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GENOTYPE X ENVIRONMENT INTERACTION AND STABILITY ANALYSIS OF CASSAVA GENOTYPES AT DIFFERENT HARVEST TIMES

Michael M. Chipeta[1, 2*], Rob Melis[1], Paul Shanahan[1], Julia Sibiya[1] and Ibrahim R. M. Benesi[3]

[1]African Centre for Crop Improvement, University of KwaZulu-Natal, P/Bag X01, Scottsville, 3209, Pietermaritzburg, South Africa
[2]Lilongwe University of Agriculture and Natural Resources, Bunda Campus, P.O BOX 219, Lilongwe, Malawi.
[3]Chitedze Agricultural Research Station, P.O Box 128, Lilongwe, Malawi
*Corresponding author: chipetamichael@gmail.com

ABSTRACT

Cassava (*Manihot esculenta* Crantz) like most other crops responds to the effect of genotype by environment interaction (GEI), which makes it difficult to identify the superior genotypes in terms of performance, stability and adaptability. Currently there is limited information about the adaptability of cassava genotypes at different times of harvesting (TOH). Due to increasing demand for early storage root bulking varieties, and confounding effects of site, crop age, and season during selection, there is a need for the objective characterization of genotypes in terms of adaptability and stability with respect to TOH. The study was, therefore, conducted to identify high yielding, stable and adaptable cassava genotypes at different times of harvesting (6, 9 and 12 months after planting, MAP) through the application of multivariate analysis techniques. The study was conducted in four environments using sixteen genotypes using a triple lattice design. Variance components for individual environment were analysed using Restricted Maximum Likelihood (REML) while combined analysis was performed using Additive Main effects and Multiplicative Interaction (AMMI) model. The AMMI analysis of variance at three TOH revealed that variances due to genotypes, environments, and GEI were significant for most of the traits. However, at 6 MAP, GEI was not significant for most of the traits. Significance of main effects indicated stability of some genotypes across environments while GEI significance indicated that some genotypes were specifically adapted to certain environments. The non-significance of GEI at 6 MAP for almost all traits means that genotypes can be reliably evaluated in any single environment. Selection of a) high yielding genotypes based on mean performance, b) stable genotypes based on GSI (mean performance and ASV) and c) adaptability of genotypes based IPCA1 versus IPCA2 identified five genotypes (Mulola, Phoso, Maunjili, Beatrice and Unknown) that exhibited consistent performance, stability and adaptability across the three harvest periods. These genotypes are therefore best candidates for production in any of the studied and other similar environments.

Key words: AMMI stability value, genotype by environment interaction, genotype selection index, time of harvest.

INTRODUCTION

Cassava (*Manihot esculenta* Crantz) is a popular food and income generating crop mainly among resource constrained farmers due to its comparative advantages over other crops, such as its drought tolerance, low requirements for inputs like fertilizers and chemicals, flexibility in planting and harvesting times, adaptation to a wide range of agro-ecological conditions, efficiency in utilization of mineral of marginal soils, diverse range of utilization and higher dry matter yield per hectare (FAO, 2013; MoAFS, 2007; Westby, 2002).

Though cassava is widely adapted to a variety of environmental conditions, it's reported that the adaptability of most varieties is narrow and shows large genotype by environment interaction (GEI) effects (Akinwale *et al*., 2011; Benesi *et al*., 2004; Dixon and Nukenine, 1997; Noerwijatia *et al*., 2014 ; Ssemakula and Dixon, 2007; Tumuhimbise *et al*., 2014). GEI may be defined as the differential genotypic expression across environments, and reduces the association between phenotypic and genotypic values (Romagosa and Fox, 1993). Presence of significant GEI makes identifying superior genotypes difficult as the rank order for genotypes will vary between environments (Bowman, 1972; Ceccarelli, 2012). The assessment of GEI is important in designing the best breeding strategy for the development of genotypes with adequate adaptation to target environments. Genotypic adaptation across environments can effectively be assessed through statistical analysis of the stability of individual genotypes. A stable genotype is one that is consistently well ranked over a wide range of environments, and such genotype is deemed to have general or wide adaptation, while in the case of stability that is confined to a limited range, the genotype is considered to have a specific or narrow adaptation (Fox *et al*., 1997). Therefore, level of GEI is a major element in determining many key aspects of a breeding programme including, whether to aim for wide or specific adaptation, and will affect the choice of locations for selection (Fox *et al*., 1997; Romagosa and Fox, 1993).

Plant breeders conduct yield trials which involves testing genotypes in a range of environments in order to identify superior genotypes for recommendation to the farmers and to identify production environments best suited to certain genotypes (Yan *et al*., 2001). Since cassava has no defined maturity time, but it can be harvested at different times, there has been increasing demand by farmers for early storage root bulking varieties (Agwu and Anyaeche, 2007; Benesi *et al*., 2010; Chipeta *et al*., 2016a; Dahniya, 1994; Munga, 2008; Okechukwu and Dixon, 2009; Tumuhimbise *et al*., 2012), and this has necessitated many researchers across the globe to develop early storage root bulking varieties that could be harvested between 6 and 10 months after planting (Kamau *et al*., 2011; Nair and Unnikrishnan, 2006; Okechukwu and Dixon, 2009; Okogbenin and Fregene, 2002; Okogbenin *et al*., 2008; Olasanmi *et al*., 2013; Suja *et al*., 2010; Tumuhimbise, 2013; Wholey and Cock, 1974). However, there is limited information about the stability and adaptability of cassava genotypes at different times of harvesting (TOH). Due to confounding effects of site, crop age, and season during selection at different times of harvesting, there is thus a need for the objective characterization of genotypes in terms of adaptability and stability with respect to TOH. There are various statistical tools applied to data obtained from multi-environment trials. Two frequently used statistical analyses have been the additive main effects and multiplicative interaction (AMMI) model and the genotype main effects and genotype x environment interaction effects (GGE) model (Crossa *et al*., 1991; Gauch, 2006; Gauch and Zobel, 1988; Yan *et al*., 2007). The present study uses AMMI to partition the overall variation into genotype main effects, environment main effects, and genotype x environment interactions (Crossa *et al*., 1991; Gauch, 2006; Gauch and Zobel, 1988). The objectives of this study were to: a) identify high yielding, stable and adaptable cassava genotypes at different times of harvesting through the application of multivariate analyses techniques, b) to explain the magnitude of interaction of each genotype and environment at different times of harvesting.

MATERIALS AND METHODS

Planting material: Planting material with a diverse background was sourced from National Agricultural Research Stations and famers' fields. A total of 16 genotypes were evaluated and their selection was based on their popularity with farmers and their response to various diseases prevalent in Malawi (Table 1).

Table 1. Cassava genotypes evaluated during studies.

Code	Genotype	Source	Code	Genotype	Source
G1	Maunjili	Introduction from IITA	G9	Phoso	Locally bred/improved
G2	Mulola	Introduction from IITA	G10	Mbundumali	Local genotype
G3	Mpale	Introduction from IITA	G11	Yizaso	Locally bred/improved
G4	TMS4(2)1425	Introduction from IITA	G12	Beatrice	Local genotype
G5	01/1316	Locally bred/Improved	G13	Unknown	Local genotype
G6	01/1569	Locally bred/Improved	G14	Kalawe	Locally bred/improved
G7	Chamandanda	Locally bred/Improved	G15	96/1708	Locally bred
G8	Sauti	Locally bred/improved	G16	MK05/0297	Locally bred

Experimental sites: The experiments were conducted in Malawi at two different sites i.e. Chitala Agricultural Research Station, Salima District (Central Malawi) and Kasinthula Agricultural Research Station, Chikwawa District (Southern Malawi) over two growing seasons (2014 and 2015). Chitala Agricultural Research Station lies on latitude 13°40' South and on longitude 34°15' East. It is at an altitude of 606 metres above sea level. The station receives rains within three months normally between December and March with mean annual temperatures of 28°C maximum and 16°C minimum (Figure. 1). The soils are sandy clay to sandy clay loam with the pH range of 4.4 to 6.7. Kasinthula Agricultural Research Station is located at 16°0'S latitude, 34°5'E longitude and 70 m above sea level. The yearly average maximum and minimum temperatures of the site are 35.6°C and 18.6°C, respectively, and annual rainfall is 520 mm on average. Table 2 details soil characteristics of the two sites.

Experimental design: The trials were laid out using a 4 x 4 lattice design constituting 16 genotypes; three replicates each with four blocks. Each plot had five ridges, each with six plants (12 net plants and 30 gross plants). Plants were spaced at 1.0 m × 1.0 m and 2.0 m between replications. The trials were planted in January in 2014 and 2015 under rainfall conditions and no fertilizers were applied.

Data collection: Data for individual genotypes were collected at harvest 6, 9 and 12 MAP for the following traits: fresh storage root yield (t/ha), dry mass yield (t/ha), shoot mass (t/ha), number of storage roots per plant, storage root length (cm), plant height (cm), plant height at first branching (cm), harvest index, root dry mass content (%), starch content (%), root diameter (cm) and levels of branching. At each harvest interval, the unit of measurement was three plants per plot.

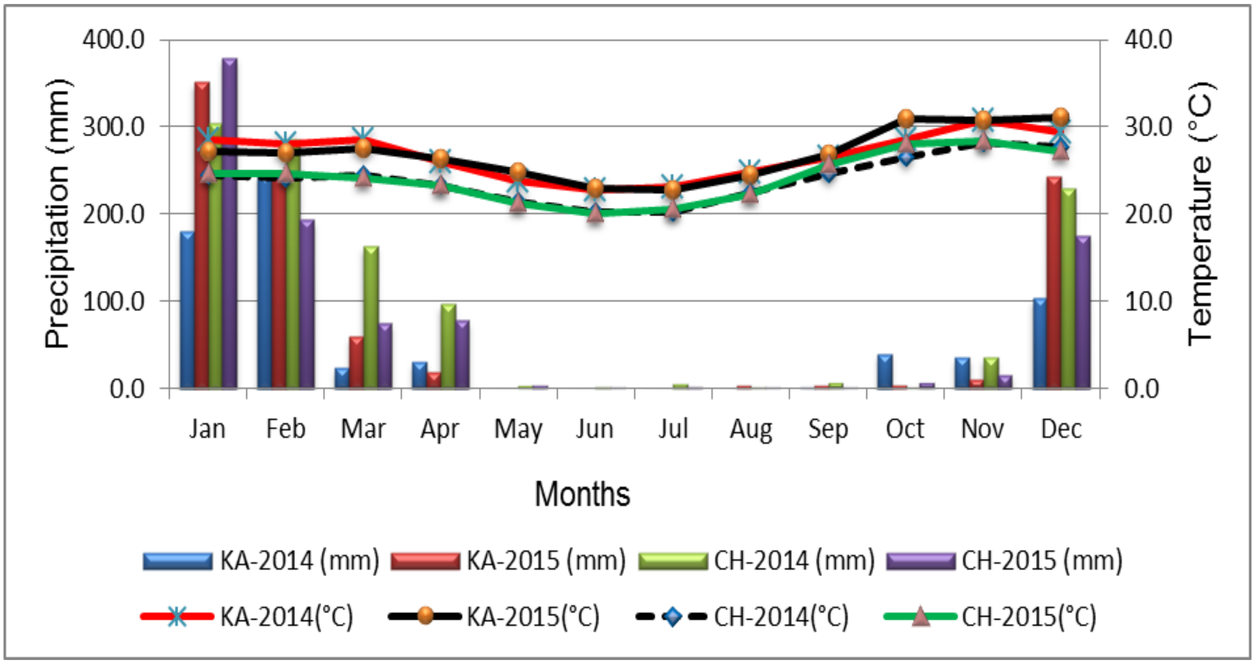

Figure 1. Total monthly rainfall (mm) and average monthly temperature (°C) for Chitala and Kasinthula in 2014 and 2015 (KA = Kasinthula Research Station, CH = Chitala Research Station)

Table 2. Soil status of the two sites during 2014 and 2015.

Characteristics	Chitala		Kasinthula	
	2014	2015	2014	2015
Soil texture	SC - SCL	SL -SC	SL -SCL	SC - C
Soil pH	4.4 - 6.7	5.9 - 6.3	5.8 - 6.1	4.2 - 4.8
Phosphorus (ppm)	1.4 - 2.2	61.6 - 97.2	58.4 - 93.1	1.4 - 4.2
Organic carbon (%)	0.8 - 1.3	0.4 - 0.5	0.5 - 0.7	0.7 - 0.9
Organic matter (%)	1.7 - 2.6	0.7 - 1.0	0.9 - 1.4	1.4 - 1.9
Estimated nitrogen (%)	0.09 - 0.13	0.04 - 0.05	0.05 - 0.07	0.07 - 0.09
Potassium (Meq/100g)	0.2 - 0.3	0.6 - 0.8	0.5 - 0.6	0.3 - 0.4

SC = sandy clay, SCL = sandy clay loam, SL = sandy loam, C = clay

Percentage dry mass (DM), starch content and harvest index (HI) were determined as described by Fukuda *et al*. (2010):

1. Dry mass (DM) % = 158.3xSG – 142.
2. Starch content (%) = 112.1xSG – 106.4; Where SG = specific gravity = $\frac{Wa}{(Wa - Ww)}$. Where Wa = mass in air of storage roots (kg) and Ww= mass in water of storage roots (kg).
3. Dry storage root yield (t/ha) = $\frac{\text{Fresh storage root yield}}{100} \times \text{DM\%}$
4. Harvest index (HI) = $\frac{\text{Mass of storage roots}}{\text{Mass of storage roots + aboveground mass}} \times 100$

Data analysis: Variance components were analysed using Restricted Maximum Likelihood (REML) procedure as described by O'Neill (2010) and Payne *et al*. (2014) using GenStat, 17th edition for each environment separately, where genotypes and environments were fitted as fixed effects while replications, blocks within replications and error were considered random effects in the model. A combined analysis of variance was done from the mean data from each environment. Bartlett (1947) test was used to determine the homogeneity of variances between environments to determine the validity of the combined analysis of variance on the data. AMMI analysis was performed on the combined data to partition the variation due to genotype (G), environment (E) and genotype by environment interaction (GEI) using GenStat, 17th edition. The following AMMI model was adopted (Gauch, 1988).

$$Y_{ge} = \mu + \alpha_g + \beta_e + \Sigma_n \lambda_n \gamma_{gn} \delta_{en} + \rho_{ge} + \varepsilon_{ger}$$

where Y_{ge} = the trait of genotype g in environment e; μ = the grand mean, α_g = the genotypes deviation from grand mean; β_e = the environment deviation; λ_n is the eigenvalue of PCA axis n; γ_{gn} and δ_{en} are the genotype and environment PCA scores for PCA axis n; ρ_{ge} is the residual of AMMI model and ε_{ger} = the random error.

Definition of environment in the study: The study was conducted at two locations (Chitala, Salima District and Kasinthula, Chikwawa District) for two growing seasons (2014 and 2015). In this study, a combination of location (L = 2) and year/season (Y = 2) constitutes a single environment. This gives a total of four test environments, that is, Chitala 2014 = E1, Chitala 2015 = E2, Kasinthula 2014 = E3 and Kasinthula 2015 = E4.

AMMI stability value (ASV): Since the AMMI model does not make provision for a quantitative stability measure, the AMMI stability value (ASV) as described by Purchase *et al*. (2000) was used to quantify and rank genotypes according to their yield stability. The ASV was calculated as follows:

$$AMMI\ Stability\ Value\ (ASV) = \sqrt{\left[\frac{IPCA1\ Sum\ of\ Squares}{IPCA2\ Sum\ of\ Squares}\left(IPCA1\ score\right)\right]^2 + \left[IPCA2\ score\right]^2}$$

Where IPCA = interaction principal component axis. However, in selecting preferred cultivars, stability *per se* is not the only parameter considered since the most stable cultivars are not necessarily the best performers for the trait of interest. Therefore, the genotype stability index (GSI) was developed to cater for both stability and performance (Farshadfar, 2008).

Genotype stability index (GSI): GSI was calculated by the following formula: GSI = RASV + RY (Farshadfar, 2008)

Where RASV is the rank of AMMI stability value and RY is the rank of genotypes mean across environments. GSI incorporate both genotype mean and stability in a single criterion. Low value of this parameter shows desirable genotypes with high genotype mean and stability. The larger the IPCA score, either negative or positive, the more specifically adapted a genotype is to certain environments. Smaller ASV scores indicate a more stable genotype across environments.

Biplots construction: To understand interaction patterns of genotypes with environments as well as identifying genotypes with specific adaptation, biplots of IPCA1 scores against IPCA2 were constructed using GenStat, 17th edition.

RESULTS

Mean square values and percentage sum of squares contribution to total variation for various traits: The AMMI analysis of variance at three times of harvest (TOH) revealed that variances due to genotypes, environments, and G x E interactions were significant for most of the traits investigated (Tables 3 and 4). However, at 6 MAP, the GEI was not significant for most of the traits except for shoot mass (t/ha), leaf retention, levels of branching, storage root number/plant and plant height (cm). At 9 MAP, only GEI for fresh storage root yield (t/ha) was not significant. At 12 MAP, variance due to GEI was not significant for dry mass content (%), harvest index and starch content (%). Since most of the traits were not significant at 6 MAP for GEI, their results have not been included in this section except where explicitly stated. Also traits whose GEI proved to be non-significant (except fresh storage root yield) at the respective harvest intervals have neither been presented nor discussed.

Fresh storage root yield, shoot mass, dry mass yield, and dry mass content: Analysis revealed that the main effects of G and E accounted for 20.1% and 20% variation, respectively, and G x E interaction effects represented 19% of the total variation for fresh storage root yield harvested at 9 MAP, while harvesting at 12 MAP, G, E and GEI accounted for 15.4%, 21.3% and 29.7% of the total variation, respectively. For dry mass yield (t/ha), G, E and GEI explained 18.7%, 30.7% and 18.9% of the variation, respectively, at 9 MAP, while at 12 MAP, G, E and GEI contributed 7.7%, 54.4% and 17.7% to the total variation, respectively. At 9 MAP, G, E and GEI contributed 11%, 27.3% and 23.8%, respectively to the total variation for dry mass content, while at 12 MAP, 4.8%, 47.3% and 13.19% were contributed by G, E and GEI, respectively. To shoot mass variation, G, E and GEI contributed about 11.3%, 32.5%, and 21.7% respectively, at 9 MAP, and 11.2%, 23.3% and 27.3% respectively, at 12 MAP. The E accounted for the largest amount of variation for fresh storage root yield, shoot mass, dry mass yield and dry mass content except fresh storage root yield and shoot mass at 12 MAP which showed that GEI was the greatest contributor (Table 3).

Harvest index, starch content, storage root length and storage root number per plant: Harvest index contribution to total variation at 9 MAP was 43.7%, 20% and 14.4% for G, E and GEI, respectively, while at 12 MAP, G, E and GEI accounted for 34.6%, 11.8% and 13.8%, respectively, of the total variation. Both At 9 and 12 MAP, G was the least contributor to variation in starch content, and highest was E (27.3% at 9 MAP and 47.0 at 12 MAP). For storage root length, E contributed the most to total variation at 9 MAP (37.8%) while at 12 MAP, G accounted for most of the variation (28.9%). GEI explained most of the variation for storage root number per plant at both 9 (28.8%) and 12 (33.4%) MAP while E was the least contributor, 2.5% at 9 MAP and 0.3% at 12 MAP (Table 4).

Percentage variance contribution of first and second interaction principal component axes (IPCA) to genotype by environment interaction: Interactive principal component axis 1 (IPCA1) was significant ($P<0.05$) for all the traits while IPCA2 was only significant for dry mass content, harvest index and starch content at 9 MAP. At 12 MAP, IPCA1 was highly significant ($P<0.001$) for fresh storage root yield, shoot mass, dry mass yield, storage root length and storage root number. On the other hand, IPCA2 was significant for fresh storage root yield, shoot mass and dry mass yield (Tables 3 and 4)

Of the GE interaction, IPCA1 and IPCA2, respectively, explained 54.4% and 31.4% at 9 MAP and 63.6% and 26.5% at 12 MAP for fresh storage root yield (Figure 2). For dry mass yield at 9 MAP, 91.6% of the GEI was explained by IPCA1 and IPCA2 while at 12 MAP, IPCA1 and IPCA2 accounted for 89.6% of the GEI (Figure 3). In terms of shoot mass, at 9 MAP, IPCA1 explained about 87.6% and IPCA2 about 7.8% of the GEI while at 12 MAP, 51.2% and 37.9% were explained by IPCA1 and IPCA2, respectively (Figure 4). For storage root number, IPCA1 and IPCA2 at 12 MAP explained greater proportion (92.7%) of GEI than at 9 MAP (78.61%) (Figure 5). IPCA1 accounted for 99.5% of the GEI for storage root length at 9 MAP while IPCA2 explained only 0.3%. At 12 MAP, IPCA1 explained 55.5% and IPCA2 explained about 25.6% of the GEI for storage root length (Figure 6).

High yielding, stable and adaptable cassava genotypes at different times of harvesting: To identify the best performing and stable genotypes across the environments, a GSI was used which selects based on both mean performance and ASV. Low value of GSI shows desirable genotypes with high genotype mean and stability. Genotypes with general or specific adaptability were identified using a biplot of IPCA1 scores against IPCA2. According to the AMMI 2 model, the genotypes scattered around the origin (0,0) indicate stability and general adaptability while distances from the origin (0,0) are indicative of the amount of interaction that was exhibited by either genotypes over environments or environments over genotypes. Genotypes and environments that fall into the same sector interact positively; negatively if they fall into opposite sectors. A genotype showing high positive interaction in an environment clearly has the ability to exploit the agro-ecological conditions of the specific environment and is therefore best suited to that environment (specific adaptation).

Fresh storage root yield and dry mass yield: At 6 MAP, Maunjili (10.5 t/ha) and Mulola (10.4 t/ha) out performed all other genotypes in terms of fresh storage root yield. Phoso and Mulola were the best yielding genotypes at both 9 and 12 MAP. For example, Phoso produced 19.7 t/ha at 9MAP and 22.1 t/ha at 12 MAP while 15.5 t/ha and 27.6 t/ha were realised from Mulola at 9 and 12 MAP, respectively. TMS4(2)1425 was the least yielding at both 6 MAP (5.2 t/ha) and 9 MAP (5.7 t/ha) while 01/1316 was the lowest yielder at 6 MAP (5.2 t/ha) and 12 MAP (10.7 t/ha). For dry mass yield (t/ha), Maunjili (4.1 t/ha), Yizaso (3.6 t/ha) and Mulola (3.6 t/ha) were ranked as best yielders at 6 MAP while Phoso yielded the best (8.8 t/ha) at 9 MAP followed by Beatrice (5.4 t/ha) while Mulola (8.2 t/ha) out yielded all other genotypes at 12 MAP and closely followed by Maunjili (7.2 t/ha). The most stable genotypes based on GSI were Maunjili and Beatrice at 9 MAP, and Phoso and Unknown at 12 MAP for fresh storage root yield. GSI selected Mbundumali at 9 MAP, and Kalawe and Chamandanda at 12 MAP as the most unstable genotypes for fresh storage root yield. For dry mass yield, Maunjili, 01/1516, Beatrice and Chamandanda were identified as the most stable genotypes at 9 MAP while Mulola and Unknown were most stable genotypes at 12 MAP. The least stable genotype for dry mass yield was Sauti at 9 MAP and 01/1316 at 12 MAP (Table 5).

According to Figure 2 at 9 MAP for fresh storage root yield: TMS4(2)1425, 01/1316, Chamandanda and Mbundumali exhibited specific adaptability for environment E3, Yizaso and Kalawe showed positive interaction and specific adaptation for E1 and E2. Mpale, 01/1569, Sauti and MK05/0297 interacted positively with E4 and specifically adapted to that environment. On the other hand, Maunjili, Mulola, Phoso, Beatrice and Unknown were not sensitive to environmental interaction and therefore showed general adaptation. E3 and E4 exerted large interactive forces and were more responsive. At 12 MAP, TMS4(2)1425 and 96/1708 revealed specific adaptation for E3, MK05/0297 for E4,

Shoot mass, storage root number/plant and storage root length: At 9 MAP, Sauti (9.4 t/ha) and Yizaso (9.1 t/ha) and at 12 MAP, Yizaso (22.6 t/ha) and Beatrice (19.2 t/ha) gave the highest shoot mass. In terms of storage root number per plant, Beatrice (5.8) and Mulola (5.7) were the best at 9 MAP, while Sauti (6.9) and Mulola (6.4) gave the highest number of storage roots at 12 MAP (Table 6). Phoso (37.7 cm) and 01/1569 (36.6 cm) outperformed all genotypes for storage root length at 9 MAP, while 01/1569 (47.0 cm) and TMS4(2)1425 (41.0 cm) were the best at 12 MAP (Table 7).

Based on GSI (Table 6), Beatrice and Phoso were the most stable genotypes at both 9 and 12 MAP for shoot mass and the most unstable genotypes were TMS4(2)1425 (at 9 and 12 MAP) and Mbundumali (at 9 MAP). For storage root number/plant, Mulola (both at 9 and 12 MAP), Beatrice (9 at MAP) and Phoso (at 12 MAP) were found to be the best performing and most stable genotypes. On the other hand TMS4(2)1425 (at 9 and 12 MAP), Mbundumali (at 9 MAP), 01/1316 (9 MAP) and Chamandanda (at 12 MAP) were least stable genotypes. For storage root length (cm), GSI selected MK05/0297 (at 9 and 12 MAP), Phoso (at 9 MAP) and Yizaso (at 12 MAP) as the most stable genotypes while TMS4(2)1425 and Mpale (at 9 MAP), 01/1316, Kalawe and Maunjili (at 12 MAP) as the most unstable genotypes (Table 7).

Ranking of all genotypes using GSI for the five traits (fresh storage root yield, dry mass yield, shoot mass, storage root number and storage root length) which exhibited significant GEI at both 9 and 12 MAP, revealed that the best five genotypes in terms of mean performance and stability were Mulola, Phoso, Maunjili, Beatrice and Unknown. The least stable genotypes based on the five traits were TMS4(2)1425, 01/1316 and Sauti (Table 8).

AMMI 2 biplots showed that, 01/1316 and Maunjili exhibited specific adaptation to E1, Kalawe and Chamandanda to E3, Mbundumali and Unknown to E2, MK05/0197, TMS4(2)1425 and Mpale to E4 for shoot mass at 9 MAP. The environment that fitted the worst was E4 as it showed the highest interactive forces. 96/1708, Phoso and Beatrice were the least sensitive genotypes and showed good performance regardless of the environment planted. At 12 MAP, E2 was the least responsive environment while Phoso, Beatrice, MK05/0297 and Unknown showed wider adaptation. E1 was more suitable for Maunjili and Kalawe. 01/1316, Yizaso and TMS4(2)1425 exploited more E3. On the other hand, 96/1708 and Chamandanda interacted positively with E4 (Figure 4).

According to Figure 5 for storage root number/plant at 9 MAP, Mbundumali and Kalawe interacted negatively with E4 while 01/1569 had a positive interaction with the same environment (E4). TMS4(2)1425, MK05/0297, 01/1316 and Phoso were more sensitive to E1 and E3. Genotypes more resilient to environmental variations were Maunjili, Mulola, Mpale, Chamandanda, Yizaso, Beatrice and Unknown. At 12 MAP, Mulola, Phoso, Unknown and MK05/0297 exhibited general adaptation. E2 was suitable for Sauti, Mbundumali and 01/1316 exploited E1, while Yizaso and Beatrice interacted positively with E3. E4 was suitable for TMS4(2)1425, Chamandanda and 96/1708. At both 9 and 12 MAP, E2 and E4 contributed the most to GEI as revealed by long projections from the origin (0, 0).

For storage root length at 9 MAP, E4 and Kalawe interacted positively and this environment showed to be the sole contributor to GEI. E1, E2 and E3 showed similar interactive forces. All genotypes except Kalawe had a similar interaction pattern with E1, E2 and E3. At 12 MAP, Mbundumali, Yizaso and MK05/0297 were generally well adapted to all the environments. Mulola was specifically adapted to E2, TMS4(2)1425 and 96/1708 adapted specifically to E3, Beatrice and Kalawe showed specific adaptation with E4. The greatest contributors to GEI were E3 and E4 for this trait (Figure 6).

Table 3. Mean square values and % sum of squares for storage root yield shoot mass, dry mass yield, dry mass content.

Source of variation	DF	Fresh storage root yield (t/ha)		Shoot mass (t/ha)		Dry mass yield (t/ha)		Dry mass content (%)	
		9 MAP	12 MAP	9 MAP	12 MAP	9 MAP	12 MAP	9 MAP	12 MAP
Total	191	45	101.4	27.45	63.5	9.22	13.88	93.4	175.6
Treatments	63	80.6***	203.8***	54.53***	119.1***	19.09***	33.58***	175.9***	347.7***
Genotypes (G)	15	115.2***	198.1***	39.45***	90.9***	21.96***	13.59***	130.8**	107.9^{ns}
Environments (E)	3	574.4***	1374.4***	568.83***	942.2***	180.28***	480.79***	1621.5***	5286.8***
Block	8	50.8	141.6	42.95	97.9	7.84	7.7	76.2	87.6^{ns}
Interactions (GEI)	45	36.2^{ns}	127.7***	25.27***	73.6***	7.39**	10.44***	94.5**	98.3^{ns}
IPCA 1	17	52.1*	215.1***	58.59***	99.7***	12.24***	18.13***	133.4***	154.1^{ns}
IPCA 2	15	34.1^{ns}	101.7***	5.9^{ns}	83.8***	6.42^{ns}	7.51*	88.8*	63.6^{ns}
Residuals	13	17.9	43.4	4.06	27.8	2.16	3.75	50.1	65.5
Error	120	25.9	44.9	12.2	32	4.13	3.95	51.3	91.1
% SS due to Treatments		59.1	66.3	65.5	61.9	68.3	79.8	62.1	65.3
% SS due to Genotype		20.1	15.4	11.3	11.2	18.7	7.7	11.0	4.8
% SS due to Environment		20.0	21.3	32.5	23.3	30.7	54.4	27.3	47.3
% SS due to GEI		19.0	29.7	21.7	27.3	18.9	17.7	23.8	13.2

*; **, *** = significant at the 5%, 1% and 0.1% probability levels, respectively, ns = not significant, DF = degrees of freedom, MAP = months after planting, GEI = genotype by environment interaction, IPCA = interaction principal component axis, SS = sum of squares

Table 4. Mean square values and % sum of squares for harvest index, starch content, storage root length and storage root number/plant.

Source of variation	DF	Harvest index		Starch content (%)		Storage root length (cm)		Storage root number/plant	
		9 MAP	12 MAP	9 MAP	12 MAP	9 MAP	12 MAP	9 MAP	12 MAP
Total	191	0.017	0.016	46.8	87.6	93.5	102.2	4.05	7.61
Treatments	63	0.041***	0.029***	88.2***	173***	190.3***	197.1***	5.29**	10.04*
Genotypes (G)	15	0.095***	0.069***	65.6**	54.1^{ns}	152.1***	376.6***	6.07*	9.58^{ns}
Environments (E)	3	0.218***	0.118***	813.2***	2623.5***	2249***	754.5***	6.45^{ns}	1.20^{ns}
Block	8	0.009	0.011	38.2	43.9	67.0	99.2	10.983	8.00
Interactions (GEI)	45	0.011**	0.009^{ns}	47.4**	49.3^{ns}	65.8*	100.1**	4.952*	10.79*
IPCA 1	17	0.017***	0.009^{ns}	66.9**	77.3^{ns}	95.1**	147.1***	5.92*	21.70***
IPCA 2	15	0.009*	0.009^{ns}	44.5*	31.9^{ns}	59.4^{ns}	76.7^{ns}	4.97^{ns}	5.42^{ns}
Residuals	13	0.003	0.009	25.1	32.9	35.0	65.5	3.67	2.71
Error	120	0.005	0.009	25.7	45.7	44.4	52.7	2.94	6.31
% SS due to Treatments		78.0	60.3	62.1	65.1	67.2	63.6	43.1	43.5
% SS due to Genotype		43.7	34.6	11.0	4.9	12.8	28.9	11.8	9.9
% SS due to Environment		20.0	11.8	27.3	47.0	37.8	11.6	2.5	0.3
% SS due to GEI		14.4	13.8	23.8	13.3	16.6	23.1	28.8	33.4

*; **, *** = significant at the 5%, 1% and 0.1% probability levels, respectively, ns = not significant, DF = degrees of freedom, MAP = months after planting, GEI = genotype by environment interaction, IPCA = interaction principal component axis, SS = sum of squares

Table 5. Ranks of 16 genotypes in four environments using mean performance, AMMI stability value and genotype selection index for fresh storage root yield and dry mass yield.

	Fresh storage root yield (t/ha)								Dry mass yield (t/ha)							
	9 months after planting				12 months after planting				9 months after planting				12 months after planting			
Genotype	**Mean**	**ASV**	**GSI**	**Rank**	**Mean**	**ASV**	**GSI**	**Rank**	**Mean**	**ASV**	**GSI**	**Rank**	**Mean**	**ASV**	**GSI**	**Rank**
Maunjili	15.1	1.14	7	1	21.6	6.21	17	6	5.3	0.65	8	1	7.2	4.88	17	6
Mbundumali	9.9	2.88	29	13	13.9	1.18	17	6	4.2	0.93	19	8	4.9	1.12	20	8
Yizaso	13.3	1.72	19	8	15.0	1.84	19	8	4.6	1.57	20	9	4.9	0.17	14	5
Beatrice	14.0	0.56	7	1	16.8	1.89	19	8	5.4	0.82	9	2	6.8	2.65	17	6
Unknown	13.4	0.56	8	2	17.9	1.36	11	2	5.2	0.68	10	3	6.0	0.66	9	2
Kalawe	13.5	4.67	22	10	17.2	6.22	25	10	5.3	1.49	13	4	6.5	4.79	19	7
96/1708	13.2	1.47	17	6	19.9	4.53	18	7	5.0	2.07	22	10	5.9	2.15	20	8
MK05/0297	11.3	1.65	23	11	17.6	2.10	17	6	4.2	1.99	26	11	5.9	0.93	12	3
Mulola	15.5	1.49	11	3	27.6	2.48	12	3	5.1	1.38	14	5	8.2	0.95	6	1
Mpale	11.5	1.31	16	5	17.3	1.50	14	4	4.4	1.85	22	10	5.8	0.78	13	4
TMS4(2)1425	5.7	1.17	21	9	20.0	9.20	20	9	2.2	0.50	18	7	5.8	2.62	22	10
01/1316	9.1	1.40	22	10	10.7	0.80	18	7	3.8	0.57	17	6	4.0	1.48	23	11
01/1569	14.3	2.49	18	7	19.6	2.12	16	5	5.0	0.47	8	1	6.2	1.41	13	4
Chamandanda	11.4	0.84	14	4	14.7	3.03	25	10	4.7	0.12	9	2	5.2	1.94	21	9
Sauti	11.3	2.15	24	12	13.1	0.56	16	5	3.7	1.91	27	12	4.9	1.48	20	8
Phoso	19.7	2.41	14	4	22.1	1.79	8	1	8.8	4.40	17	6	7.1	1.53	12	3

ASV = AMMI stability value, GSI = genotype selection index.

Table 6. Ranks of 16 genotypes in four environments using mean performance, AMMI stability value and genotype selection index for shoot mass and storage root number/plant.

	Shoot mass (t/ha)								Storage root number/plant							
	9 months after planting				12 months after planting				9 months after planting				12 months after planting			
Genotype	**Mean**	**ASV**	**GSI**	**Rank**	**Mean**	**ASV**	**GSI**	**Rank**	**Mean**	**ASV**	**GSI**	**Rank**	**Mean**	**ASV**	**GSI**	**Rank**
Maunjili	5. 6	6.71	17	5	15.4	4.74	24	10	4.3	0.06	13	5	3.7	0.53	19	10
Mbundumali	7.1	10.99	22	9	13.3	0.63	16	5	4.6	1.24	23	10	4.8	1.43	12	4
Yizaso	9.1	14.81	17	5	22.6	2.24	13	4	4.5	0.52	18	7	4.7	2.00	18	9
Beatrice	9.0	5.38	6	1	19.2	0.94	7	2	5.8	0.54	9	2	4.6	2.36	22	11
Unknown	6.0	10.24	21	8	14.3	0.45	13	4	4.9	0.28	11	3	4.7	0.44	10	3
Kalawe	7.4	17.55	20	7	14.4	1.26	18	6	5.0	2.14	21	9	5.2	1.81	13	5
96/1708	7.4	8.83	13	3	16.0	2.42	19	7	4.2	0.47	20	8	4.6	1.15	15	7
MK05/0297	11.1	25.95	17	5	17.5	0.81	8	3	5.2	0.57	13	5	4.2	0.33	13	5
Mulola	4.4	6.75	21	8	12.5	0.96	21	8	5.7	0.31	6	1	6.4	1.26	9	2
Mpale	7.2	9.59	18	6	15.7	1.49	16	5	4.9	0.44	12	4	4.8	1.73	13	5

TMS4(2)1425	7.2	14.79	22	9	14.0	2.70	27	11	2.9	0.86	28	11	3.7	2.68	28	14
01/1316	7.3	10.59	18	6	15.0	2.42	23	9	4.2	0.57	23	10	4.4	2.05	24	12
01/1569	4.9	5.83	18	6	15.5	1.80	18	6	5.0	1.75	20	8	4.6	0.51	14	6
Chamandanda	5.0	8.88	21	8	11.1	1.46	24	10	4.0	0.25	17	6	3.6	1.85	26	13
Sauti	9.4	11.10	14	4	16.8	2.07	16	5	5.2	1.79	18	7	6.9	14.04	17	8
Phoso	7.4	2.12	7	2	17.9	0.81	6	1	4.9	0.74	20	8	4.7	0.42	7	1

ASV=AMMI stability value, GSI=genotype selection index

Table 7. Ranks of 16 genotypes in four environments using mean performance, AMMI stability value and genotype selection index for storage root length.

	Storage root length (cm)							
	9 months after planting				12 months after planting			
Genotype	**Mean**	**ASV**	**GSI**	**Rank**	**Mean**	**ASV**	**GSI**	**Rank**
Maunjili	27.8	1.38	18	8	27.2	1.56	22	10
Mbundumali	30.8	0.70	9	2	32.6	0.20	13	4
Yizaso	33.6	4.67	20	9	37.5	0.24	9	1
Beatrice	33.0	1.85	13	4	39.1	3.86	18	7
Unknown	29.4	2.18	21	10	33.0	2.70	21	9
Kalawe	32.5	2.12	16	6	35.8	3.64	22	10
96/1708	36.4	2.54	15	5	40.2	4.95	18	7
MK05/0297	31.8	1.09	9	2	38.5	0.64	10	2
Mulola	30.3	1.17	12	3	39.0	3.37	17	6
Mpale	28.6	3.25	24	12	35.8	1.63	18	7
TMS4(2)1425	27.5	3.58	29	13	41.0	7.96	18	7
01/1316	28.6	1.44	17	7	28.1	1.77	23	11
01/1569	36.6	3.61	17	7	47.0	3.04	12	3
Chamandanda	27.8	2.11	22	11	27.0	0.62	19	8
Sauti	26.1	1.56	22	11	29.8	1.02	18	7
Phoso	37.7	1.58	8	1	37.1	1.24	14	5

ASV = AMMI stability value, GSI = genotype selection index

Table 8. Overall ranking of genotypes based on GSI for five traits evaluated at 9 and 12 MAP.

	9 Months after planting						12 Months after planting						
Genotype	**FSRY (t/ha)**	**DMY (t/ha)**	**SM (t/ha)**	**SRN/plant**	**SRL (cm)**	**Mean rank**	**FSRY (t/ha)**	**DMY (t/ha)**	**SM (t/ha)**	**SRN/plant**	**SRL (cm)**	**Mean rank**	**Overall rank**
Maunjili	1	1	5	5	8	2	6	6	1	10	10	7	3
Mbundumali	13	8	9	10	2	13	6	8	2	4	4	4	8
Yizaso	8	9	5	7	9	11	8	5	3	9	1	5	7
Beatrice	1	2	1	2	4	1	8	6	4	11	7	9	4
Unknown	2	3	8	3	10	4	2	2	4	3	9	2	2
Kalawe	10	4	7	9	6	9	10	7	5	5	10	10	9
96/1708	6	10	3	8	5	7	7	8	5	7	7	8	6
MK05/0297	11	11	5	5	2	8	6	3	5	5	2	3	5
Mulola	3	5	8	1	3	2	3	1	6	2	6	1	1
Mpale	5	10	6	4	12	10	4	4	6	5	7	5	6
TMS4(2)1425	9	7	9	11	13	15	9	10	7	14	7	12	12
01/1316	10	6	6	10	7	12	7	11	8	12	11	13	11
01/1569	7	1	6	8	7	5	5	4	9	6	3	6	5
Chamandanda	4	2	8	6	11	6	10	9	10	13	8	14	10
Sauti	12	12	4	7	11	14	5	8	10	8	7	11	11
Phoso	4	6	2	8	1	3	1	3	11	1	5	3	2

FSRY = fresh storage root yield, DMY = dry mass yield, SM = shoot mass, SRN = storage root number, SRL = storage root length

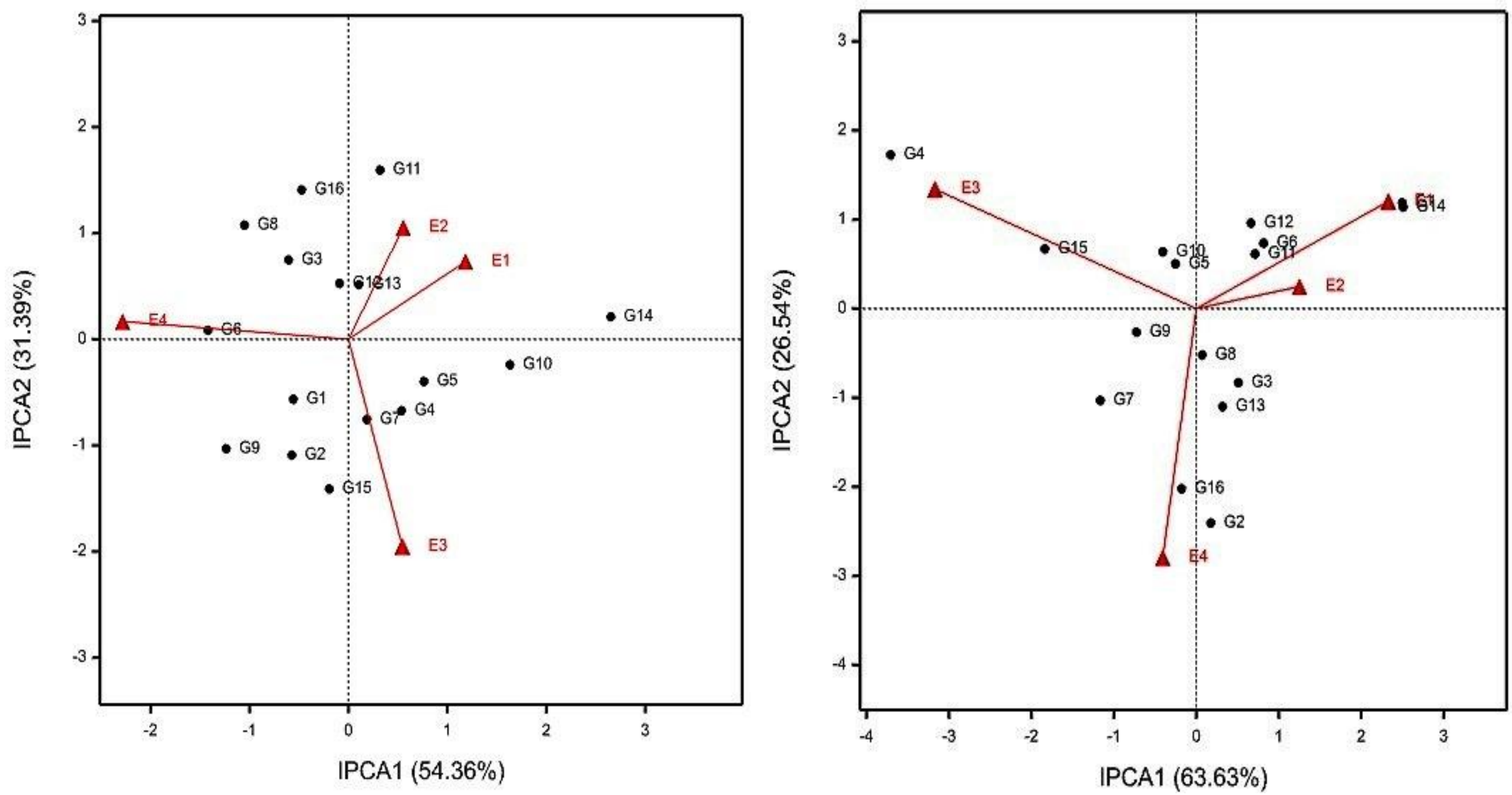

Figure 2. Biplots of the first interaction principal component axis (IPCA1) versus the second interaction principal component axis (IPCA2) for fresh storage root yield (t/ha) at 9 and 12 months after planting

(G1 = Maunjili, G2 = Mulola, G3 = Mpale, G4 = TMS4(2)1425, G5 = 01/1316, G6 = 01/1569, G7 = Chamandanda, G8 = Sauti, G9 = Phoso, G10 = Mbundumali, G11 = Yizaso, G12 = Beatrice, G13 = Unknown, G14 = Kalawe, G15 = 96/1708, G16 = MK05/0297, E1 = Chitala 2014, E2 = Chitala 2015, E3 = Kasinthula 2014, E4 = Kasinthula 2015)

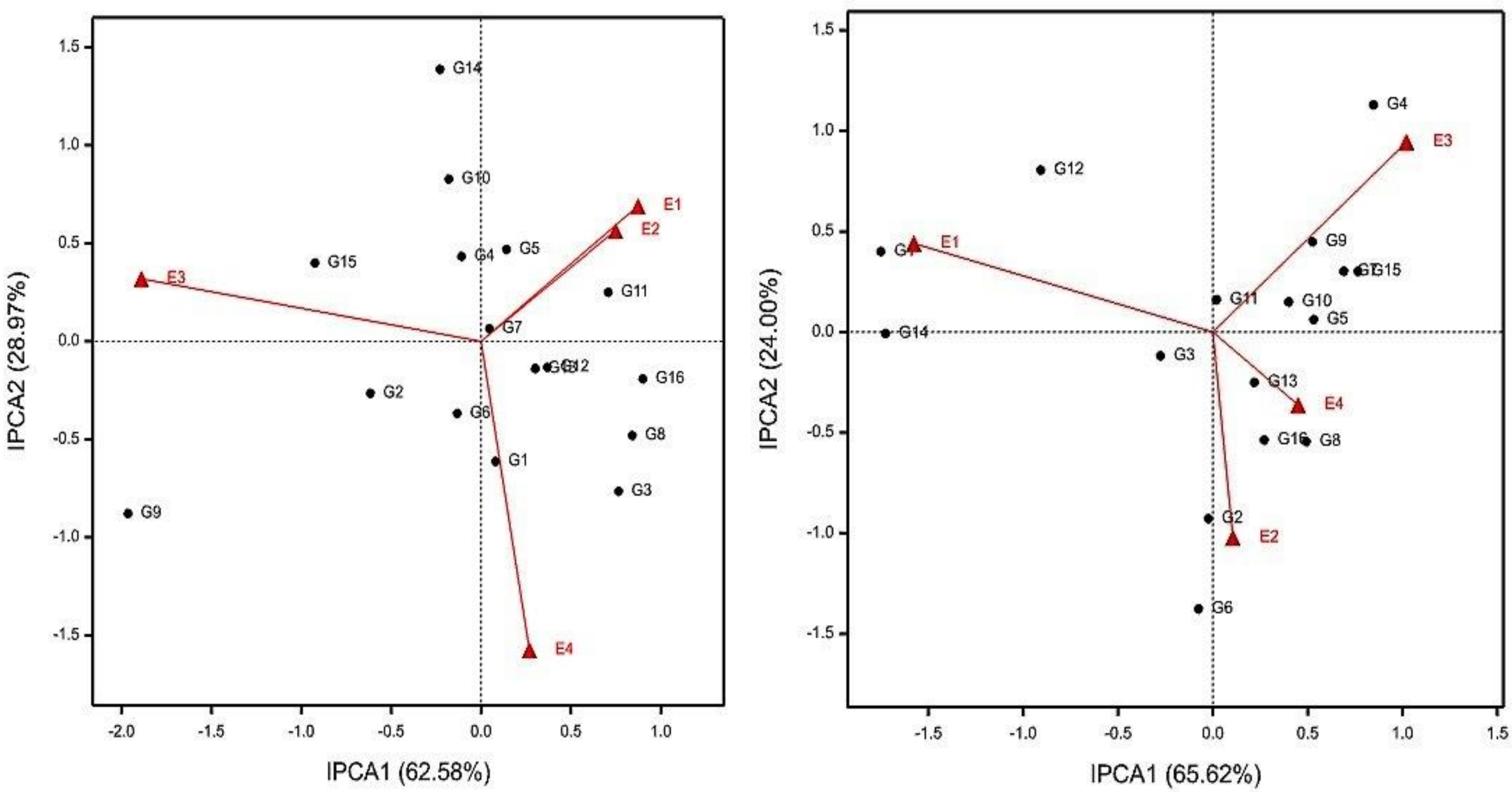

Figure 3. Biplots of the first interaction principal component axis (IPCA1) versus the second interaction principal component axis (IPCA2) for dry mass yield (t/ha) at 9 and 12 months after planting

(G1 =Maunjili, G2 = Mulola, G3 = Mpale, G4 = TMS4(2)1425, G5 = 01/1316, G6 = 01/1569, G7 = Chamandanda, G8 = Sauti, G9 = Phoso, G10 = Mbundumali, G11 = Yizaso, G12 = Beatrice, G13 = Unknown, G14 = Kalawe, G15 = 96/1708, G16 = MK05/0297, E1 = Chitala 2014, E2 = Chitala 2015, E3 = Kasinthula 2014, E4 = Kasinthula 2015)

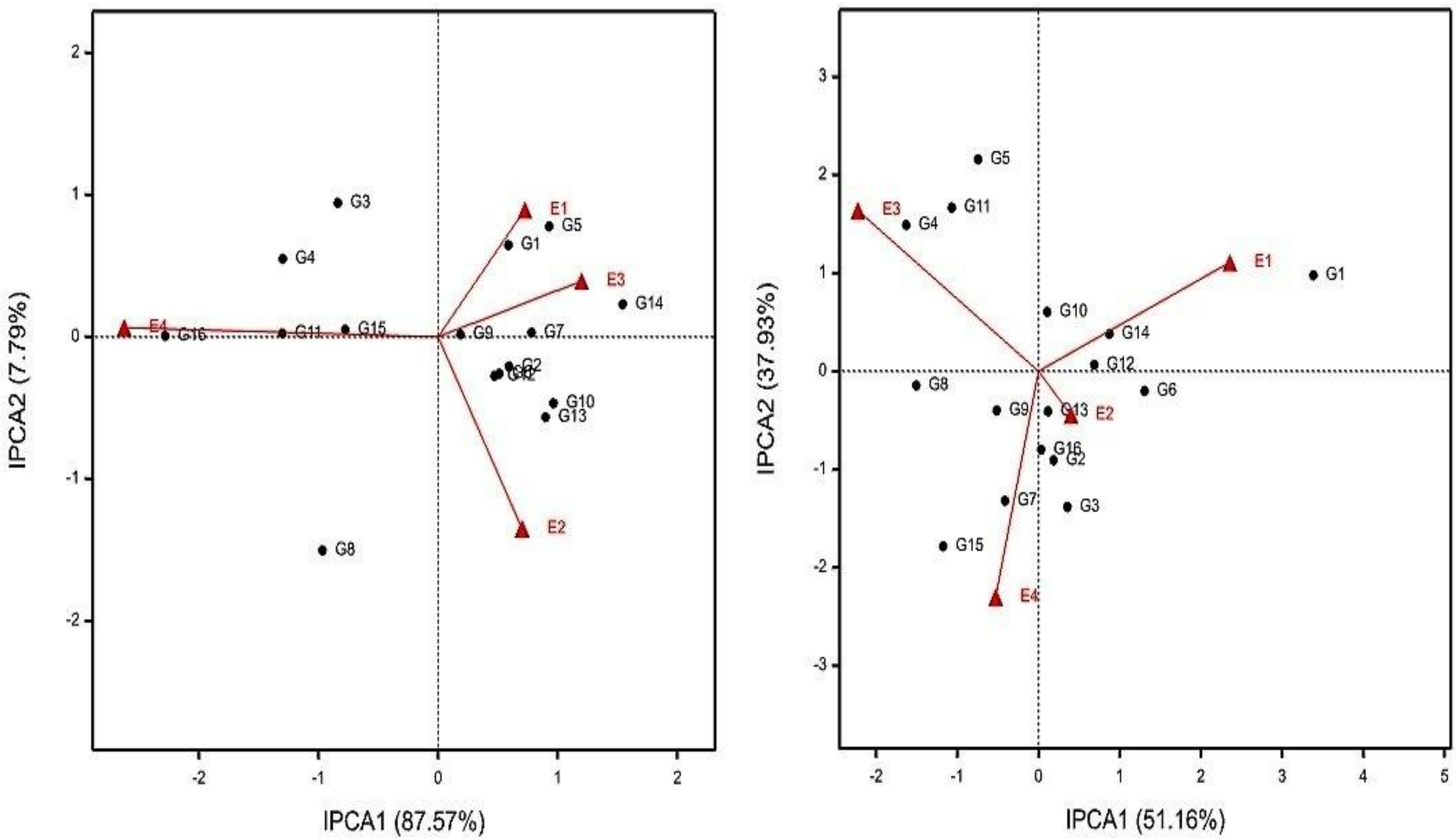

Figure 4. Biplots of the first interaction principal component axis (IPCA1) versus the second interaction principal component axis (IPCA 2) for shoot mass (t/ha)

(G1 = Maunjili, G2 = Mulola, G3 = Mpale, G4 = TMS4(2)1425, G5 = 01/1316, G6 = 01/1569, G7 = Chamandanda, G8 = Sauti, G9 = Phoso, G10 = Mbundumali, G11 = Yizaso, G12 = Beatrice, G13 = Unknown, G14 = Kalawe, G15 = 96/1708, G16 = MK05/0297, E1 = Chitala 2014, E2 = Chitala 2015, E3 = Kasinthula 2014, E4 = Kasinthula 2015)

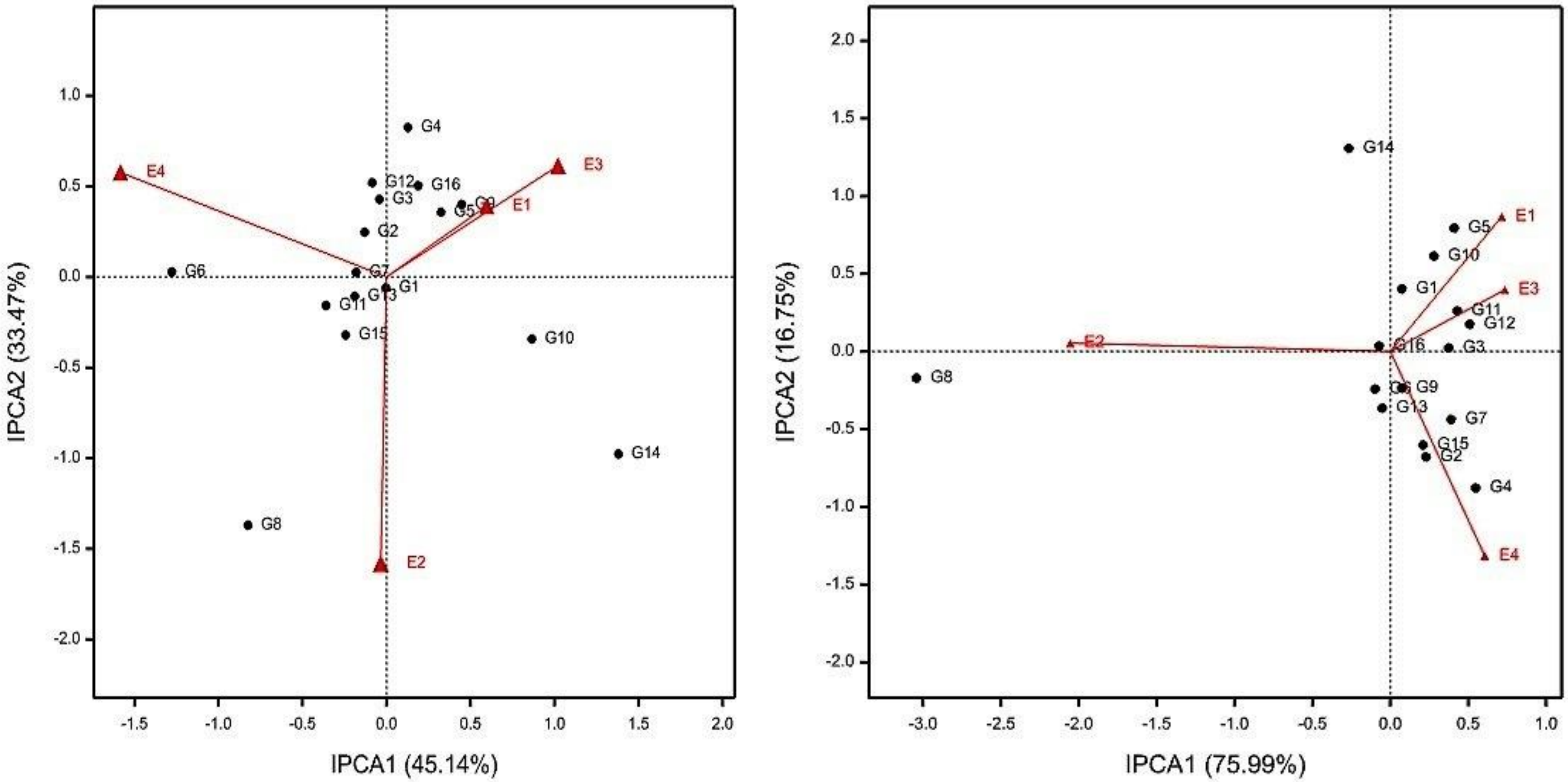

Figure 5. Biplots of the first interaction principal component axis (IPCA1) versus the second interaction principal component axis (IPCA2) for storage root number/plant at 9 and 12 months after planting

(G1 = Maunjili, G2 = Mulola, G3 = Mpale, G4 = TMS4(2)1425, G5 = 01/1316, G6 = 01/1569, G7 = Chamandanda, G8 = Sauti, G9 = Phoso, G10 = Mbundumali, G11 = Yizaso, G12 = Beatrice, G13 = Unknown, G14 = Kalawe, G15 = 96/1708, G16 = MK05/0297, E1 = Chitala 2014, E2 = Chitala 2015, E3 = Kasinthula 2014, E4 = Kasinthula 2015)

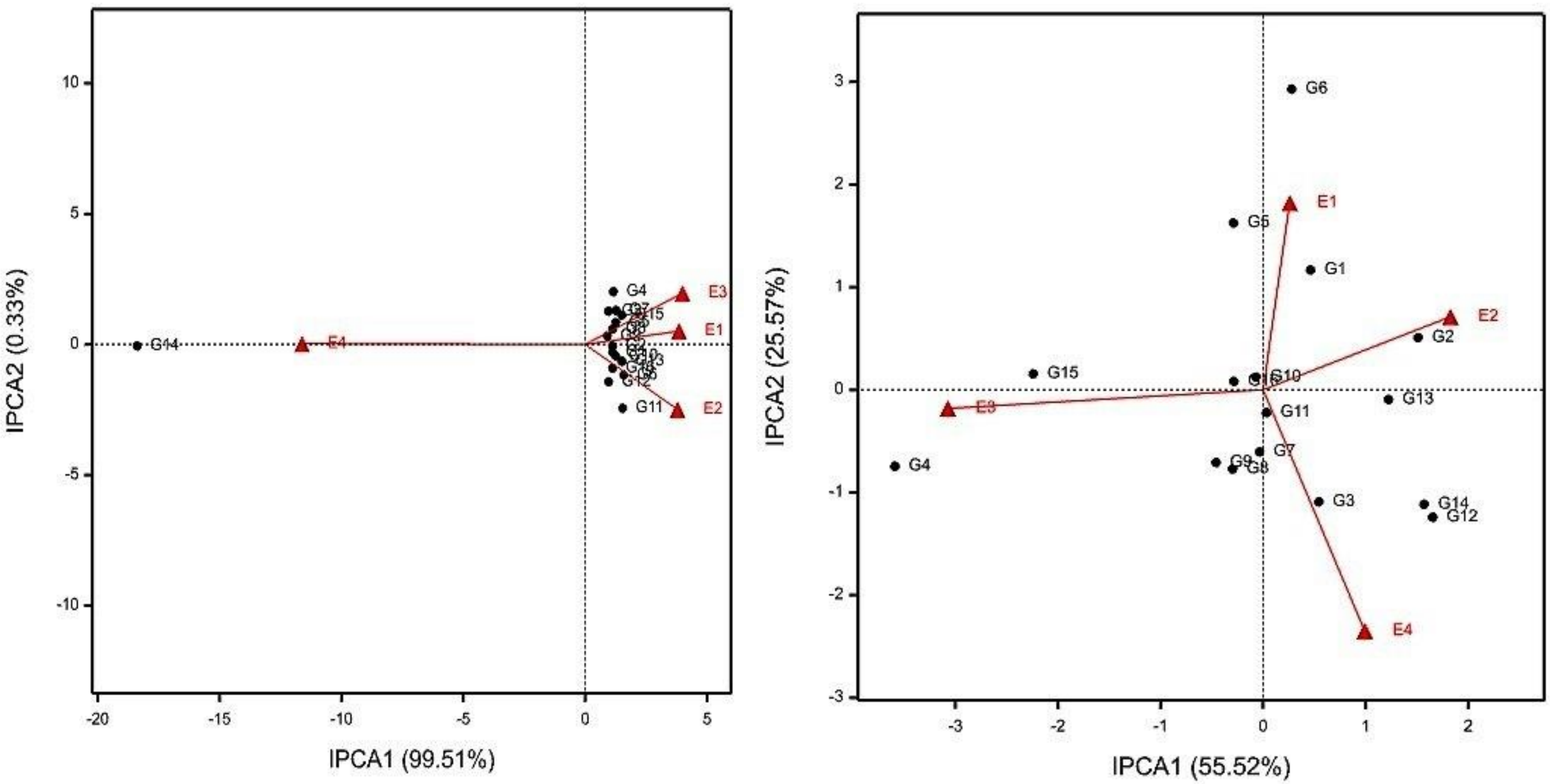

Figure 6. Biplots of the first interaction principal component axis (IPCA1) versus the second interaction principal component axis (IPCA2) for storage root length (cm) at 9 and 12 months after planting

(G1 = Maunjili, G2 = Mulola, G3 = Mpale, G4 = TMS4(2)1425, G5 = 01/1316, G6 = 01/1569, G7 = Chamandanda, G8 = Sauti, G9 = Phoso, G10 = Mbundumali, G11 = Yizaso, G12 = Beatrice, G13 = Unknown, G14 = Kalawe, G15 = 96/1708, G16 = MK05/0297, E1 = Chitala 2014, E2 = Chitala 2015, E3 = Kasinthula 2014, E4 = Kasinthula 2015)

DISCUSSION

Significance of main effects of genotypes and environments indicated stability of some genotypes across environments while GEI significance indicated that some genotypes were specifically adapted to certain environments.

The significance of genotypic variances at the three harvesting periods (6, 9 and 12 MAP) for fresh storage root yield and most other traits indicated the presence of high variability between genotypes. This suggests that judicious selection among these genotypes may result in more significant genetic gains in a breeding program aimed at improving the targets traits. Fresh storage root yield variation due to genotype was higher than environmental influence at 6 MAP, had an equal contribution at 9 MAP and was lower at 12 MAP which suggests that yield is a complex polygenic trait influenced by both genotype and environment. This means that superior and better performing genotypes are those having good genetic background managed under ideal growing conditions (environment). Harvest index and storage root number/plant were largely controlled by genotypic effects regardless of the harvest time. This agrees with Kawano (2003) who reported that harvest index is largely under genetic control. And this trait has been widely used to select indirectly for storage root yield (Alves, 2002). Alves (2002) indicated that storage root number per plant is determined at an early stage of cassava development and is a strong indicator of the potential of the variety to yield more, and elsewhere (Akinwale *et al*., 2010; Alves, 2002; Chipeta *et al*., 2013; Chipeta *et al*., 2016b; DaSilva, 2008; Kamau *et al*., 2010; Ntawuruhungu *et al*., 2001) it has shown strong positive correlation with storage root yield. This means that potential yield of a genotype can be determined at an early stage. Some farmers use storage root number as a measure of potential yield for a particular variety (Chipeta *et al*., 2016a).

The large and significant environmental variances for most traits such as shoot mass, dry mass yield, dry mass content and starch content at all harvest periods indicate the significant differences between the averages of some environments, which caused most of the variation in the cassava genotypes. A significant effect of the GEI revealed the differential performance of genotypes in different environments (specific adaptation). Therefore, this change in the average performance of cassava genotypes due to the environment rationalizes the need for a more definitive analysis to increase selection efficiency and varietal recommendations. This differential performance (GEI) can be reduced by selecting genotypes that are stable within a wide range of environments. The non-significance of GEI at 6 MAP for almost all traits means that genotypes can be reliably evaluated in any single environment. These results, therefore, imply that early storage root bulking cultivars (harvested at 6 MAP) may not necessarily be subjected to multi-location trials for their stability performance. However, GEI in cassava is a common occurrence as shown at 9 and 12 MAP which also agrees with other reports (Agyeman *et al*., 2015; Aina *et al*., 2009; Akinwale *et al*., 2011; Alves, 2002; Benesi *et al*., 2004; Dixon and Nukenine, 1997; Kundy *et al*., 2014; Kvitschal *et al*., 2006, 2009; Mtunda, 2009; Noerwijatia *et al*., 2014 ; Ssemakula and Dixon, 2007; Tumuhimbise *et al*., 2014) which confirms the need for multi-location trials (Fox *et al*., 1997; Romagosa and Fox, 1993).

IPCAs that were significant indicated a significant contribution to GEI. However, IPCA1 had the greatest contribution to the GEI as it explained more of the GEI variation. Only two IPCAs were selected because they accounted for most of the variation which ranged from 78.61% to 99.84% for all traits. This agreed with the findings of Gauch and Zobel (1996) who recommended that the most accurate model for AMMI can be predicted using the first two IPCAs. The two IPCAs scores were then used in calculation of ASV as postulated by Purchase *et al*. (2000).

Selection of 1) high yielding genotypes based on mean performance, 2) stable genotypes based on GSI (mean performance and ASV) and 3) adaptability of genotypes based on biplots of the first interaction principal component axis (IPCA1) versus the second interaction principal component axis (IPCA2) identified five genotypes (Mulola, Phoso, Maunjili, Beatrice and Unknown) that exhibited consistent performance, stability and adaptability across the three harvest periods. In addition, these genotypes would be regarded as early storage root bulking cultivars because regardless of the harvesting period (6, 9 and 12) they give very high yields despite being produced under very minimal inputs (no chemical fertilizers, no pesticides application and no supplementary irrigation), that is, up to 11 t/ha at 6 MAP, 20 t/ha at 9 MAP and 28 t/ha at 12 MAP. On the other hand, TMS4(2)1425, Sauti, 01/1316 and Chamandanda were identified as the least performers, most unstable and having specific adaptation to certain environments.

Most studies on stability and adaptability in cassava have been based on a single harvest time mainly at 12 MAP (Agyeman *et al*., 2015; Aina *et al*., 2009; Akinwale *et al*., 2011; Benesi *et al*., 2004; Ssemakula and Dixon, 2007), at 10 MAP (Noerwijatia *et al*., 2014) and at 9 MAP (Tumuhimbise, 2013). The present study is, therefore, the first to report on performance, stability and adaptability across different harvest periods using AMMI.

Conclusions: High variability existed among cassava genotypes for fresh storage root yield and related traits. The study revealed that large and significant environmental variances for most traits at all harvest periods caused significant differences between the averages of some environments, which caused most of the variation in the cassava genotypes. Most of the cassava genotypes exhibited specific adaptation to certain environments except for Mulola, Phoso, Maunjili, Beatrice and Unknown which were high yielding, stable and adaptable to a wide range of environments at 6, 9 and 12 MAP. It has also been shown that multilocation studies in cassava regardless of the harvesting time help to discriminate genotypes with superior performance, stability and general adaptation.

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