095	**< 0.001**	**< 0.001**	0.243	**0.036**	**< 0.001**

W1- well-watered regime; W2- supplemental regime; H1-no vine harvest; H2-vine harvest. $LSD_{0.05}$ is the least significant differences of the means. P-values in bold are lower than 0.05.

4. Discussion

This study evaluated the potential of utilising orange-fleshed sweet potato (var. Bophelo) as a dual-purpose food crop; producing a green leafy vegetable and storage roots for human consumption. The well-watered orange-fleshed sweet potato produced the highest storage root yields (total storage root and marketable storage root) for both seasons; however, the 2014/15 season gave a larger storage root yield than the 2013/14 season (Fig. 1b and e). This resulted because, firstly, the 2014/15 season received more and better-distributed rain compared to the 2013/14 season (Fig. 1a). Secondly, in the 2013/14 season, storage roots were harvested ≈ 130 days after planting, whereas in 2014/15, the growing season was almost two months longer, with harvest ≈ 180 days after planting; therefore, more solar radiation was intercepted during the 2014/15 season than during the 2013/14 season, resulting in higher productivity. We made a calculation of orange-fleshed sweet potato productivity per day for the well-managed treatment (well-watered, full fertilisation, and no vine harvesting) based on the assumption that storage root formation starts at ≈ 52 days after planting. Our findings indicated that orange-fleshed sweet potato productivity per day was the same for both seasons (at 132 kg DM ha^{-1} day^{-1} in 2013/14 and 133 kg DM ha^{-1} day^{-1} in 2014/15.) During the 2013/14 season, storage root yields for the well-watered and the supplemental irrigation treatments were similar (Fig. 1b and e). Perhaps the length (130 days) of the growing season caused the similarity in that the duration of water stress was shorter during the 2013/14 season than for the 2014/15 season where there was a clear difference in storage root yield between the two water treatments (Fig. 1b and e).

Vine harvesting reduced storage root yields (total storage root and marketable storage root), as found in studies by Gomes and Carr (2001,a) and Van An et al. (2003). This authenticates our hypothesis that vine harvesting of orange-fleshed sweet potato reduces storage root yield. The 2014/15 results of this study showed that under low input management (supplemental rather than full irrigation and no fertiliser application); storage root production (total storage root and marketable storage root) was reduced (Fig. 1b–f). In addition, our results highlighted that when considering orange-fleshed sweet potato as a dual-purpose food crop, trade-off considerations have to be made. For example, utilising orange-fleshed sweet potato as a dual-purpose food crop is not an ideal practice for market-oriented farming; the loss of marketable storage root was ≈ 50% under well-fertilised conditions (Fig. 1f). For subsistence-oriented farming (rural resource-poor households), using orange-fleshed sweet potato as a dual-purpose food crop makes more sense, as the aboveground edible biomass is available for consumption during the growing season (Table A1). At the end of the growing season, storage roots can then be consumed. However, the consequence of vine harvesting is a reduction in the total storage root yield (Fig. 1c). Our results indicated that without fertiliser application, total storage root productivity declined from 7.8 to 6.7 t DM ha^{-1}, whereas under full fertilisation, the penalty of vine harvesting was higher; total storage root yield dropped from 11.6 to 7.1 t DM ha^{-1}. This implies that for subsistence-oriented-farming, soil fertilisation combined with vine harvesting is not an ideal practice because the reduction in total storage root yield is huge. The grand mean results of this study further displayed that the vine harvesting treatment reduced iron, zinc, and β-carotene concentrations of the storage root (Table 4), in line with our hypothesis. This has implications for nutritional food security of rural resource-poor households. The loss in nutrients of harvested storage root caused by vine harvesting was compensated by the availability of highly nutritious green aboveground edible biomass, which rural resource-poor households can consume as a relish with maize porridge (Mavengahama et al., 2013). In the winter season, the storage root becomes available for consumption; this spreads food availability over a longer period, thereby improving the nutritional food security of rural resource-poor households.

We expected that vine harvesting of orange-fleshed sweet potato would reduce storage root nutritional yield. Our results concurred with our hypothesis; however, vine harvesting improved total nutritional yields of iron and zinc, whereas there was a minimal increase for total β-carotene nutritional yield (Table 5). This is mainly because the aboveground edible biomass of orange-fleshed sweet potato contributed the least amount of β-carotene to the total nutritional yield. Irrigation and fertiliser application are considered important inputs that determine nutritional yields of iron, zinc, and β-carotene (Laurie et al., 2012a). The results of this study agreed with our expectations that high inputs (well-fertilised and well-watered treatments) improve the nutritional yield of selected nutrients. This agrees with Laurie et al. (2012a) findings, which showed that optimum management is the best for an improved nutritional yield of the storage root (Table 5). However, the consequence of vine harvesting combined with no fertiliser application is a reduction in total nutrients that can be harvested; it was reduced by ≈ 42% for iron, ≈ 45% for zinc, and ≈ 52% for β-carotene, relative to no vine harvesting and fertiliser application. Similarly, vine harvesting combined with supplemental irrigation resulted in the reduction of nutrients by ≈ 47% for iron, ≈ 38% for zinc, and ≈ 39% for β-carotene, relative to no vine harvesting and full irrigation. Laurie et al. (2012a) showed that planting one hectare of sweet potato by community members is feasible. For boiled orange-fleshed sweet potato total storage root, assessments showed that the number of people one could feed for a period of 90 days from one hectare for the requirements of iron and zinc is very low under high input (iron = 7 people and zinc = 4 people) and low input (iron = 7 people and zinc = 2 people) optimization (Table A2). Practically, this suggests that people would need to consume huge amounts of boiled orange-fleshed sweet potato storage root to meet their daily iron and zinc dietary requirements; therefore, the storage root cannot be recommended as a food source for iron and zinc. However, for β-carotene, one hectare of orange-fleshed sweet potato storage root could potentially supply 1570 (≈ 262 households) people with the required amount of vitamin A for a period of 90 days, under high input regime. The number of households that can be fed for vitamin A requirement were reduced by ≈ three-fold under the low input regime (Table A2). Our results showed that treatments (irrigation regime, soil fertilisation, and vine harvesting) did not affect β-carotene potential contribution to the daily-recommended nutrient intake for all age groups; under the low input management, storage roots could still provide more than the daily-recommended nutrient requirements by ≈ 6-fold (Table A3). A study conducted by Nyathi et al. (2018b) indicated that boiled aboveground edible biomass of Amaranth (*Amaranthus cruentus*) and Spider flower (*Cleome gynandra*) could potentially meet human nutritional requirements for iron and zinc. To consume a balanced diet that can alleviate micronutrients deficiency (iron, zinc, and vitamin A), we recommend that rural resource-poor households should prepare a side dish made up of orange-fleshed sweet potato plant tissues (storage root and the aboveground biomass), combined with Amaranth and Spider flower.

The main aim of the water productivity concept is to produce “more crop’’ with limited water use (actual evapotranspiration) (Nyathi et al., 2018b). Our results (2013/14) concurred with other studies (Chimonyo et al., 2016; Laurie et al., 2012a; Mabhaudhi et al., 2013; Motsa et al., 2015; Nyathi et al., 2018b) that showed superior water productivity for sorghum (*Sorghum bicolor*), taro (*Colocasia esculenta*), sweet potato (*Ipomoea batatas*), and selected leafy vegetables [Amaranth (*Amaranthus cruentus*), Spider flower (*Cleome gynandra*), and Swiss chard (*Beta vulguris*)] under water stress and well-fertilised conditions. The results of this study further revealed that there was a variation in water productivity between seasons; the 2014/15 results indicated lower water productivity compared to the 2013/14 season (Table A4). In addition, water productivity results for the

2014/15 season exhibited contrary results compared with the 2013/14 season; the well-watered regime and soil fertilisation improved water productivity. We expected consistency in terms of the effect of water stress and soil fertilisation on water productivity for both seasons. The difference in water productivity for both seasons might have been caused by different meteorological conditions (temperature, rain, radiation, and vapour pressure deficit) (Table 2) and the length of the growing season (Steduto et al., 2007). Chibarabada et al. (2017) averred that water use in agriculture, crop production, and nutritional requirements are assessed in isolation; this procedure is not ideal because of the three aspects interlink. Several studies (Chibarabada et al., 2017; Mdemu et al., 2009; Nyathi et al., 2018b; Renault and Wallender, 2000) have assessed nutritional water productivity [NWP (an index that combines aspects of water use, crop production, and human nutrition)] of selected crops [cowpea (*Vigna unguiculata*), Bambara groundnut (*Vigna subterranea*), dry bean (*Phaseolus vulgaris*), groundnut (*Arachis hypogaea*), tomato (*Solanum lycopersicum*), rice (*Oryza sativa*), onion (*Allium cepa*), amaranth (*Amaranthus cruentus*), spider flower (*Cleome gynandra*), Swiss chard (*Beta vulgaris* var. Fordhook giant)]. As far as can be ascertained, our study is the first attempt to assess iron, zinc, and β-carotene nutritional water productivities of orange-fleshed sweet potato var. Bophelo [storage root and total edible biomass (storage root plus the aboveground edible biomass)] using datasets [storage root yield, aboveground edible biomass, evapotranspiration, and nutrient concentrations (iron, zinc, and β-carotene)] from the same experiment; therefore, this study serves as a benchmark. The mean for both seasons (2013/14 and 2014/15) displayed superior nutritional water productivities (storage root and total biomass) under the supplemental irrigation regime (Table 6). Interestingly, total nutritional water productivity was higher than the storage root nutritional water productivity. In addition, the mean for both seasons displayed that nutritional water productivity (iron, zinc, and β-carotene) for the storage root and total edible biomass, declined under the practice of vine harvesting (Table 6). This highlights that some compromises have to be made when considering orange-fleshed sweet potato as a dual-purpose food crop.

Quite surprisingly, utilising orange-fleshed sweet potato as a dual-purpose food crop can be recommended because selected micronutrients and β-carotene nutritional productivities were maximised per unit water used. Our results illustrated that considering orange-fleshed sweet potato as a dual-purpose food crop required less water to meet total human nutrition requirements (iron = 942 litres person^{-1} day^{-1}, zinc = 3915 litres person^{-1} day^{-1}, β-carotene = 12 litres person^{-1} day^{-1}) under low input management (Fig. A3b and c). In contrast, considering orange-fleshed sweet potato as a storage root only (Fig. A3a and c) required more water to meet total human nutrition requirements (iron = 3561 litres person^{-1} day^{-1}, zinc = 6091 litres person^{-1} day^{-1}, and β-carotene = 13 litres person^{-1} day^{-1}). Limited information exists on nutritional water productivity of crops; a study by Nyathi et al. (2018b) reported nutritional water productivity values for selected leafy vegetables ranging from 226 to 1323 mg m^{-3} for iron, 60 to 160 mg m^{-3} for zinc, and 365 to 1886 mg m^{-3} for β-carotene. At a glance, this suggests that selected leafy vegetables are more productive than orange-fleshed sweet potato storage root in terms of iron and zinc nutritional water productivities. However, caution has to be exercised when comparing leafy vegetables and orange-fleshed sweet potato storage root; the duration of the growing season differs. Sweet potato maximum growing period is ≈ 180 days, whereas for leafy vegetables it is ≈ 100 days. Therefore, orange-fleshed sweet potato utilises more water (219–658 mm) than leafy vegetables (147–457 mm) to produce selected micronutrients. This highlights the importance of crop diversification in meeting human nutrition requirements with less water consumed. For example, leafy vegetables are superior in iron and zinc per unit of water used, whereas orange-fleshed sweet potato is rich in β-carotene per unit of water used. A diet consisting of leafy vegetables and orange-fleshed sweet potato (leaves and storage root) will reduce the amount of water used to produce iron, zinc, and β-carotene.

5. Conclusions

This study showed that there is an opportunity of utilising orange-fleshed sweet potato var. Bophelo as a dual-purpose food crop (green leafy vegetable and staple storage root for human consumption). Our results showed that the dual use of orange-fleshed sweet potato is not ideal for market-oriented farming, because marketable storage root yield decreased by half. In contrast, the dual use of orange-fleshed sweet potato can be considered for less market-oriented rural resource-poor households; the leaves could provide fresh greens for home consumption or for sale, in addition to the storage root. This spreads food availability over a longer period, hence an improvement in the nutritional food security of rural resource-poor households. However, the consequence of the dual use of orange-fleshed sweet potato is the reduction in total storage root yield, whose effect depends on soil fertilisation [no fertiliser application (7.8 to 6.7 t DM ha^{-1}) and N, P and K fertiliser application at a recommended rate (11.6–7.1 t DM ha^{-1})]. With vine harvesting, total storage root yield was reduced and total nutritional yield (iron, zinc, and β-carotene) was improved. The mean results for both seasons showed higher iron nutritional yield (0.94 kg DM ha^{-1}) under the practice of vine harvesting combined with no fertiliser application; the highest zinc (0.16 kg DM ha^{-1}) and β-carotene (26 kg DM ha^{-1}) nutritional yields were obtained under the practice of no vine harvesting combined with the well-fertilised treatment. Assessments showed that orange-fleshed sweet potato storage root cannot be recommended for iron and zinc dietary requirements, because of the huge amounts that need to be consumed; however, the storage root can meet vitamin A human nutritional requirements for all age groups even under the low input regime (water stressed and no fertiliser application conditions). It was interesting to note that more water was needed to meet the daily-recommended nutrient intake (iron, zinc, and β-carotene) if orange-fleshed sweet potato was grown for its storage root than when it was grown as a dual-purpose food crop. This highlights that nutritional water productivities of rural resource-poor households can be maximised. These results have to be taken into consideration when making decisions about the nutritional food security of rural resource-poor households. Future research is needed to confirm these findings across a large set of orange-fleshed sweet potato varieties that might respond differently to vine harvesting for selected plant parameters (storage root yield, evapotranspiration, water productivity, nutrient concentration, nutritional yield, and nutritional water productivity). This research should be conducted on the farm so that suitable varieties are selected for the dual use of orange-fleshed sweet potato. Rural resource-poor households are encouraged to produce orange-fleshed sweet potato for their own consumption and any surplus could be sold at the local market. We recommend that crop growth models such as AquaCrop, the Soil Water Balance (SWB) model, the Agricultural Production System Simulator (APSIM), and the World Food Studies (WOFOST) model should be calibrated and validated using field experimental data for the aboveground biomass, storage root yield, evapotranspiration, and water productivity. This will make the results of this study more generic and applicable to various locations.

Acknowledgements

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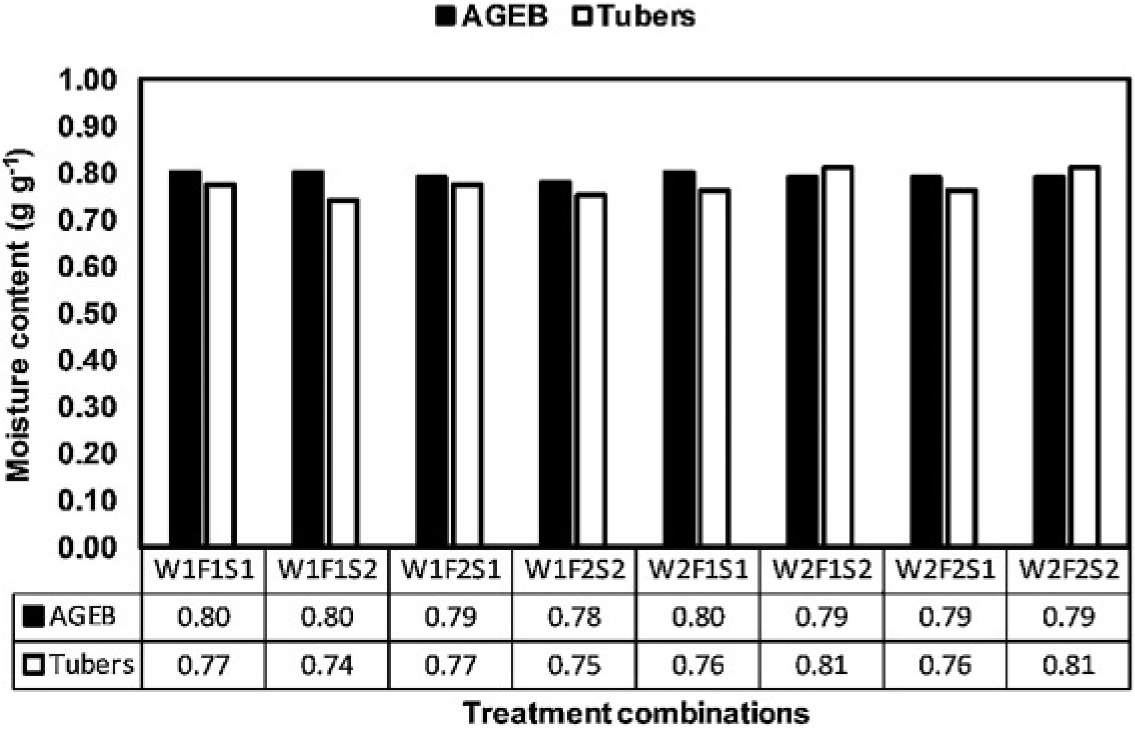
Appendix A



	W1F1S1	W1F1S2	W1F2S1	W1F2S2	W2F1S1	W2F1S2	W2F2S1	W2F2S2
■AGEB	0.80	0.80	0.79	0.78	0.80	0.79	0.79	0.79
□Tubers	0.77	0.74	0.77	0.75	0.76	0.81	0.76	0.81

Fig. A1. Moisture content values for aboveground edible biomass (AGEB) and storage root (Tubers) for orange-fleshed sweet potato var. Bophelo.

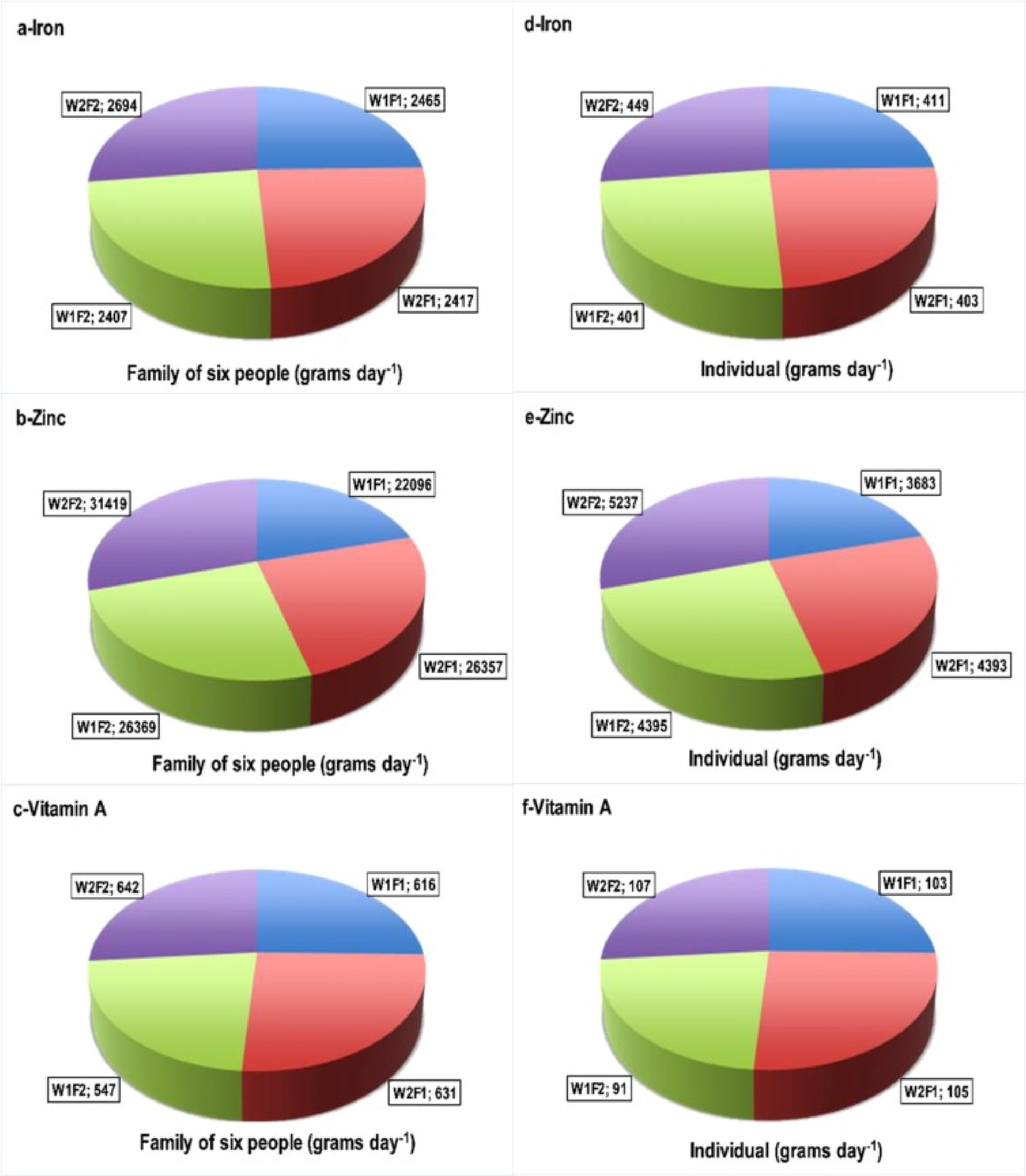


Fig. A2. The amount of boiled orange-fleshed sweet potato (var. Bophelo) aboveground edible biomass harvested during the growing seasons to meet iron, zinc, and vitamin A daily-recommended nutrient intakes for a family of six people (one male adult; one female adult; two 1–3 year infants; two 4–9 year old children). Irrigation regime [(W1-well-watered, W2-supplemental) and soil fertility [(F1- 100% N, P, and K application, F2-0% N, P, and K application)].

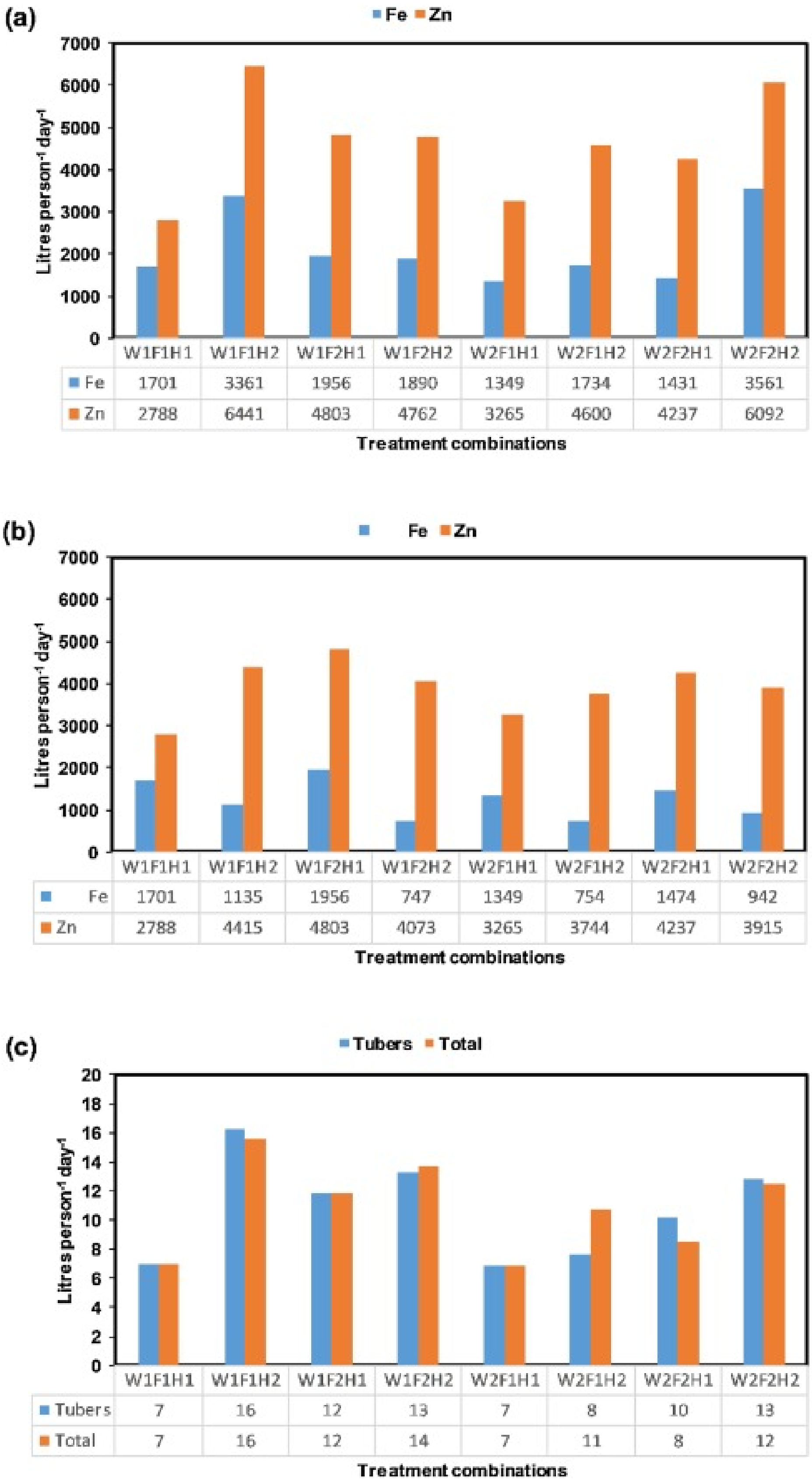


Fig. A3. The amount of water needed (Litres person^{-1} day^{-1}) to meet human nutrition requirements for iron (Fe), zinc (Zn), and vitamin A (β-Carotene). **a** is for Fe and Zn in storage root; **b** is for Fe and Zn in total (storage roots plus aboveground biomass harvested during the growing seasons), and **c** is for vitamin A [storage roots (Tubers) and Total (storage roots plus aboveground biomass harvested during the growing seasons)].

Table A1

Treatment effects (water regime, soil fertilisation, and vine harvesting) on biomass (dry mass) and other selected plant parameters during the two growing seasons (2013/14 and 2014/15).

Treatments	AGEB[a] t ha^{-1}	Tuber[b] t ha^{-1}	Total AGB[c] t ha^{-1}	Total BM[d] t ha^{-1}	HI[e] unit less	ET$_a$[f] mm	WP[g] kg ha^{-1} mm^{-1}
2013/14							
W1F1H1	n.d[h]	10.0 (2.19)	2.5 (0.12)	13.0 (2.16)	0.80 (0.03)	491 (19)	26 (4.4)
W1F1H2	1.0 (0.12)	5.7 (0.30)	4.4 (0.20)	10.0 (0.13)	0.57 (0.02)	427 (28)	24 (1.5)
W2F1H1	n.d	5.8 (1.27)	2.4 (0.33)	8.2 (1.57)	0.70 (0.03)	244 (5.9)	34 (7.1)
W2F1H2	1.1 (0.08)	5.8 (1.04)	3.0 (0.30)	8.7 (1.20)	0.66 (0.04)	257 (6.7)	34 (5.1)
W1F2H1	n.d	8.1 (1.73)	1.9 (0.44)	10.0 (2.16)	0.81 (0.01)	460 (24)	22 (4.3)
W1F2H2	0.9 (0.10)	4.7 (0.67)	4.1 (0.32)	8.8 (0.55)	0.53 (0.05)	446 (11)	20 (1.6)
W2F2H1	n.d	5.9 (0.89)	1.2 (0.17)	7.1 (1.04)	0.83 (0.01)	218 (14)	33 (5.8)
W2F2H2	0.9 (0.23)	4.4 (1.18)	3.0 (0.42)	7.4 (0.76)	0.58 (0.10)	231 (3.8)	32 (3.8)
2014/15							
W1F1H1	n.d	17.0 (0.39)	2.6 (0.22)	2.00 (0.51)	0.87 (0.01)	658 (17)	30 (1.4)
W1F1H2	1.5 (0.05)	11.0 (3.41)	3.4 (0.20)	14.0 (3.36)	0.75 (0.07)	629 (40)	22 (3.9)
W2F1H1	n.d	13.0 (1.70)	2.1 (0.04)	15.0 (1.70)	0.86 (0.02)	467 (2.6)	32 (3.8)
W2F1H2	1.3 (0.06)	11.0 (2.17)	3.2 (0.23)	14.0 (2.36)	0.78 (0.03)	462 (8.2)	31 (5.4)
W1F2H1	n.d	11.0 (2.45)	1.9 (0.37)	13.0 (2.80)	0.85 (0.01)	595 (17)	22 (4.8)
W1F2H2	1.3 (0.10)	7.1 (0.43)	2.8 (0.24)	10.0 (0.19)	0.72 (0.03)	592 (23)	17 (0.6)
W2F2H1	n.d	6.5 (0.41)	1.7 (0.19)	8.2 (0.38)	0.79 (0.02)	447 (7.7)	18 (1.1)
W2F2H2	1.2 (0.12)	5.2 (1.56)	2.5 (0.34)	7.7 (1.90)	0.67 (0.04)	439 (8.0)	18 (4.4)

Values in brackets present the standard deviation of the means. W1- well-watered regime; W2- Supplemental regime; F1- 100% N, P, and K application; F2- 0% N, P, and K application.

[a] AGEB- aboveground edible biomass.

[b] Tuber- storage root.

[c] Total AGB- total aboveground biomass.

[d] Total biomass (storage root plus aboveground biomass).

[e] HI- harvest index (computed as the ratio of storage root divided by total biomass).

[f] ETa- actual evapotranspiration.

[g] WP- water productivity.

[h] n.d means there are no data values for the no vine harvesting since the leaves are not consumed.

Table A2

Number of people (iron, zinc, and β-carotene) and households (β-carotene) that one hectare of orange-fleshed sweet potato var. Bophelo could possibly feed (fresh edible portion) for a period of ninety days.

Treatments	Iron		Zinc		β-carotene		β-carotene	
	Tuber People	Total People	Tuber People	Total People	Tuber People	Total People	Tuber Households	Total Households
W1F1H1	7	7	4	4	1570	1570	262	262
W1F1H2	3	9	2	2	598	627	100	104
W1F2H1	6	6	2	2	994	994	166	166
W1F2H2	6	13	2	2	756	735	126	123
W2F1H1	6	6	2	2	937	937	156	156
W2F1H2	4	9	2	2	717	635	120	106
W2F2H1	4	4	2	2	707	707	118	118
W2F2H2	2	7	1	2	491	496	82	83
Mean	**5**	**8**	**2**	**2**	**846**	**838**	**141**	**140**

Table A3

Mean values across 2013/14 and 2014/15 seasons of the estimated percentage nutrient contribution of orange-fleshed sweet potato (var. Bophelo) aboveground edible biomass (AGEB) and storage root of the daily recommended nutrient intake for four groups on the basis of 100 g fresh boiled product intake per person per day.

	AGEB (H2)				Storage roots (H1)				Storage roots (H2)			
	Infants	Children	Male adults	Female adults	Infants	Children	Male adults	Female adults	Infants	Children	Male adults	Female adults
Iron	%	%	%	%	%	%	%	%	%	%	%	%
W1F1	87	15	37	17	8.9	1.6	3.8	1.7	9	2	2	2
W1F2	105	19	44	20	12.5	2.2	5.3	2.4	12	2	2	2
W2F1	82	15	35	16	10.8	1.9	4.6	2.1	10	2	2	2
W2F2	82	15	35	16	13.9	2.5	5.9	2.7	6	1	2	1
Zinc												
W1F1	6	3	4	5	2.2	1.3	1.3	1.9	1.8	1.1	1.1	1.6
W1F2	9	5	5	7	1.8	1.0	1.1	1.5	1.9	1.1	1.1	1.6
W2F1	7	4	4	6	1.7	1.0	1.0	1.4	1.5	0.9	0.9	1.3
W2F2	4	2	2	4	1.9	1.1	1.2	1.6	1.6	0.9	1.0	1.4
β-Carotene												
W1F1	117	78	78	93	815	543	543	652	691	461	461	553
W1F2	158	106	106	127	711	474	474	568	621	414	414	497
W2F1	138	92	92	110	674	449	449	539	660	440	440	528
W2F2	145	97	97	116	795	530	530	636	662	441	441	529

Calculations of micronutrient concentrations and Vitamin A were conducted on fresh mass basis. W1- well-watered regime and W2- supplemental regime; F1- 100% N, P, and K application and F2- 0% N, P, and K application; H1- no vine harvesting and H2- vine harvesting. The four age groups are infants (1–3 years), children (4–18 years), male adults (19–65 years), and female adults (19–65 years).

Table A4
Storage root and total (storage root plus the aboveground edible biomass) nutritional water productivities (NWP) of iron (Fe), zinc (Zn), and β-Carotene (β) for orange-fleshed sweet potato var. Bophelo during the two growing seasons (2013/14 and 2014/15).

Season x treatment	Storage root NWP (mg m^{-3})			Total NWP (mg m^{-3})		
	Fe	Zn	β	Fe	Zn	β[a]
2013/14						
W1F1H1	84	35	4906	84	35	4906
W1F1H2	61	21	2875	186	29	2974
W1F2H1	64	18	2401	64	18	2401
W1F2H2	63	20	2367	235	28	2524
W2F1H1	99	**46**	**6119**	99	**46**	**6119**
W2F1H2	80	24	5893	**246**	35	4004
W2F2H1	**107**	45	3838	107	45	3838
W2F2H2	55	28	3724	226	39	3894
2014/15						
W1F1H1	116	**33**	5675	116	**33**	5675
W1F1H2	60	16	2689	170	24	2775
W1F2H1	135	23	4665	135	23	4665
W1F2H2	139	20	3256	**236**	22	3338
W2F1H1	**210**	27	**5966**	210	27	**5966**
W2F1H2	99	15	3336	235	22	3468
W2F2H1	160	19	4307	150	19	4307
W2F2H2	47	13	2712	174	21	2845

The values represent the interaction of irrigation regime [(W1-well-watered, W2-supplemental), soil fertility [(F1- 100% N, P, and K application, F2- 0% N, P, and K application)], and harvest [(H1- no vine harvest, H2- vine harvest)] for the 2013/14 and 2014/15 growing seasons. Values in bold are the highest values within a column.

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