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Exploring the yield gap of orange-fleshed sweet potato varieties on smallholder farmers' fields in Malawi

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ABSTRACT

Orange-fleshed sweet potato (OFSP) can contribute to combating vitamin A deficiency and establishing more resilient cropping systems in sub-Saharan Africa. There is limited understanding of the factors that affect yield and quality of OFSP on smallholder farmers' fields. This study aimed to assess the performance of six OFSP varieties, identify factors limiting productivity and explore options to close the gap between actual and attainable OFSP yields on fields of smallholder farmers. Data were collected in the 2015/16 growing season from 221 on-farm variety demonstrations in seven districts in Central and Southern Malawi. Dependent variables of interest included crop establishment, vine yields, storage root formation, root yields, percentage of marketable root yield, and weevil infestation. Using linear mixed models, a range of biophysical, climatic, management and socio-economic factors and variables was used to identify associations with these dependent variables. The root yield gap was explored using a multivariate boundary line model to identify the most yield limiting factors. Results show a large variability across farmers' fields and a wide range of interacting factors affecting the variables of interest. Varieties Chipika and Kadyaubwerere attained good yields and were preferred by farmers in terms of taste. Varieties Zondeni and Anaakwanire gave a poor root yield, but a good vine yield. Timely planting is crucial to attain good root yields by making better use of the available rainfall. There was a varietal effect on weevil infestation and Kaphulira was most affected. Weevil control is required for market-oriented producers to enhance the percentage of marketable roots. The average attainable fresh root yield ranged from 18 t ha^{-1} for Zondeni to 32 t ha^{-1} for Mathuthu, against actual yields of 5–9 t ha^{-1}. Elevation, planting date, rainfall and crop establishment could explain only 28 percent of the average yield gap, while 49 percent was explained for Mathuthu. Other factors that may explain the yield gap, but were not included in the model are: tillage methods and soil nutrient limitations. Male host farmers received better quality cuttings and planted in better soil moisture conditions, resulting in better establishment and vine yields. OFSP productivity can be enhanced through gender-sensitive extension, by ensuring male and female farmers can plant clean planting material of a suitable variety early in the rainy season. This requires additional efforts in vine multiplication of the required variety prior to the onset of the rains.

1. Introduction

The population in sub-Saharan Africa is expected to increase 2.5-fold and the demand for cereals to triple by 2050, indicating a pressing need to close yield gaps and increase cropping intensity to reduce future dependence on food imports (van Ittersum et al., 2016). At the same time food systems should not only feed the population, but also provide affordable nutritious diets (Haddad et al., 2016). Micronutrient deficiencies are a major health concern in Sub-Saharan Africa caused by a lack of crop diversity, limited access to markets with nutritious food and consequently limited dietary diversity (Luckett et al., 2015). Sweet potato (*Ipomoea batatas* [L.] Lam) fits well in this context, since it is widely produced and rich in carbohydrates, protein, calcium, iron, potassium, carotenoids, dietary fiber, and vitamins (especially C, folate, and B_6), and very low in fat and sodium (Bovell-Benjamin, 2007). Sweet potato production in Africa has doubled from 1.0 to 2.0 million tons between 2002 and 2012 (FAO, 2017). Predominantly white or yellow fleshed varieties are cultivated, while orange-fleshed sweet potato (OFSP) is rich in beta-carotene which is converted into vitamin A in the human body (Low et al., 2017). Vitamin A is an essential nutrient that

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prevents blindness in children and pregnant women. It is deficient among people in most sub-Saharan African countries, which results in increased risks of severe infections and even death from common diseases such as diarrhea and measles (WHO, 2017). Promotion of OFSP has proven to be an effective food based approach to increase vitamin A intake and serum retinol concentrations in young children in rural Mozambique (Low et al., 2007). As a result of a growing evidence base on the effectiveness of OFSP to improve nutritional status (Tanumihardjo et al., 2017), to date 42 OFSP varieties have been bred in Africa (Low et al., 2017). Sweet potato in Africa is perceived as a drought tolerant food security crop (Motsa et al., 2015). Mass relief distributions of planting material to drought-, flood- or conflict-affected households are common (Kapinga et al., 2005). There is limited awareness on the potential of sweet potato as a viable cash crop. Consumers that were well informed about the nutritional benefits were willing to pay 51% more for OFSP than for white-fleshed sweet potato in Mozambique (Naico and Lusk, 2010) and 25% more in Uganda (Chowdhury et al., 2011), while without prior nutritional information this is not the case. This corresponds with results of a meta-analysis of 23 studies that shows consumers are willing to pay 21% more for biofortified crops (De Steur et al., 2017).

Better OFSP yields will enable smallholder farmers to harvest more beta-carotene per ha for home consumption or market sales to the wider rural and urban population. Breeding programs continue releasing new OFSP varieties in Africa (Andrade et al., 2016). Besides good potential yields, traits of particular importance include storability, sweet and dry taste, early maturity, drought tolerance and high beta-carotene content (Laurie et al., 2004). The actual yields of sweet potato in Southern Africa are estimated to be as low as 3 t fresh root ha^{-1} in the period 2010–2014 (FAO, 2017) compared with attainable yields of 27 t ha^{-1} reported in Mozambique (Andrade et al., 2016) and 35 t ha^{-1} in Malawi (Chipungu, 2015). This shows that despite breeding efforts, smallholder farmers are often unable to benefit from yield gains from genetic improvement (Tittonell and Giller, 2013) due to other yield reducing factors.

Despite the relative drought tolerance of sweet potato compared to cereal crops (Motsa et al., 2015), water limitations greatly affect crop development. Root formation on freshly planted cuttings is optimal at a soil water content of 80% of field capacity, though even at 40% of field capacity considerable root formation still occurs (Belehu, 2003). Crop water use of sweet potato under full irrigation in Mozambique was 800 mm with root yields of 33 t ha^{-1} compared to 360 mm and 15 t ha^{-1} in the same site under rain fed production (Gomes and Carr, 2001, 2003). Other studies confirmed that irrigation can enhance yields (Ghuman and Lal, 1983) and total nitrogen concentration, but can reduce dry matter concentration in the roots (Ekanayake and Collins, 2004). Despite common low-input cultivation practices, sweet potato shows a large yield response to nutrient input application via fertilizer and manure (Agbede, 2010). Potassium enhances root yields and quality by increasing the root: top ratio, dry matter concentration and beta-carotene and anthocyanin contents (George et al., 2002). Phosphorus and nitrogen application also enhance yields (Dumbuya et al., 2016) (Ankumah et al., 2003). Tillage benefits root yield by reducing the bulk density of the soil (Agbede, 2010), while production on ridges may result in better yields than production on mounds (Dumbuya et al., 2016).

The most serious sweet potato disease in Africa is the sweet potato virus disease (SPVD) which is caused by combined infection with sweet potato chlorotic stunt virus by whiteflies and sweet potato feathery mottle virus by aphids (Karyeija et al., 1998; Gibson et al., 2004). Sweet potato weevil (C. *formicarius* complex) is worldwide considered the biggest pest attacking both cultivated and stored sweet potatoes (Chalfant et al., 1990; Allemann et al., 2004). Severity of weevil infestation depends on variety (Stathers et al., 2003b) and increases with delaying the harvest of mature roots (Smit, 1997). Both SPVD and weevils can infect new fields via planting material. Timely access by farmers to sufficient quantities of clean planting material is a challenge in areas with a long dry season due to limited knowledge of technologies to conserve vines (Okello et al., 2015). A final challenge affecting smallholder sweet potato producers is poor storability of roots compared to grain crops (Abidin et al., 2016).

Low crop yields are usually caused by a multitude of interacting biophysical, socio-economic and management constraints that determine final production on farmers' fields (Fermont et al., 2009). Production ecology concepts (Van Ittersum and Rabbinge, 1997) are often used to quantify the yield gaps between potential, water- or nutrient-limited and actual yields. The extent to which biotic stresses such as pests, diseases and weeds or abiotic stresses such as nutrient deficiencies and drought affect the yield gap can vary across regions (Wairegi et al., 2010). To target interventions that aim to improve OFSP productivity on smallholder farmers' fields we need to identify the main factors contributing to the yield gap. This study reports on data collected in on-farm variety demonstration plots in seven districts in Central and Southern Malawi in the 2015/16 rainy season. We aimed to (i) assess the performance of six released OFSP varieties on a large number of farmers' fields in different agro-ecological conditions; (ii) identify important varietal, abiotic, biotic and crop management factors limiting smallholder OFSP production; (iii) discuss opportunities to enhance OFSP productivity for smallholder farmers, and; (v) draw lessons on the conditions under which OFSP planting material distributions to smallholder farmers will be most beneficial.

2. Materials and methods

2.1. Location and approach of the study

The study was conducted under the project 'Feed the Future Malawi Improved Seed Systems and Technologies' which aims to scale out seed and other crop technologies of various crops to > 280,000 rural households in seven districts (Mchinji, Lilongwe, Dedza, Ntcheu, Balaka, Machinga and Mangochi) in Central and Southern Malawi. This target area represents three agro-ecological zones (AEZ) as defined in Malawi (Saka et al., 2006): AEZ 1 represents the lake shore, middle and upper Shire at an elevation of 200–760 m above sea level (masl), AEZ 2 the mid-elevation upland plateau at 760–1300 masl, and AEZ 3 the highlands at > 1300 masl (Fig. 1).

Malawi has a unimodal rainfall distribution with rains from December to April, followed by a long dry season. Long term average total rainfall in the research sites ranges from 801 to 1000 mm with 1001–1200 mm in the higher elevation areas of Dedza and Ntcheu (METMALAWI, 2017). On farm demonstrations were established in 390 sites in the 2015/16 rainy season. Eleven project partners including government and NGO's were responsible for implementation of the field activities and data collection. Each demonstration site consisted of six plots each planted with a different OFSP variety. *Zondeni* is a local variety that was recommended by the Department of Agricultural Research Services (DARS) in 2008 for scaling out, because there were no released OFSP varieties in Malawi yet. It matures late in 5–6 months and has a yield potential of only 16 t ha^{-1}. Five other varieties were released by DARS in 2011 (Chipungu, 2015). These are *Anaakwanire* with a 5–6 months maturity period and yield potential of 25 t ha^{-1}, *Chipika* and *Kadyaubwerere* with a medium maturity period of 4–5 months and 35 t ha^{-1}, *Mathuthu* with 4–5 months and 25 t ha^{-1} and *Kaphulira* which is the earliest maturing variety with a growing period of 3–4 months and a potential yield of 35 t ha^{-1}. Each demonstration served as a learning site for fifty farmers who also received one bundle of planting material to plant in their own fields to apply what they learnt.

2.2. Trial design and data collection

The field study was considered as a variety trial with 390 blocks that

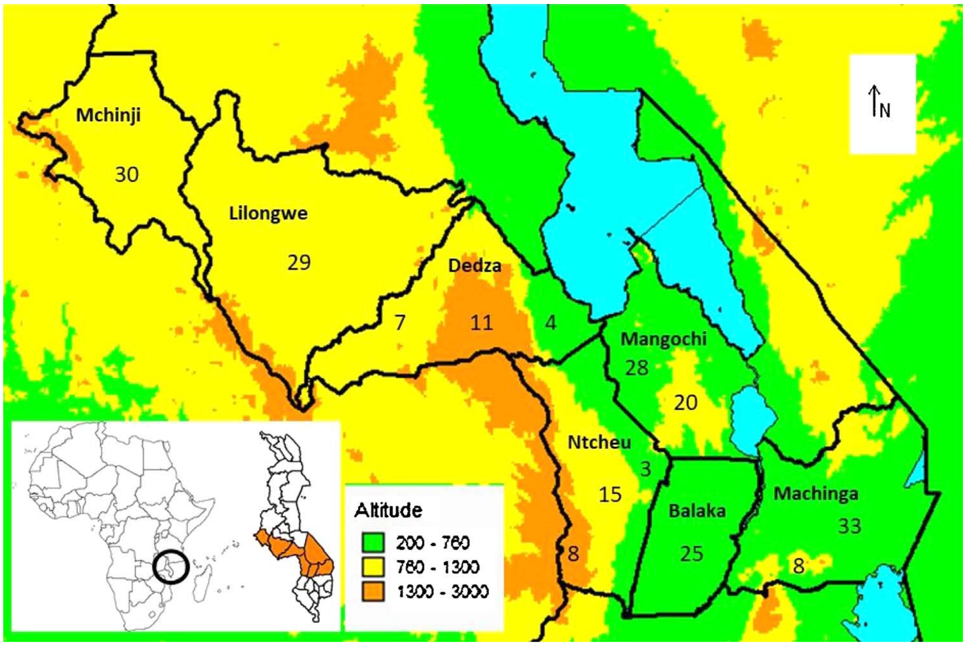

Fig. 1. Location and number of OFSP Mother Baby Trials in seven districts in three Agro Ecological Zones in Central and Southern Malawi.

we refer to as ‘demonstration sites’. Each site was a replication and contained six plots. The demonstration sites were established jointly by research, extension and farmers to ensure uniformity amongst treatments allowing for visual comparison and the collection of quantitative data. Each of the six varieties was planted in a plot of 5.4 m by 3.75 m (20.25 m^2). The plots consisted of five ridges of 5.4 m length with a spacing of 0.75 cm between ridges. The plants on each ridge were spaced at 32 cm resulting in 17 planting stations per ridge and 85 per plot, which equals 41,975 plants per ha. The sites were planted from December 26 to March 3 in AEZ 1, December 22 to February 23 in AEZ 2 and December 30 to January 23 in AEZ 3. This resulted in the five planting date classes: 16–31 December ($n = 41$), 1–15 January ($n = 24$), 16–31 January ($n = 90$), 1–15 February ($n = 58$) and > 16 February ($n = 8$). The boundaries of the planting date classes were set at approximately two-week intervals starting at the beginning or the middle of a month to ensure that a representative sample was included in each class and planting date recommendations can be derived. No fertilizer, manure or chemicals to control pests and diseases were applied at any stage during the season. Within the first month after planting (MAP), composite soil samples (0–20 cm) were collected in 70 sites (10 per district) by taking six subsamples in each site. Subsamples were taken at the flank of the ridge in the middle of each plot, mixed, air-dried, crushed and sieved through a 2-mm sieve. They were analyzed at SGS in South Africa for soil pH (1 M KCl), available P (Bray-1), K, Ca, Mg (Amm Acetate), Cu, Zn, Mn, Fe (0.1 M HCl), B (H_2O), S (Am Ac), texture (hydrometer), soil organic carbon (Walkley-Black) and organic matter. Each district is divided in 5–6 administrative units called extension planning areas (EPAs). Monthly accumulated rainfall data (mm) and the number of rainy days per month were provided by government for each EPA following regular district level data collection. These data were used to estimate the total rainfall received in the season (November to May) for each demonstration site. The last month with rainfall was defined as the last month in the growing season with more than 20 mm rainfall (in most cases March or April). The last date with effective rainfall was estimated by dividing the total rainfall received in the last month with rainfall by a daily evapotranspiration rate of 4 mm. The number of days between planting the site and the estimated last available rainfall date was calculated to estimate the period over which each site received rainfall, also referred to as rainfall exposure period.

Data collected at planting included gender of the host farmer of the demonstration site, planting date, GPS coordinates and elevation. The quality of the cuttings was categorized as poor, just fine, or healthy and soil moisture content as dry, moist or wet. In most demonstration sites, field facilitators and the 50 satellite farmers counted the number of plants that established out of the 85 cuttings in each plot between one and two months after planting. Weeding dates were not recorded, but prior to or during participatory vine establishment all fields were cleared of weeds. At the time of participatory harvest an area of 4.20 by 2.25 m was demarcated as the ‘net plot’ for each variety excluding the two border ridges and two planting stations on each end of the three middle ridges. First, the vines and roots from these border plants were harvested, labelled and removed from the field. After this, the net plot with a maximum on 39 plants was harvested. Data collected included the total number of plants harvested, the number of plants that had storage roots, and the fresh weight of the vines from the net plot. Roots were harvested and separated into marketable (> 100 g) and non-marketable (< 100 g) sizes. Besides root size, the marketability was determined based on farmers’ assessment whether they would be able to sell the roots on the local fresh root market or not. The number of roots and total weight of marketable and non-marketable roots was recorded separately. The total number of weevil infested roots was recorded in each plot. Weevil infestation was identified by dark scarred spots on the root surface where weevils penetrated to feed on the roots (Stathers et al., 2003a).

Data on sensory evaluation of the six OFSP varieties were recorded in 94 sites (50 in AEZ 1, 41 in AEZ 2, and 3 in AEZ 3) with the farmers that participated in the harvest. Groups in each site consisted of about 40–60 people including men, women and children in different ratios depending on the site. A group of women boiled the roots harvested from the border ridges in six pots up to the point a fork could enter the root without it breaking. The roots were cut in pieces and presented on six plates without mention of the name of the variety. All participants could see and taste a sample of each variety. Thereafter they were asked to stand in a line behind the plate of their most preferred variety and the number of people in each line were counted. The varieties were subsequently ranked from 1 (most preferred) to 6 (least preferred).

2.3. Data handling and statistical analysis

Sites with yield data on less than four out of the six plots were excluded from analysis, resulting in a data set of 221 sites with soil data

Table 1
Biophysical conditions, crop management components and gender participation in three agro-ecological zones (AEZ), mean and standard deviations from mean between brackets.

	AEZ 1 (n = 92)	AEZ 2 (n = 110)	AEZ 3 (n = 19)	Mean (n = 221)	SED[a]
Continuous					
Elevation[b] (masl)	585 (107)	1036 (141)	1465 (102)	885 (306)	27*
Planting date[c] (days)	35 (13)	26 (17)	15 (8.8)	29 (16)	3.2*
Harvest date[d] (days)	38 (16)	31 (13)	28 (11)	34 (14)	1.2*
Growing period (days)	135 (16)	137 (16)	144 (13)	137 (16)	n.s.
Total rainfall (mm)	513 (181)	635 (169)	780 (131)	597 (189)	15*
Rainfall exposure[e] (days)	78 (16)	89 (24)	105 (14)	86 (22)	4.4*
Plant population (1000 pl ha^{-1})	30 (17)	33 (9)	28 (11)	32 (10)	1.1*
Categorical					
Female host farmers (% of farmers)	26	36	47	33	
Soil moisture at planting					
Dry (% of sites)	7	6	11	6	
Moist (% of sites)	68	25	73	48	
Wet (% of sites)	25	69	16	46	
Condition of cuttings at planting					
Poor (% of sites)	0	2	11	2	
Just fine (% of sites)	33	19	21	25	
Healthy (% of sites)	67	79	68	73	

[a] Standard Error of Differences.
[b] meters above sea level.
[c] expressed as the number of days after the first trial was established.
[d] number of days after the first trial was harvested.
[e] number of days from planting to the last effective rainfall event.
* $p < 0.001$.

available for 63 of these sites. To explore variability in the dependent variables (establishment percentage, vine yield, total root yield, percentage of marketable root yield and percentage of weevil infested roots), these were presented by variety in cumulative probability curves (Vanlauwe et al., 2016). Linear mixed model (REML) analysis in Genstat 18th edition was used to test which categorical factors were significantly associated with the dependent variables. Categorical factors included AEZ, variety, planting date class, gender, condition of cuttings and soil moisture at planting. A linear mixed model was also used to test for significant associations between continuous independent variables on the same dependent variables of interest, while adding relevant categorical factors as random factors in the model. The continuous variables included elevation, planting date, rainfall exposure days, total rainfall, harvest date, growing period and all soil parameters. Spearmans Rank Correlation coefficients were calculated to determine the strength and the direction of the association. Correlation analysis was also done to assess associations between the dependent variables: percentage establishment, vine yield, percentage of plants harvested with roots, total root yield, percentage of root yield that is marketable and percentage weevil infested roots. The sum of preference rank scores was calculated for each variety. Differences in sensory preference for the varieties were analyzed using critical values for the differences between rank sums ($p < 0.05$). The critical values were derived from expanded tables for multiple comparison of ranked data (Newell and MacFarlane, 1988). This was done for all sites (n = 94) and by AEZ. Due to the small number of data points (n = 3) in AEZ 3, these were merged with AEZ 2.

2.4. Root yield gap analysis

We assessed correlations between root yield and continuous variables with Spearman's test for non-parametric data and explored functional relationships in scatter graphs. Variables with a correlation coefficient > 0.3 (Van Asten et al., 2003), a significant correlation ($p < 0.05$), or where the upper points in the scatter plot with yield suggested a functional relationship (Wairegi et al., 2010) were included in the boundary line analysis. Plots with missing data for one or more variables were removed from the analysis and 1057 plots from 191 trials were included. Several methods have been reported to fit boundary lines through the upper boundary points of the data clouds. Simple methods include drawing the lines by hand (Chambers et al., 1985) or manually selecting upper points and fitting a linear, logarithmic or polynomial regression line (Van Asten et al., 2003). In this study we explored two more advanced methods. Firstly, we split data sets into 8–10 equidistant groups on the X-axis followed by calculating the boundary points as the upper confidence interval (Casanova et al., 1999; Schmidt et al., 2000). We selected 'mean + 3x STDEV' as boundary points. In the second method, we applied the model $y_l = \frac{y_{max}}{1+K^{-Rx}}$ where y_{max} is the observed attainable yield level, x is the independent variable, and K and R are constants (Fermont et al., 2009; Wairegi et al., 2010). In both methods the best boundary line model was obtained by minimizing the root mean squared error (RMSE) between the fitted boundary line (y_l) and the boundary points. In case of a negative correlation between the two variables we fitted a linear or polynomial boundary line through the boundary points. After visual assessment of the boundary lines resulting from both methods, the upper confidence interval method was selected for further analysis. We combined the boundary lines for each variable in a multivariate model and predicted the yield for each individual plot by identifying the most limiting factor following von Liebigs law of the minimum (von Liebig, 1863; Shatar and McBratney, 2004). We ranked the most limiting constraints for each variety by counting the frequency that each variable is responsible for the lowest predicted yield. To evaluate this multivariate model we plotted the predicted yields for each plot against actual yields in scatter graphs. The difference between the attainable yield (Yatt) and the minimum yield predicted by the model (Ymin) was defined as the explainable yield gap. We quantified Yatt for each variety as the mean + 3x STDEV of the total root yield. The difference between Ymin and the actual yield (Yact) was defined as the unexplained yield gap. When the unexplained yield gap is large this means that not all important variables have been included in the analysis (Van Asten et al., 2003). Yield gaps have been quantified in similar way for cereals (Casanova et al., 1999), cassava (Fermont et al., 2009) and East African highland bananas (Wairegi et al., 2010).

3. Results

3.1. Biophysical and climatic conditions of the trial sites

Among farmers hosting a demonstration, 33% were female. Planting took place between December 22, 2015 and March 3, 2016. A mismatch between time of distribution of perishable planting materials and distribution of rainfall resulted in planting demonstrations under dry soil conditions in 6% of the sites and poor quality planting material was planted in 2% of the sites (Table 1).

The average plant stand 1–2 months after planting was 32,000 plants ha^{-1} out of a planting density of 41,975 cuttings ha^{-1}. Harvesting took place in the period May 2 to July 22 in AEZ 1, May 12 to July 10 in AEZ 2 and May 19 to June 27 in AEZ 3. The average growing period from planting to harvest was 137 days (Table 1). The demonstrations were established in a season that was considered poor in rainfall, with especially AEZ 1 and AEZ 2 receiving on average only 513 and 635 mm. Due to the wide range in planting dates, demonstration sites in these AEZ's did not equally benefit from the available rainfall. The average rainfall exposure period ranged from 78 days in AEZ 1 to 105 days in AEZ 3 (Table 1). After the last effective rainfall event the sweet potato roots stayed in the soil for an average of 51 days

Table 2
Soil characteristics in selected trial sites, mean and standard deviations from the mean between brackets.

Soil parameter		AEZ 1 (n = 23)		AEZ 2 (n = 32)		AEZ 3 (n = 8)		SED[a]
pH[b]	(KCl)	4.9		4.9		4.7		0.22
Carbon	(g kg^{-1})	12	(4.6)	12	(5.6)	12	(3.5)	0.7
OM	(g kg^{-1})	21	(7.9)	21	(9.7)	20	(6.0)	1.3
Available P	(mg kg^{-1})	27	(18.7)	18	(14.6)	40	(14.8)	2.4**
CEC	(cmol kg^{-1})	6.80	(4.20)	5.84	(3.06)	6.35	(3.57)	0.53
Exch. K^+	(cmol kg^{-1})	0.43	(0.20)	0.33	(0.18)	0.40	(0.16)	0.03**
Exch. Ca^{2+}	(cmol kg^{-1})	4.53	(2.51)	4.29	(2.13)	4.32	(2.47)	0.34
Exch. Mg^{2+}	(cmol kg^{-1})	1.55	(0.93)	1.21	(0.88)	1.62	(1.06)	0.14**
Exch. Na^+	(cmol kg^{-1})	0.05	(0.02)	0.05	(0.02)	0.05	(0.01)	0.00*
Cu	(mg kg^{-1})	0.7	(0.22)	1.1	(0.45)	1.4	(0.76)	0.07**
Zn	(mg kg^{-1})	2.9	(2.27)	1.8	(1.63)	2.4	(1.90)	0.28**
Mn	(mg kg^{-1})	28	(10.2)	26	(16.1)	28	(7.66)	2.0
B	(mg kg^{-1})	0.35	(0.14)	0.26	(0.16)	0.28	(0.12)	0.02**
S	(mg kg^{-1})	12	(7.4)	11	(4.8)	11	(5.6)	0.9
Clay	(g kg^{-1})	107	(50)	150	(56)	168	(85)	8.6**
Silt	(g kg^{-1})	134	(49)	126	(46)	158	(33)	6.7**
Sand	(g kg^{-1})	759	(84)	724	(91)	675	(99)	13.1**

[a] Standard Error of Differences.
[b] pH data were back-log transformed before calculating the means and therefore standard deviation are not provided; pH values ranged from 4.3 to 6.4.
* $p < 0.01$.
** $p < 0.001$.

before harvesting. The relatively low soil OM content (Table 2) indicates that nitrogen (not measured) may be limiting OFSP yields. Available P appears less limiting but the large variability shows it may limit yields in several sites, especially in AEZ 1 and 2. The soils do not show severe signs of K deficiency, though the large crop requirement for K may result in yield limitations. The average soil pH was in the range of 4.7-4.9 (in KCl) and the smallest pH of 4.3 was unlikely to limit yields. Soils in AEZ 1 and 2 contained more sand than in AEZ 3.

3.2. Exploring variability in establishment, vine yield, total and marketable root yield, and weevil infestation

The effects of variety, AEZ and planting date class (Table 3) and the cumulative probability charts (Fig. 2) demonstrate the variability in establishment, vine yield, root yield, percentage of root yield that is marketable and the percentage of roots affected by weevils. The percentage establishment was associated with total root yield ($r = 0.18$; $p < 0.001$). Vine yield correlated with root yield ($r = 0.41$; $p < 0.001$) and percentage marketable yield ($r = 0.14$; $p < 0.001$). Root yield correlated with the number of plants with roots harvested per ha ($r = 0.42$; $p < 0.001$) and percentage marketable yield

Table 3
Effect of variety, AEZ and planting date class on OFSP establishment, root and vine yields and weevil infestation in Central and Southern Malawi.

Independent factor	Establishment (%)	Vine yield (t ha^{-1})	Plants with roots harvested (%)	Total root yield (t ha^{-1})	Marketable root yield (t ha^{-1})	Marketable root yield (%)	Weevil affected roots (%)
Variety							
Anaakwanire	72	7.5	79	5.9	3.7	57	15
Chipika	75	8.0	84	9.0	5.8	65	16
Kadyaubwerere	79	7.1	85	9.1	6.0	63	19
Kaphulira	77	7.3	80	8.7	5.5	62	27
Mathuthu	73	5.8	84	9.6	6.3	65	18
Zondeni	77	8.3	60	4.2	2.3	50	18
SED[a] $_{Variety}$	2.4*	0.6**	2.3***	0.6***	0.5***	2.2***	2.1***
AEZ							
AEZ 1 (n = 92)	71	6.4	70	5.4	3.6	61	22
AEZ 2 (n=110)	79	7.5	83	8.6	5.3	59	17
AEZ 3 (n = 19)	68	10.7	94	13.8	9.2	65	19
SED $_{AEZ}$	2.5***	0.6***	2.2***	0.6***	0.4***	2.0*	2.0**
Planting date class (PDC)							
16–31 Dec (n = 41)	71	8.9	81	10.8	7.4	65	28
1–15 Jan (n = 24)	74	9.6	85	12.2	7.7	59	23
16–31 Jan (n = 90)	79	7.2	78	7.1	4.2	58	20
1–15 Feb (n = 58)	76	5.8	74	5.2	3.5	62	11
> 16 Feb (n = 8)	59	4.9	81	4.2	2.7	58	13
SED $_{PDC}$	2.8***	0.7***	3.0***	0.7***	0.6***	2.7**	2.5***
SED $_{VarietyxAEZ}$	n.s.	1.3*	4.8***	n.s.	1.0**	4.7**	n.s.
SED $_{VarietyxPDC}$	n.s.	n.s.	n.s.	3.2***	1.3***	n.s.	n.s.
SED $_{AEZxPDC}$	5.3***	0.7*	5.1*	n.s.	1.0*	n.s.	n.s.

[a] Standard Error of Differences.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

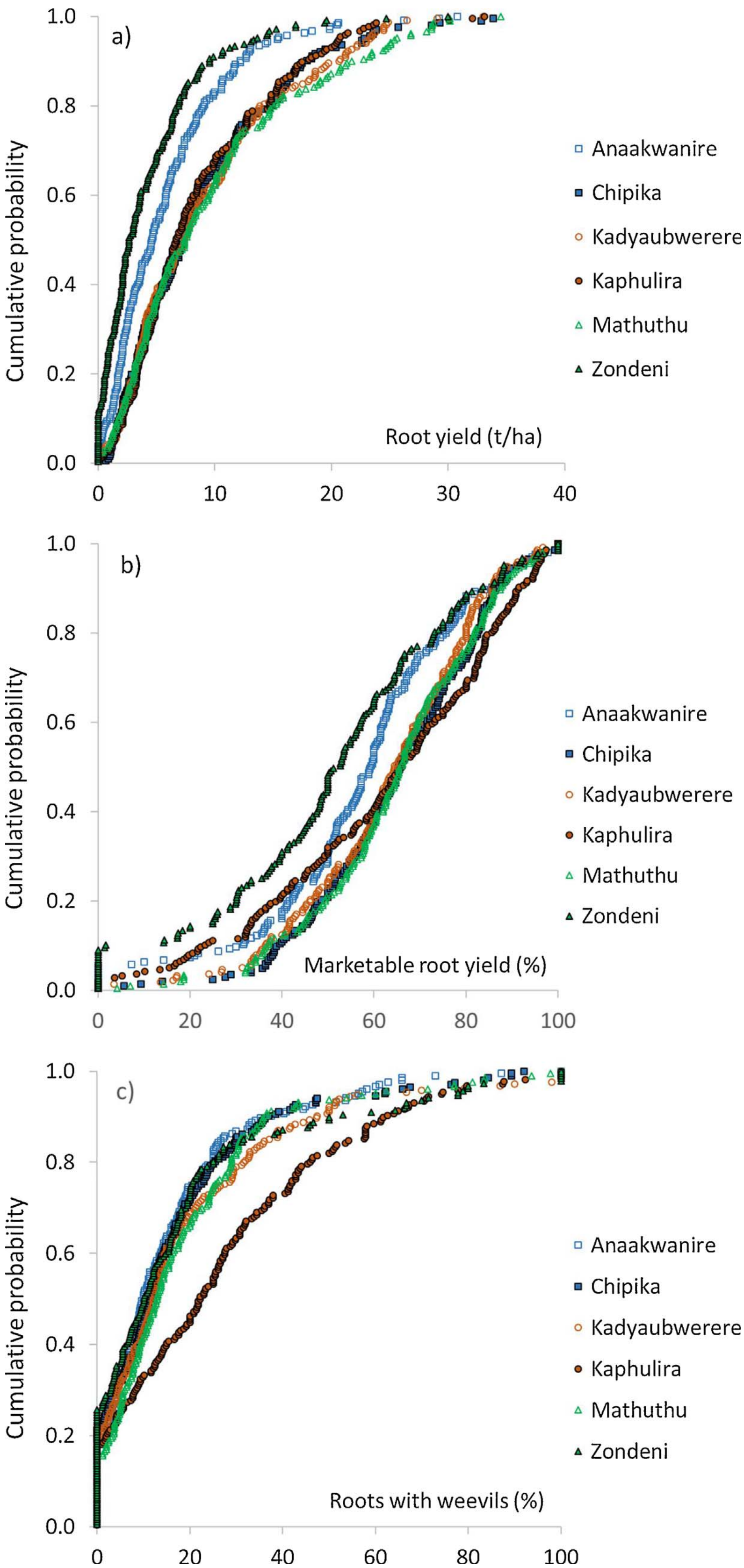

Fig. 2. Cumulative probability charts for six OFSP varieties of a) root yield, b) marketable root yield (% of root weight) and c) percentage of roots infested with weevils.

($r = 0.18$; $p < 0.001$). Marketable root yield (%) was negatively associated with percentage of roots affected by weevils ($r = -0.27$; $p < 0.001$).

The REML resulted in additional categorical and continuous variables that are significantly associated with the dependent variables of interest (Table 4).

On average 31,718 out of the 41,975 cuttings ha^{-1} (76%) established well. Kadyubwerere established better than Anaakwanire. AEZ

Table 4
Factors affecting plant establishment, vine yield, root yield, percentage marketable root yield and percentage of weevil affected roots. The values are the F-probabilities generated by the REML analysis with the direction of the association given in brackets for the continuous variables.

Explanatory variables	Establishment	Vine yield	Plants with roots harvested (%)	Root yield	Marketable root yield (%)	Weevil infested roots (%)	Random Factors[a]
Categorical factors	(n[b] = 139)	(n = 221)	(n = 221)	(n = 221)	(n = 221)	(n = 221)	
Agro Ecological Zone	< 0.001	< 0.001	< 0.001	< 0.001	0.017	< 0.001	V,P
Variety	0.020	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	A,P
Planting date class	< 0.001	< 0.001	0.042	< 0.001	0.002	< 0.001	A,V
Gender	< 0.001	0.004	0.561	0.177	0.468	0.017	A,V,P
Condition of cutting	0.047	< 0.001	0.229	0.058	0.015	0.027	A,V,P
Soil moisture at planting	< 0.001	< 0.001	0.395	< 0.001	0.642	0.138	A,V,P
Continuous variables	(n = 139)	(n = 221)	(n = 221)	(n = 221)	(n = 221)	(n = 221)	
Elevation	0.004 (+)	0.005 (+)	0.003 (+)	0.003 (+)	0.107 (+)	0.007 (−)	A,V,P
Planting date	0.819 (+)	< 0.001 (−)	0.384 (−)	0.009 (−)	0.592 (−)	< 0.001 (−)	A,V,P
Rainfall exposure days	0.165 (−)	0.107 (+)	0.405 (+)	< 0.001 (+)	0.255 (+)	< 0.001 (+)	A,V,P
Total rainfall	0.021 (−)	0.005 (+)	0.054 (+)	< 0.001 (+)	< 0.001 (+)	0.008 (−)	A,V,P
Harvest date	X	< 0.001 (−)	< 0.001 (−)	0.059 (−)	0.024 (+)	0.143 (−)	A,V,P
Growing period	X	< 0.001 (+)	< 0.001 (−)	0.238 (-+)	0.065 (+)	0.006 (+)	A,V,P
Soil parameters[c]	(n = 55)	(n = 61)	(n = 61)	(n = 61)	(n = 61)	(n = 61)	
pH	0.015 (−)	0.007 (+)	0.431 (−)	0.134 (−)	0.009 (+)	0.003 (−)	A,V,P
P	0.803 (+)	0.176 (+)	0.129 (+)	< 0.001 (+)	0.954 (−)	0.982 (+)	A,V,P
CEC	0.554 (+)	0.016 (+)	0.037 (+)	0.036 (+)	0.001 (+)	0.175 (−)	A,V,P
K	0.247 (+)	< 0.001 (+)	0.801 (−)	0.361 (−)	0.105 (+)	0.101 (−)	A,V,P
Ca	0.686 (+)	0.140 (+)	0.142 (−)	0.132 (+)	0.014 (+)	0.159 (−)	A,V,P
Mg	0.954 (−)	0.062 (+)	0.113 (+)	0.105 (+)	0.007 (+)	0.093 (−)	A,V,P
Na	0.075 (−)	0.124 (+)	0.471 (−)	0.119 (−)	0.003 (+)	0.011 (−)	A,V,P
Zn	0.452 (+)	0.131 (−)	0.482 (−)	0.104 (−)	0.755 (−)	0.017 (+)	A,V,P
Mn	0.344 (+)	0.590 (−)	0.795 (−)	0.533 (−)	0.026 (+)	0.685 (+)	A,V,P
B	0.942 (+)	0.043 (−)	0.603 (−)	0.889 (−)	0.854 (−)	0.002 (+)	A,V,P
S	0.772 (+)	0.101 (+)	0.067 (+)	0.153 (+)	0.017 (+)	0.221 (−)	A,V,P
Clay	0.289 (−)	0.003 (+)	0.035 (+)	0.300 (+)	0.615 (+)	0.139 (+)	A,V,P
Silt	0.064 (+)	0.009 (+)	0.021 (+)	0.033 (+)	0.862 (+)	0.016 (+)	A,V,P
Sand	0.668 (−)	< 0.001 (−)	0.011 (−)	0.079 (−)	0.827 (−)	0.028 (−)	A,V,P

[a] Random factors included in the REML model: A = Agro-ecological zone, V = Variety, P = Planting date class.
[b] n = the number of trials with data to include in the model.
[c] Carbon, OM and Cu were not associated with any of the dependent variables.

and planting date class also affected establishment with the best establishment observed in AEZ 2, and in sites planted between 16 and 31 January (Table 3). Good establishment of more than 80% was achieved in 50% of the sites for Anaakwanire and 61% of the sites for Kadyaubwerere. Poor establishment of less than 50% ranged from 12% of the sites for Kadyaubwerere to 22% for Anaakwanire. Healthy cuttings resulted in better establishment (72% establishment) than cuttings of fine (69%) or poor (64%) quality. Soil moisture conditions at planting also affected establishment with 76% achieved in wet soils compared to 69% in moist and 67% in dry soil conditions. Plants in male host farmers' fields established better (72%) than in female farmers' fields (67%). Gender interacted with both quality of cuttings ($p = 0.007$) and soil moisture condition at planting ($p < 0.001$) which suggests female farmers received poorer quality planting material at a time with less soil moisture content than male host farmers.

Mathuthu had a slightly smaller vine yield at harvest though overall vine yield did not differ much between varieties (Table 3). Vine yields were better in AEZ 3 and in sites planted before January 16 (Table 3). Fresh vine yield of over 10 t ha^{-1} was achieved in 15% of the sites for Mathuthu to 27% for Zondeni. Male farmers had better vine yields of 8.2 t ha^{-1} than female farmers with 7.1 t ha^{-1}. Plots planted with healthy or medium quality cuttings yielded more vines (8.3 and 8.0 t ha^{-1}) than with poor quality cuttings (3.3 t ha^{-1}). There was an interaction between gender and quality of cuttings ($p = 0.034$). Soil moisture conditions at planting also affected vine yields with 9.0 t ha^{-1} achieved in wet soils compared to 7.6 t ha^{-1} in moist and 5.9 t ha^{-1} in dry soil conditions. Vine yield correlated ($r > 0.2$ or < -0.2) with the continuous variables elevation ($r = 0.20$; $p < 0.001$), root yield ($r = 0.40$; $p < 0.001$), clay content ($r = 0.24$; $p < 0.001$) and sand content ($r = -0.24$; $p < 0.001$).

At harvest on average 30,490 plants ha^{-1} (96% of established plants) were uprooted. An average of 79% of these had storage roots. Root set for Zondeni and Anaakwanire was only 40% and 67% in AEZ 1 while it was 90% and 94% in AEZ 3. AEZ also affected the root set of other varieties but not to the same extend (Table 3). Soil texture affected root set (Table 4), as larger clay concentration correlated with more ($r = 0.23$; $p < 0.01$), and larger sand concentration with less ($r = -0.22$; $p < 0.01$) plants with roots. The percentage of plants with roots was also associated with total root yield ($r = 0.33$; $p < 0.001$) and the percentage marketable yield ($r = 0.17$; $p < 0.01$).

Fresh root yields differed by variety with Zondeni and Anaakwanire achieving much smaller root yields than the other varieties (Table 3, Fig. 2a). Yields over 5 t ha^{-1} were achieved on 30% of sites for Zondeni, 46% for Anaakwanire, and 62–63% of sites for the other varieties. Yields over 20 t ha^{-1} were achieved on less than 2% of sites for Zondeni and Anaakwanire, and 6–12% of the sites for the other varieties. Sites in AEZ 3 achieved the best average root yields of 14 t ha^{-1}. This was 60% more than in AEZ 2 and even 156% more than in AEZ 1 (Table 3). Root yield was strongly affected by planting date with sites planted between 16 and 31 January (Class 3) achieving only 58% of the yields of sites planted in the first half of January (Class 2) with further yield reductions observed in sites planted in February. Root yield was affected by soil moisture conditions at planting with 9.9 t ha^{-1} achieved when planted in wet soils compared to 8.5 t ha^{-1} in moist and 6.5 t ha^{-1} in dry soil conditions. Root yield was associated with the continuous variables elevation ($r = 0.38$; $p < 0.001$), planting date ($r = -0.33$; $p < 0.001$), rainfall exposure days ($r = 0.33$; $p < 0.001$), total rainfall ($r = 0.31$; $p < 0.001$) and vine yield ($r = 0.40$; $p < 0.001$).

The percentage of the total root yield considered as marketable was best in AEZ 3, though still only 65% (Table 3). It was smallest for

Zondeni and Anaakwanire (Table 3) and highly variable across sites (Fig. 2b). Less than 50% of root yield was marketable in 44% of the sites for Zondeni, 30% for Kaphulira, 28% for Anaakwanire and 21–23% of the sites for Chipika, Mathuthu and Kadyaubwerere. Plots planted with healthy or medium quality cuttings had a larger percentage of marketable root yield (63 and 61%) than plots planted with poor quality cuttings (50%). Marketable root yield was also associated with percentage weevil infested roots ($r = -0.26$; $p < 0.001$).

Fields in AEZ 1 had the largest percentage of roots infested with weevils (Table 3). It was also observed that sites that were planted early were more affected by weevils than those planted in February or March. Kaphulira was more affected by weevils than the five other varieties at harvest (Fig. 2c). The percentage of sites without weevil infestation ranged from 15% for Mathuthu to 26% for Zondeni. On female farmers' fields 20% of the roots were infested with weevils compared to 17% on male farmers' fields. There was an interaction between the condition of the cuttings at planting and gender ($p = 0.01$) on weevil infestation. The percentage of infested roots correlated with planting date ($r = -0.27$; $p < 0.001$), rainfall exposure days ($r = 0.25$; $p < 0.001$), growing period ($r = 0.20$; $p < 0.001$) and% marketable root yield ($r = -0.27$; $p < 0.001$).

3.3. Interactions between variety, environment and management affecting total root yield

There was a strong interaction observed between the effects of variety and categorical planting date class ($p < 0.001$) and planting date as continuous variable ($p < 0.001$) on root yield. Delaying planting from the first to the second half of January resulted in 6.1–7.0 t ha^{-1} yield reduction for the better yielding varieties Chipika, Kadyaubwerere, Kaphulira and Mathuthu (Fig. 3). This reduction was only 0.7 t ha^{-1} for Anaakwanire and 2.9 t ha^{-1} for Zondeni. Variety also interacted with continuous variables harvest date ($p = 0.02$), rainfall exposure days ($p < 0.001$) and total rainfall ($p = 0.026$). Planting date correlated strongly ($p < 0.001$) with all these variables and especially with rainfall exposure days ($r = -0.86$). Varieties did not differ in yield response to elevation or soil properties.

3.4. Yield gap analysis

From the continuous variables that are significantly associated with root yield (Table 4), the correlations between soil parameters and yield were weak ($r = 0.12$ for soil available P and $r = 0.13$ for silt). The variables elevation, planting date, rainfall exposure days and total rainfall correlated more strongly with root yield ($r = > 0.3$ or < -0.3) and were therefore included in the boundary line analysis. Out of these, only elevation and total rainfall strongly interacted ($p < 0.001$) in the association with root yield because the highlands in

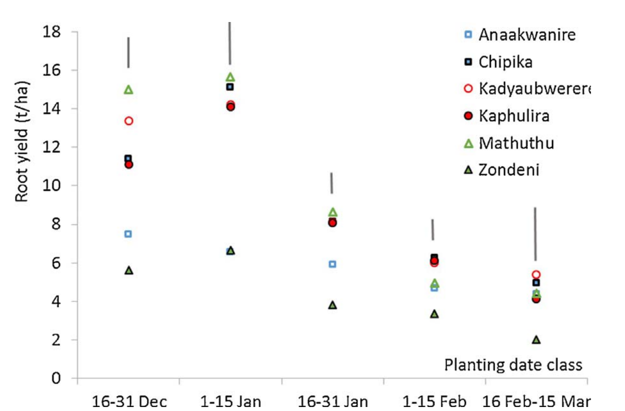

Fig. 3. Average OFSP root yields for six varieties by planting date class. The vertical lines represent the standard error of differences between means.

Dedza and Ntcheu received more rainfall than the southern districts. The percentage establishment had a weak correlation with yield ($r = 0.18$; $p < 0.001$), but was included in the model because the scatter graph showed a clear association. Boundary regression lines were therefore conducted using the factors elevation, planting date, rainfall exposure days, total rainfall and percentage establishment (Fig. 4).

Out of these, total rainfall was the most limiting factor in 30% of all plots, followed by elevation (23%), planting date (21%), percentage establishment (18%) and rainfall exposure period (8%). There was little difference between varieties in the percentage of fields in which each variable is most limiting (Fig. 5).

The attainable yield ranged from 17.6 t ha^{-1} for Zondeni to 32.0 t ha^{-1} for Mathuthu (Table 5), while actual yields of these varieties were only 4.5 and 9.3 t ha^{-1}. Across varieties, average root yields were only 29% of the attainable yield and the average yield gap was 18.6 t ha^{-1}. The factors included in the multivariate boundary line model could explain 31% of the yield gap. The explainable yield gap for the low yielding varieties Anaakwanire (2.5 t ha^{-1}) and Zondeni (0.8 t ha^{-1}) was small compared to that of the four better yielding varieties (6.1–11.2 t ha^{-1}). Mathuthu had the largest explainable yield gap (Fig. 6), but 48% was nevertheless unexplainable.

It is therefore not surprising that the multivariate model did not serve well to predict yields based on the most limiting factor (Fig. 7). The predicted root yields were much larger than the actual yields and the R^2 of the regression line was only 0.16. When testing the model with data for individual varieties the graphs looked similar (not presented) and R^2 ranged from 0.11 for Anaakwanire to 0.22 for Mathuthu.

3.5. Sensory evaluations

Kadyaubwerere and Chipika were the most preferred varieties in terms of consumption of boiled roots (Table 6). Zondeni was ranked third and was preferred over the varieties Anaakwanire, Mathuthu and Kaphulira. Preferences differed slightly between AEZs since Zondeni was ranked significantly lower than Chipika in lower areas but not in higher elevations. Overall, the top three most preferred varieties were the same in all AEZs.

4. Discussion

4.1. Methodological considerations

The large number of sites allowed for a good quantification of the variability in performance of the six OFSP varieties, exploration of yield limiting factors and identification of opportunities to enhance productivity. The demonstration sites did not fully reflect farmers' practices since land preparation and plant and row spacing were pre-defined. Planting material was sourced from the formal market and diseased plants were removed during and after establishment as part of the training of farmers, which probably reduced incidences of SPVD and weevils compared to farmers' practices and using locally sourced planting material. On the other hand, local sourcing could have resulted in fresher planting material by cutting out transport and distribution time. Since varieties have different maturity periods, yield assessment may have been better by harvesting each variety at the optimal harvest time. However, in that case the participatory harvest evaluations and sensory evaluations with the satellite farmers would not have been possible. The type of information provided before tasting could have affected the sensory evaluations (Lagerkvist et al., 2016), for example understanding that darker orange flesh-color corresponds with higher beta-carotene content may lead to preference for Kadyaubwerere. While lining up for the preferred variety, peer pressure may have affected independence of the ranking between individual evaluators. The taste and sweetness of sweet potato change when stored for a couple of days after harvest, though differences in sensory preferences are mainly

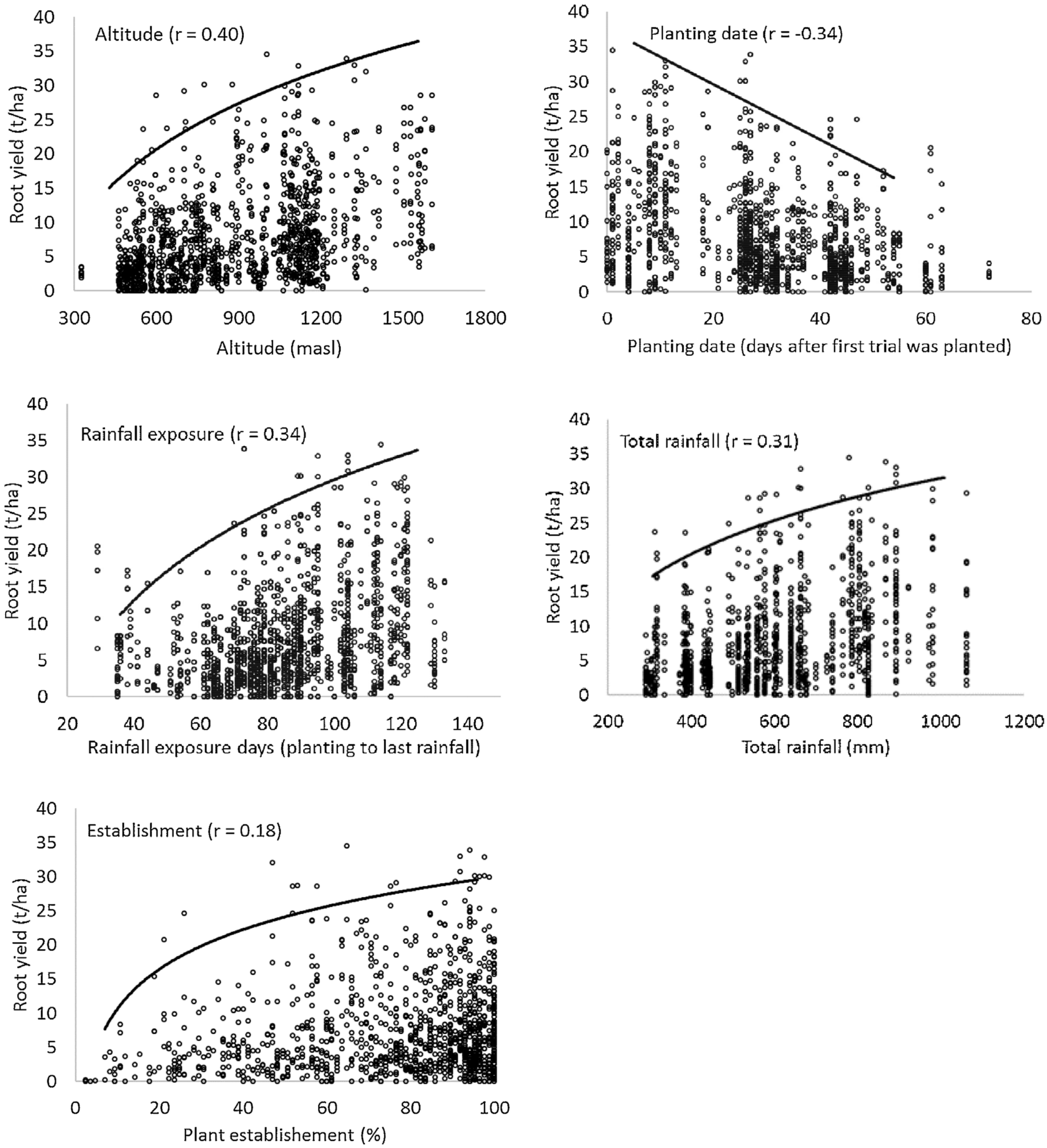

Fig. 4. Boundary lines for sweet potato yields. 'r' represents the correlation coefficient between the two variables.

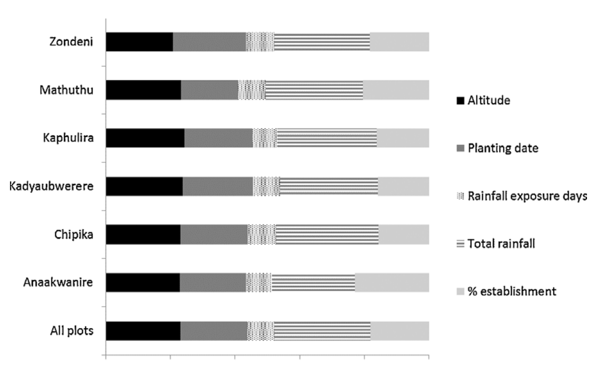

Fig. 5. The most limiting factors identified using the boundary line approach and the corresponding proportion of plots (%) in which these factors were most limiting by variety and for all plots.

determined by texture which is not much affected by storage (van Oirschot et al., 2003).

4.2. Performance of six OFSP varieties

Suitability of a variety depends on the characteristics a farmer is looking for and can included vine production, total and marketable root yield, resistance to pests, storability and sensory characteristics (Ndolo et al., 2001). While vine yield may have been affected by theft and roaming livestock, it still largely correlated with total root yields. Anaakwanire and Zondeni had better vine to root ratios than the other varieties (Table 3). These varieties may not be recommended since they consistently underperform in terms of root yield even when planted early in the season (Fig. 3). The poor attainable yields of 22 t ha^{-1} (Anaakwanire) and 18 t ha^{-1} (Zondeni) compared to 27–32 t ha^{-1} for the other varieties (Table 5) indicate a limited genetic potential of these varieties. Probably due to small root size, also the percentage of marketable root yield of these two varieties is poor (Table 3), limiting

Table 5
Explained and unexplained average root yield gap using the multivariate boundary line model.

Variety	*n*	Attainable yield (t ha^{-1})	Actual yield (t ha^{-1})	Total yield gap (t ha^{-1})	Explainable yield gap (t ha^{-1})	Unexplainable yield gap (t ha^{-1})
Anaakwanire	175	21.6	5.8	15.7	2.5	13.3
Chipika	173	28.4	8.5	20.0	7.5	12.5
Kadyaubwerere	189	29.0	8.7	20.3	7.9	12.5
Kaphulira	185	27.2	8.4	18.9	6.1	12.8
Mathuthu	176	32.0	9.3	22.7	11.2	11.4
Zondeni	159	17.6	4.5	13.0	0.8	12.2
All data	1057	26.1	7.6	18.6	6.1	12.5

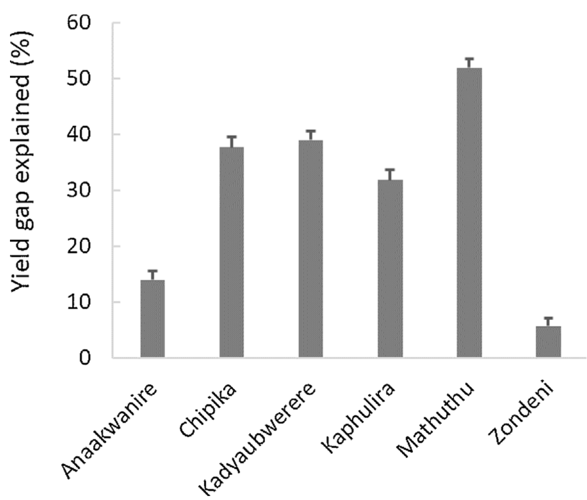

Fig. 6. The percentage of the sweet potato yield gap that could be explained by the model for six varieties. Whiskers indicate standard errors. The standard error of differences between means is 2.4.

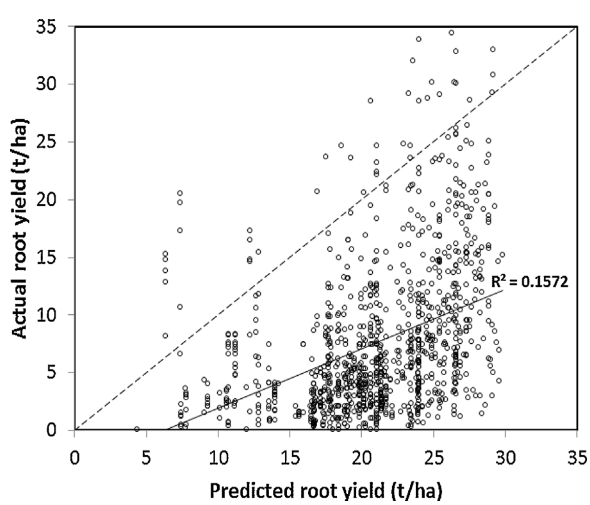

Fig. 7. Actual and predicted yield from the multivariate boundary line model. The dotted diagonal line depicts the relationship y = x and the other line is the linear regression line.

options for commercialized market oriented production. Our data did not show any interactive effect on root yield between variety and AEZ indicating there is no need to recommend certain varieties for specific environmental conditions. Timely planting (which strongly correlates with the number of days a site is exposed to rainfall) will mostly benefit the better yielding varieties Chipika, Kadyaubwerere, Kaphulira and Mathuthu (Fig. 3). While Kaphulira achieved good yields, the large percentage of roots infected with weevils (Table 3) may limit its marketability. Weevils were encountered on 74%–85% of sites depending on variety. The correlation between weevil infestation and planting date ($r = -0.27$) and growing period ($r = 0.20$) suggest farmers can

Table 6
Sensory evaluations of six OFSP varieties in three Agro Ecological Zones (AEZ) in Central and Southern Malawi.

Variety	Sum of preference rank scores[b]			
	Rank[a]	All sites (n = 94)	AEZ 1 200–760 masl[c] (n = 50)	AEZ 2&3 > 760–1300 masl (n = 44)
Kadyaubwerere	1	220	116	104
Chipika	2	239	120	119
Zondeni	3	300	179	121
Anaakwanire	4	380	209	171
Mathuthu	5	399	198	201
Kaphulira	6	423	225	198
Critical value[d]		74	54	51

[a] Ranking from 1 = most preferred to 6 = least preferred.
[b] Each variety received a rank score (1 = most preferred to 6 = least preferred) in each of the 94 sites. The data represent the sum of the rank scores given to each variety.
[c] Meters above sea level.
[d] According to expanded tables for comparison of ranked data (Newell and MacFarlane, 1988), this critical value is the least significant difference ($p < 0.05$) in the sum of preference ranks between varieties.

reduce weevil infestation by earlier harvesting. Studies in Cameroon (Parr et al., 2014) and Uganda (Smit, 1997) confirm that delayed harvesting increases weevil infestation. Since industrial processing of OFSP for human consumption is gaining momentum in Malawi and weevils are not tolerated, additional measures are needed to control weevils. These can include hilling up twice at 4 and 6 weeks after planting (Pardales and Cerna, 1987), filling cracks in the soil with loose soil when roots expand, or piece-meal harvesting as soon as cracks form (Ebregt et al., 2007). Besides high weevil infestation, Kaphulira also scored low on sensory preferences (Table 6). Similar to Mathuthu, this may affect willingness to adopt the variety for household consumption. Kadyaubwerere and Chipika stand out as promising varieties that receive the best sensory preference score (Table 5), are preferred by industrial processors (UIL, 2017), achieve good root yields (Table 3) especially when planted early (Fig. 3) and are less susceptible to weevil infestation than Kaphulira.

4.3. Important factors limiting smallholder OFSP production

Besides variety choice several other factors affected total root yield. The final yield of any crop is a product of interacting genetic, environmental, management and socio-economic factors (Tittonell and Giller, 2013). Using fresh planting material and planting in wet soil positively affected the crop establishment (Table 4), while poor establishment was the most root yield limiting factor in 18% of the sites (Fig. 4). This suggests that timely access to fresh planting material will benefit final productivity. Once established, the percentage of plants that will form storage roots can be enhanced by choosing the right variety for the AEZ (no Zondeni in AEZ 1) and avoiding soils that are too sandy (Table 4). The strong effect of AEZ on root formation suggests farmers may benefit from larger planting densities in AEZ 1 to compensate for the reduced root set, which strongly correlates with total root yield (r = 0.33). Our results show that the importance of timely planting to make optimal use of available rainfall cannot be overemphasized to achieve good yields (Table 4, Figs. 3 and 4) The strong correlations between planting date and rainfall exposure days ($r = -0.86$, $p < 0.001$; most limiting on 8% of sites) and total rainfall (most limiting on 30% of sites) indicates that these factors may be confounded in the yield gap analysis. The strong effect of AEZ on yield may also partly be explained by the correlation between elevation and rainfall exposure days ($r = 0.34$, $p < 0.001$) and the fact that sites in AEZ 3 were planted earlier and AEZ 3 received more rain (Table 1).

The large unexplainable yield gap (Table 5) and the systematic overestimation of yields (Fig. 6) suggest there are several other yield limiting factors unaccounted for by the model. The poor yield predictions for Anaakwanire and Zondeni (Table 5) may be due to the overriding constraint of poor genetic yield potential. Addressing the constraining factors included in the boundary line model may result in yield increases of 6.1–11.2 t ha^{-1} for the other four varieties, leaving an unexplainable yield gap of 11.4–12.8 t ha^{-1} (Table 6). Soil fertility constraints were not captured in the model due to the small sample size ($n = 61$) and small correlations with root yield. Soil nitrogen content was not measured, but a positive association between soil available P, CEC and root yield was found and texture may have had some effect (Table 4). Soil fertility may become a constraint to achieve attainable yields, since for each ton of root yield, an estimated 10 kg N, 2 kg P and 17 kg K is removed from the soil (IPNI, 2017). Improved tillage and nutrient input applications (Agbede, 2010) could have made a significant contribution to closing the yield gap. Yield reducing factors such as weeds, pests and diseases were assumed negligible due to the controlled nature of the demonstrations. Weeds, viruses-infested plants and plants with other disease symptoms were uprooted and removed from the field during farmer trainings, and weevil infestation only affected marketability but not the total root yield. The yield reductions caused by viral disease in smallholder sweet potato crops needs more research and more technology transfer efforts. Most farmers in our study could not recognize a plant virus, while these can lead to large yield reductions or complete crop failure (Adikini et al., 2016). Male host farmers' fields had better crop establishment, better vine yields and less weevil infestation, but there was no effect of gender on root yield (Table 4). The interactions between gender and the quality of cuttings and soil moisture condition at planting, suggest that when planting material arrived in an area to establish several demonstration sites, male farmers could have been prioritized by extension agents resulting in fresher planting material and timely planting in male host farmers' fields.

4.4. Recommendations to enhance OFSP productivity on smallholder farms

Sweet potato development objectives in sub-Saharan Africa include emergency relief distributions of planting material to vulnerable households, reducing Vitamin A deficiency with nutritious OFSP, and product development and commercialization. Enhanced productivity will benefit all these objectives and should first include promotion of the better yielding varieties Chipika, Kadyaubwerere, Kaphulira and Mathuthu. Emergency distributions of sweet potato planting material as a drought tolerant crop in case it is too late to plant maize is probably not a good strategy to promote its cultivation and use, because delayed planting will result in poor root yields (Fig. 3). Transportation time and distances result in farmers receiving poor quality cuttings and risks planting in soils without adequate moisture content. This will affect establishment and yield (Table 4). The nutritional and commercialization objectives require awareness efforts to change the farmers' and consumers' mindset that sweet potato is a 'poor men's crop'. The varieties Kadyaubwerere and Chipika may be prioritized as they are both highly ranked in sensory evaluations (Table 6) and suitable for processing. Market-oriented producers will benefit from adopting measures to control weevils to reduce the percentage of unmarketable yield. Farmers often do not have access to sufficient planting material at the onset of the rains and therefore plant later in the season by cutting and transplanting material that sprouted in the early weeks of the rainy season. More training on the importance of early planting (Tables 3 and 4, Fig. 3) should therefore be combined with initiatives that ensure availability of quality planting material of the most preferred varieties at the right time. This can be achieved by promoting rapid vine multiplication techniques under irrigation in the dry season either for own use or as a business opportunity to sell to others (McEwan et al., 2017), though sustainable vine multiplication business can only be achieved where there is sufficient demand (Rao and Huggins, 2017). Promotion of OFSP in combination with training on vine conservation has proven to enhance conservation practices by farmers (Okello et al., 2015). There should be special emphasis on gender in extension programs to ensure both men and women benefit equality from timely access to quality planting material.

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