African Journal of Biotechnology Vol. 8 (19), pp. 4933-4945, 5 October, 2009
Available online at http://www.academicjournals.org/AJB
ISSN 1684–5315 © 2009 Academic Journals

Full Length Research Paper

G×E interaction effects on yield and yield components of cassava (landraces and improved) genotypes in the savanna regions of Nigeria

O. O. Aina[1,2,3*], A. G. O. Dixon[1], Ilona Paul[1] and E. A. Akinrinde[3]

[1]International Institute of Tropical Agriculture, P. M. B. 5320, Ibadan, Nigeria.
[2]College of Agricultural Sciences, Joseph Ayo Babalola University, Ikeji Arakeji, P. M. B. 5006, Osun State, Nigeria.
[3]Department of Agronomy, University of Ibadan, Nigeria.

Accepted 5 June, 2009

Genetic enhancement of cassava aimed at increasing production and productivity through the provision of broad-based improved germplasm is a major goal for cassava breeders. At the International Institute of Tropical Agriculture (IITA), Nigeria, 18 varieties comprising 12 landraces and 6 broad-based and improved varieties were evaluated at 4 locations in 3 years in a randomized complete block design in 4 replicates to determine variability among cultivars for yield components and adaptation to different environments. Results showed fresh root yield was significantly correlated (P < 0.001*)* with number of roots, harvest index, shoot weight and number of stands harvested. AMMI analysis partitioned main effects into genotypes, environments and G × E with all the components showing highly significant effects (P < 0.001). Environment had the greatest effect (70.3%), G × E interaction (19.0%) and genotype (10.7%). AMMI1 and unadjusted means selected the same winner in 9 out of 12 environments (75%), but differently in 3 environments. The GGE biplot (E and GxE interaction) delineated environments into mega-environments. Cultivar 4(2)1425 (moderately yielding) was the most stable and specifically adapted to Zaria. ABBEY-IFE, ATU-IWO and 2ND-AGRIC though moderately yielding were highly tolerant to CMD, suggesting a rich resource within the germplasm that could be enhanced for further genetic improvement of the crop.

Key words: Cassava, AMMI analysis, GGE biplot, GxE interaction, mega-environment.

INTRODUCTION

Cassava (*Manihot esculenta* Crantz) is a perennial crop, native to tropical America (Olsen and Schaal, 2001) and constitutes an essential part of the diet of most tropical countries of the world (Calle et al., 2005) about 70 million people derive more than 500 cal/day from food based on its roots (Chavez et al., 2005). Cassava is, however, faced with production constraints from pests, diseases and poor soil fertility everywhere it is grown on the African continent. One of the goals of the cassava breeding unit of the international institute of tropical agriculture (IITA), Nigeria, is genetic enhancement aimed at increasing the cassava's productivity through the provision of broad-based improved germplasm that combines multiple disease resistance ability with a high yield and other desirable traits.

One major way of realizing this objective is through the conservation and maintenance of the valuable genetic resources made possible by sustaining landrace germplasm that constitutes useful starting materials for variety development. Maintaining the landrace germplasm is, therefore, a method of conserving the valuable genetic resources available within the gene pool. This helps to increase agricultural production and enhances food security through crop improvement strategies carried out at present and also for future use. A more efficient use of plant genetic diversity is a prerequisite to meeting the challenges of development, food security and poverty alleviation (FAO, 1996).

Landraces have been found to be characterized with diverse morphological traits, yield traits and resistance to

*Corresponding author. E-mail: f_aina2002@yahoo.com.

important pests and diseases. Landraces were considered to be the most likely sources of tolerance to the reniform nematode in pigeonpea (Sharma et al., 2000). Landraces of white lupin have also been identified as important source of alleles for shortening the vegetative period, reducing plant height, as well as improving yield components (Raza and Msgsrd, 2005). Evidence of drought tolerance has also been identified among landraces of chickpea (Kashiwagi et al., 2005). Wide variation exists, indicating wide genetic variability. (Rubio et al., 2004) observed wide variation among landraces for trait phenology, plant structure, and yield characters, indicating the possibility of improving yield components and increasing yield among locally adapted landraces of lupins. The findings of (Brocke et al., 2003) also confirmed higher variations within landrace populations' of pearl millet than for other samples. (Sharma et al., 2000) discovered that traditional landraces of durum wheat were low yielding but generally stable and suggested the need to enhance landrace cultivation with modern varieties to improve competitiveness in yield with other modern varieties, Oliveira et al. (2000) reported that wheat landraces performed as well as the comercial cultivars for grain yield and grain quality. Also, Ceccarelli et al. (1998) showed that landraces of barley from very dry areas were the highest yielding lines under stress environments. Landraces have been found useful in the incorporation of disease and pest resistance genes into *Musa* sp. in IITA (Herzberg et al., 2004). The improved new rice for Africa (NERICA) rice was a result of crosses between the African local landrace, *Oryza glaberrima* and the Asian rice, *Oryza sativa*, which produces combined positive characters of high grain yield and resistance to pests and diseases (Futakuchi et al., 2003).

Agriculture today is characterized by a sharp reduction in the diversity of cultivated plants (Maxted et al., 2002). The genetic improvement of plant genetic resources for specific traits, followed by the successful cultivation of the improved materials, is therefore one of the sustainable ways to conserve valuable genetic resources for the future. Conserving plant genetic resources is helpful to: i) developing cultivars that are specifically adapted to marginal or stress environments, ii) assuring sustainable production in high yielding environments through better input-output relations, that is, through reduced application of agrochemicals and iii) increasing nutrient and water efficiency to open production alternatives for farmers through the development of industrial or pharmaceutical crops.

The aim of maintaining plant genetic resources is not only to exploit intraspecific variation within a crop but also to increase interspecific diversity in agriculture through genetic improvement and the promotion of less popular, neglected, or underutilized crop species (Padulosi et al., 2002). Most of the recent breeders' lines are constituted from crosses made on different selected landraces that had been pre-selected for agronomic traits and yield performance. These are intercrossed, recombined and then selected for adaptation to the target environment, breeders' preference, consumers' preference and desirable quality characteristics.

Cassava is a crop that prospers in difficult and variable environments and breeders are faced with the need to consider many characters, each with multigenic control (Kawano et al., 1998). Improvement of the crop has been primarily oriented towards relatively few traits, especially yield and pest and disease resistance. Yield, however, is a complex trait with many individual components, each involving numerous biochemical pathways. Recent efforts are being directed towards expanding the production of cassava into the highlands and the semi-arid regions of Africa, which needs selection for drought tolerance. The basis for genetic improvement is the identification of representative environments where the principal traits of interest are consistently expressed at levels appropriate for selection (Iglesias et al., 1996). Landraces, therefore, constitute an important starting material from where desirable traits can be tapped for improvement purposes. We need to conserve these rich sources of genetic variation.

The objective of this study is to evaluate some cassava landraces for variability in yield and yield-related attributes and specific adaptation to different environments. The aim is to ensure their long-term conservation and increased utilization.

MATERIALS AND METHODS

Yield trials were conducted for 3 planting seasons (1998/1999, 1999/2000 and 2000/2001) using 18 cassava landraces from the collections available at the (IITA), Ibadan. Trials were conducted at 4 locations belonging to the moist and dry savanna agroecological zones of Nigeria: Ibadan (transition forest savanna), Mokwa (southern Guinea savanna), Zaria (northern Guinea savanna) and Mallamadori (Sudan savanna). The genotypes were grown under rainfed conditions in a randomized complete block design with 4 replicates. Neither pesticides nor fertilizers were applied and planting was done using disease-free stakes planted on 4–row plots of 10 plants/row with a plot size of 40 m^2. Plants were harvested at 12 months after planting yield data were determined on a plot basis using the 2 inner rows for each genotype on root number (RTNO), root weight (RTWT) and fresh root yield (FYLD) (t/ha). Other parameters evaluated included root size, the plants' reaction to cassava mosaic disease severity (CMDS) and incidence (CMDI) and the level of cyanogenic glucosides potential (CNP).

Statistical analysis

Analysis of variance (ANOVA) combined over locations and years was done on a plot mean basis and pooled over locations and seasons using the generalized linear model procedures of the statistical analytical system (SAS) version, 2000). Correlation between different traits was determined using the proc corr procedures, also of SAS. The additive main effects and multiplicative interactions (AMMI) statistical model (MATMODEL 2.0 (Gauch, 1993) was used to analyze the yield data to obtain AMMI analysis of variance and AMMI mean estimates. The E and GxE interaction

Table 1. Combined analysis of variance for yield component and disease tolerance of 12 cassava landraces and 6 improved genotypes grown in 12 environments (4 locations for 3 years) in Nigeria.

Source	DF	NOHAR	RTNO	RTWT(kg)	FYLD(t/ha)	HI	DM	CMDS	CMDI	CBBS	CBBI
Environment (E)	11	934.5***	48518.57***	6979.73***	1744.93***	0.49***	1315.55***	27.44***	1.21***	58.38***	5.17***
Year (y)	2	370.76***	17182.07***	1118.93***	279.73***	0.05***	1041.66***	1.07***	0.23***	29.10***	0.38***
Location (L)	3	2230.26***	109885.67***	20221.93***	5055.48***	0.99***	2544.26***	97.90***	4.20***	51.63***	2.01***
Y × L	6	475.29***	28142.01***	2084.65***	521.16***	0.23***	635.97***	1.01***	0.04***	69.68***	9.18***
Rep (Y× L)	24	17.39***	713.01***	141.31***	35.33***	0.02***	18.25	0.16	0.01	0.14	0.03
Genotype (G)	17	168.25***	8109.05***	1133.77***	283.44***	0.12***	244.93***	22.21***	1.94***	1.19***	0.36***
G×E	187	27.73***	1178.31***	178.7***	44.68***	0.02***	31.79***	0.72***	0.05***	0.31***	0.08***
G×Y	34	19.82***	842.33***	93.28***	23.32***	0.01***	27.07**	0.54***	0.02***	0.30***	0.08***
G×L	51	40.19***	2370.02***	419.05***	104.76***	0.03***	51.25***	1.70***	0.13***	0.36***	0.09***
G×L×Y	102	23.77***	675.9***	82.18***	20.55***	0.01***	22.05**	0.29***	0.01*	0.28***	0.07***
Pooled error	588	9.29	248.8	30.01	7.5	0.01	14.82	0.19	0.12	0.2	0.1

*,**, *** Significant level at P < 0.05, 0.01 and 0.001; ns = not significant.

biplot analysis for windows application version 4.1 (Yan, 2001) was used to generate the E and GxE interaction biplot used to analyze the multi-environment trial (MET) data. The model used for the E and G × E interaction biplot analysis was the no-scaling and tester-centered model.

RESULTS AND DISCUSSION

The combined analysis of variance across environments (Table 1) showed highly significant (P < 0.001) mean squares (MS) for yield and yield-related traits and also for disease tolerance for nearly all the sources of variation. Environment (E), genotypes (G) and genotype by environment interaction (G×E) showed highly significant MS (P < 0.001) for all traits evaluated. Effects from G and E that showed highly significant MS reflected genotypic differences towards adaptation to different environments, thus the highly significant G×E effects suggests that cultivars may be selected for adaptation to specific environments. High variability was observed among cultivars as indicated by the range of their mean performance (Table 2). The number of roots harvested ranged between 78 (30572) and 21 (Isu), with FYLD ranging from 12.47 t/ha in (82/00058) to 2.90 t/ha in the variety that also had the lowest number of stands at harvest, thereby recording the lowest yield. The low yielding ability observed for Isu was due to the high susceptibility of the cultivar to prevalent diseases, where the highest CMDS and CMD were recorded. Isu being highly susceptible to CMD and cassava bacterial blight was used as a spreader line in this trial. Landrace cultivars Abbey-Ife and Atu-Iwo showed high levels of tolerance to CBB severity and incidence, but were moderately yielding, most of the improved lines (30572, 82/00058, 82/00661 and 81/00110) were high yielding and moderately tolerant to CMD severity and incidence (Table 2). The lower FYLD observed among cultivars could be attributed to the soil nutrient status. This falls below the critical levels for the major nutrient elements of organic C, total N and exchangeable P in all the locations, therefore limiting the crop from reaching its yield maximum potential (Table 3).

Results of correlation analysis showed a highly significant correlation (P < 0.001) between fresh root yield and number of roots (RTNO), root weight, harvest index and shoot weight and also a significant correlation (P < 0.01) with number of stands harvested and CNP. However, FYLD was highly significant but negatively correlated (P < 0.001). CBB severity and CBB incidence of CBB were also negatively but not significantly correlated with dry matter, CMDS and CMDI (Table 4). Harvest index and number of roots that showed a strong positive correlation with fresh tuber yield have been confirmed as good indicators of yield in cassava (Lian, 1985). Although dry matter showed no significant correlation with fresh root yield, it is assumed to be one of the most important storage root components. Kawano et al. (1998) and Ntawuruhunga et al. (2001) reported that selection for dry matter content could be conducted without any serious effect on other yield components.

The comparative performance of the cultivars across locations (Figure 1) revealed that Mokwa had the best performance for FYLD, RTNO and

Table 2. Mean performance of 18 landrace cultivars 12 cassava landraces and 6 improved genotypes in 12 environments (4 locations in 3 years) in Nigeria.

Clone	NOHAR	RTNO	RTWT (kg)	FYLD (t/ha)	HI	SHWT	DM	CNP	SPR	CMDS	CMDI	CBBS	CBBI
30572	14.92	78.40	24.48	12.24	0.48	29.07	26.98	14.05	0.88	2.03	0.17	2.33	0.58
2ND-AGRIC	14.26	51.98	18.39	9.20	0.42	23.78	32.23	12.25	0.95	1.26	0.04	2.55	0.75
4(2)1425	13.96	49.83	20.39	10.19	0.49	22.40	27.95	9.41	0.84	2.46	0.25	2.07	0.51
81/00110	11.52	62.35	23.07	11.54	0.50	25.40	26.85	15.91	0.67	2.09	0.24	2.28	0.54
82/00058	12.81	77.40	24.94	12.47	0.47	33.58	23.96	19.41	0.78	1.73	0.12	2.28	0.57
82/00661	13.24	55.22	23.39	11.69	0.50	23.48	27.63	9.49	0.81	1.82	0.12	2.32	0.57
ABBEY-IFE	13.92	48.58	15.80	7.90	0.41	22.69	30.77	11.87	0.96	1.10	0.01	2.58	0.75
ALICE-LOCAL	11.85	43.59	13.22	6.61	0.38	22.17	25.79	5.87	0.82	1.24	0.03	2.54	0.69
AMALA	8.09	28.58	8.15	4.08	0.34	15.89	30.45	9.21	0.70	1.36	0.05	2.65	0.68
ANTIOTA	12.62	52.40	16.03	8.01	0.39	25.41	27.64	5.66	0.88	1.62	0.12	2.46	0.68
ATU-IWO	13.74	45.43	14.60	7.30	0.38	23.25	30.70	12.39	0.95	1.17	0.02	2.59	0.78
BAGI-WAWA	13.65	50.40	16.90	8.45	0.40	22.54	31.80	11.94	0.96	1.35	0.07	2.53	0.71
ISU	8.39	21.62	5.81	2.90	0.26	14.97	25.56	6.48	0.83	3.96	0.89	2.59	0.64
LAPA1-1	13.34	47.53	15.61	7.80	0.40	23.47	29.76	12.78	0.94	1.27	0.04	2.58	0.75
MS20	13.23	50.77	15.69	7.85	0.39	24.32	26.56	5.52	0.89	1.58	0.10	2.64	0.69
OFEGE	12.19	48.23	14.85	7.43	0.41	23.66	27.05	5.88	0.83	1.63	0.12	2.46	0.67
OKO-IYAWO	14.17	51.77	17.43	8.71	0.39	25.34	31.66	12.49	0.95	1.23	0.04	2.52	0.75
TOKUNBO	14.31	49.44	17.36	8.68	0.42	23.54	30.92	12.03	0.95	1.23	0.03	2.54	0.75
Mean	12.79	50.75	17.01	8.50	0.41	23.61	28.57	10.70	0.86	1.67	0.14	2.47	0.67
Se ±	0.46	3.26	1.24	0.62	0.01	0.98	0.60	0.94	0.02	0.17	0.05	0.04	0.02
Cv (%)	14.72	26.51	30.07	30.07	14.43	17.17	8.71	36.09	10.36	40.66	86.50	6.27	12.40

RTWT for the 3 planting seasons. Zaria recorded the highest dry matter (%) for the first 2 seasons and Mallamadori had the highest dry matter in the third season. Since rainfall is the critical climatic factor that distinguishes the different agroecological zones, the climatic data (Table 5) showed that Ibadan and Mokwa had sufficient rainfall and an appreciable length of growing period. Zaria and Mallamadori had less rainfall and a reduced number of growing days, signifying the possibility of soil moisture stress that resulted in a high reduction in the performance of cultivars for yield and yield-related traits. The higher mean performance observed in Mokwa than in Ibadan could be due to a more favorable micro-climate and the higher radiation in Mokwa which resulted in higher yield responses.

AMMI analysis in 12 environments (Table 6) shows that AMMI analysis partitioned main effects into genotypes, environments and G × E, with all the components show-ing highly significant effects ($P < 0.001$). The environment had the greatest effect and accounted for 70.3% of the treatment sum of squares (SS); the G × E interaction accounted for 19.0%; G had the least effect and accountted for only 10.7%. The highly significant effects of E indicated high differential responses among cultivars across the different E. The variation in soil moisture availability across the different E was thus considered as a major causal factor for the G × E interaction that was observed. The higher relative magnitude of the environment thus suggested that environmental factors have a large influence on cultivar performance. The first interaction principal component axis (IPCA1) was highly significant ($P < 0.001$) and explained the interaction pattern better than other interaction axes. The postdictive success for AMMI indicated that the treatment SS was partitioned into 2 components: 85.86% due to the pattern (G main effects and IPCA1) and 14.14% as residual or random variation (noise), related to the experi-

Table 3. Soil physical and chemical properties in 4 locations for 3 planting seasons (1997/1998, 1998/1999, 1999/2000) in Nigeria.

Properties	Ibadan			Mokwa			Zaria			M/madori		
	97/98	**98/99**	**99/00**	**97/98**	**98/99**	**99/00**	**97/98**	**98/99**	**99/00**	**97/98**	**98/99**	**99/00**
pH H^2O	5.4	5.5	6.4	6.1	6.3	6.4	5.7	5.5	5.8	5.6	5.6	6.1
Organic C (%) (3)	0.91	0.98	0.60	0.63	0.65	0.60	0.49	0.48	0.61	0.32	0.27	0.42
Total N (%) (5)	0.123	0.106	0.039	0.048	0.043	0.039	0.049	0.043	0.056	0.031	0.021	0.032
Avail P (mg/kg) (7)	34.4	33.6	37.4	3.0	3.2	3.7	1.6	1.8	1.5	10.6	10.5	9.0
Exch Ca (cmol kg) (0.6)	2.2	1.7	1.7	1.9	1.5	1.9	2.7	2.7	2.3	2.9	3.5	1.3
Exch Mg (cmol kg) (0.25)	0.4	0.3	0.4	0.4	0.3	0.5	1.2	0.8	1.0	0.9	0.8	0.4
Exch k (cmol kg) (0.18)	0.3	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.3	0.3	0.3	0.2
Cu (ppm) (5)	2.9	2.2	2.0	1.4	1.3	1.5	1.5	1.6	1.8	0.8	0.8	1.0
Zn (ppm) (30)	5.0	4.0	4.6	1.3	1.3	1.3	1.3	1.8	1.8	1.6	1.5	1.6
Mn (ppm) (50)	82.7	70.1	80.9	70.2	68.3	70.3	29.4	30.2	28.6	17.2	16.8	17.0
Fe (ppm) (60)	16.9	14.6	18.6	11.4	10.5	18.5	22.5	25.2	26.4	4.8	5.2	3.3
Sand (%)	86	76	81	83	80	81	50	44	40	78	85	70
Silt (%)	5	9	8	9	11	8	14	15	13	12	9	20
Clay (%)	9	15	11	8	9	11	36	41	47	10	6	11
Textural class	Sandy loam			Sandy loam			Sandy clay			Sandy soil		

Critical levels in parentheses and in bold.

mental design. Within environments, AMMI1 frequently ranked cultivars differently from unadjusted means with AMMI1 and unadjusted means, selecting the same winner in 9 out of 12 environments (75%), but different winners in the remaining 3 (25%). (Dixon and Nukenine, 1997) showed that AMMI estimates ranked top performing entries differently in more than half of the environments when compared with the unadjusted means in cassava. The mean values from AMMI estimates and unadjusted means for FYLD were similar for cultivars and for environments (Table 7). AMMI and unadjusted means recorded higher FYLD for the improved cultivars than for the landraces with cultivar Isu having the lowest yield in both cases. AMMI and unadjusted means for E were the same in six environments with the remaining 6 showing only slight variation. The G and (G×E) interaction (GGE) biplot define an ideal genotype, based on both mean performance and stability across environments. The GGE biplot explains more G+GE than AMMI and therefore is considered a better presentation of the GGE data. In the AMMI biplot, each genotype is represented by a linear line defined by the genotype's mean yield and its IPCA score on the Y-axis and mean yield on the X-axis. Both axes in GGE biplot are results of least square solutions, whereas only the IPC1 is the result of least squares in AMMI. The GGE biplot therefore exemplifies data from (MET) indicating the accurate positioning of both cultivars and environments on a single biplot.

AMMI bilpot with GGE analysis

The GGE biplot for AMMI (Figure 2) explained by the 2 axes showed that E explained 58.3%, G 16.8% and the IPCA1 15.6%, reflecting 90.7% of the yield variation due to AMMI. The AMMI biplot from GGE analysis showed that G1, G5 and G6 are high yielding and highly stable cultivars, G4 was also highly stable but low yielding, G3, though moderately yielding, was the most stable cultivar across all environments. G12, G17 and G18 were also moderately stable but low yielding. G2 was also moderately stable with moderate yield. G10, G11, G14 and G15 were, however, found to be highly unstable, though high yielding. G7, G8, G9, G13 and G16 were low yielding and also very unstable across environments. G1 was found to be specifically adapted to ENV 5, G4 was adapted to ENV1, G15 and G16 were adapted to ENV 12 and G9 and G13 were specifically adapted to ENV 3.

Which genotype won where and mega-environments with GGE biplot

The GGE biplot (Figure 3) depicts the cultivars that had the best performance in each environment. The model used to generate the biplot explained 63.4% in axis 1 and 22.1% in axis 2, both reflecting 85.5% of the yield variation due to GGE. A convex-hull drawn on cultivars from the biplot origin gave 5 sectors with G1, G2, G5, G12 and G13 as the vertex cultivars. ENV 5 fell in the sector in which G1 was the vertex cultivar and E1 G5, E10, E6 and E2 for G2, meaning that these cultivars are best in these environments. No environment fell into sectors with G12 and G13 as the vertices, indicating that these cultivars were not the best in any environment and

Table 4. Phenotypic correlation coefficients for 12 cassava landraces and 6 improved genotypes in 4 locations for 3 planting seasons (1997/1998, 1998/99, 1999/2000) in Nigeria.

	FYLD (t/ha)	NOHAR	RTNO	RTWT (kg)	HI	SHWT	DM	CMDS	CMDI	CBBS	CBBI	CNP
FYLD (t/ha)	1	0.67**	0.93***	0.98***	0.94***	0.84***	–0.16	–0.17	–0.33	–0.72***	–0.49	0.62**
NOHAR		1	0.64***	0.67**	0.60**	0.65**	0.33	–0.48	–0.55*	–0.26	0.17	0.34
RTNO			1	0.93***	0.81***	0.95***	–0.24	–0.23	–0.36	–0.58*	–0.37	0.63**
RTWT (kg)				1	0.94***	0.84**	–0.16	–0.17	–0.33	–0.72***	–0.49	0.62**
HI					1	0.69**	–0.12	–0.21	–0.40	–0.78***	–0.55	0.51
SHWT						1	–0.26	–0.31	–0.40	–0.47	–0.22	0.59**
DM							1	–0.55*	–0.47	0.41	0.67**	0.12
CMDS								1	0.97***	–0.32	–0.59*	–0.18
CMDI									1	–0.12	–0.40	–0.22
CBBS										1	0.85***	–0.33
CBBI											1	–0.13
CNP												1

*, **, *** Significant level at $P < 0.05$, 0.01 and 0.001, respectively.

the poorest cultivars in some or all of the environments. The GGE biplot in Figure 3 also indicates environmental groupings and suggests the possible existence of mega-environments. Thus, ENV2 (MK YR1), ENV6 (MK YR2), ENV10 (MK YR3) and ENV11 (ZR YR3) were grouped as the first mega-environment, environments 1 (IB YR1), 3 (ZR YR1) 4 (MM YR1), 7(ZR YR2), 8 (MM YR 2) and 12 (MM YR 3) were grouped as the second and ENV 5 (IB YR2) and 9 (IB YR 3) were grouped as the third. This indicated that the cultivars could be successfully evalua-ted in 3 instead of 4 locations, thus Ibadan, Mokwa and either Zaria or Mallamadori were identified as mega-environments for the evaluation of cassava in Nigeria.

GGE biplot for representativeness and discriminating ability of environments

The representativeness and discrimination ability of the environments as reflected in the GGE biplot (Figure 4) uses the absolute distance between a marker of an envi-ronment and the plot origin as a measure of the discriminating ability, the longer the vector, the more discriminating the environ-ment. Thus, EVN8 was the most representative with a near zero projection on the average tester coordinate (ATC) y-axis. ENV2 and ENV5 were the most discriminating, far away from the origin and not representative of the average environ-ment. ENV1, ENV9 and ENV10 were neither discriminating nor represent-tative as reflected on the GGE biplot (Figure 4).

GGE biplot for average yield and stability of cultivars

The GGE biplot for the average yield and stability of dif-ferent landrace cultivars (Figure 5) is based on the appro-ximated projections of the markers for each cultivar to the ATC x-axis. G5 that had the highest projection thus had the highest ave-rage yield followed by G1. G13 with the lowest projection had the lowest average yield. Cultivars stability measured by their projection to the ATC y-axis, showed that G3 was the most stable cultivar and G12 was the least stable (Figure 5).

GGE biplot examining the performance of cultivars relative to a check cultivar (G3)

Examining the performance of cultivars in relation to an ideal entry (check cultivar), as shown in (Figure 6) revealed that G1, G4, G5 and G6 performed better than average yield of the check cultivar (G3). All the other cultivars performed below the average yield of the check cultivar, with G13 having the worst performance. The biplot also revealed that the check cultivar was best in ENV 3 and G1 was best in ENV 5.

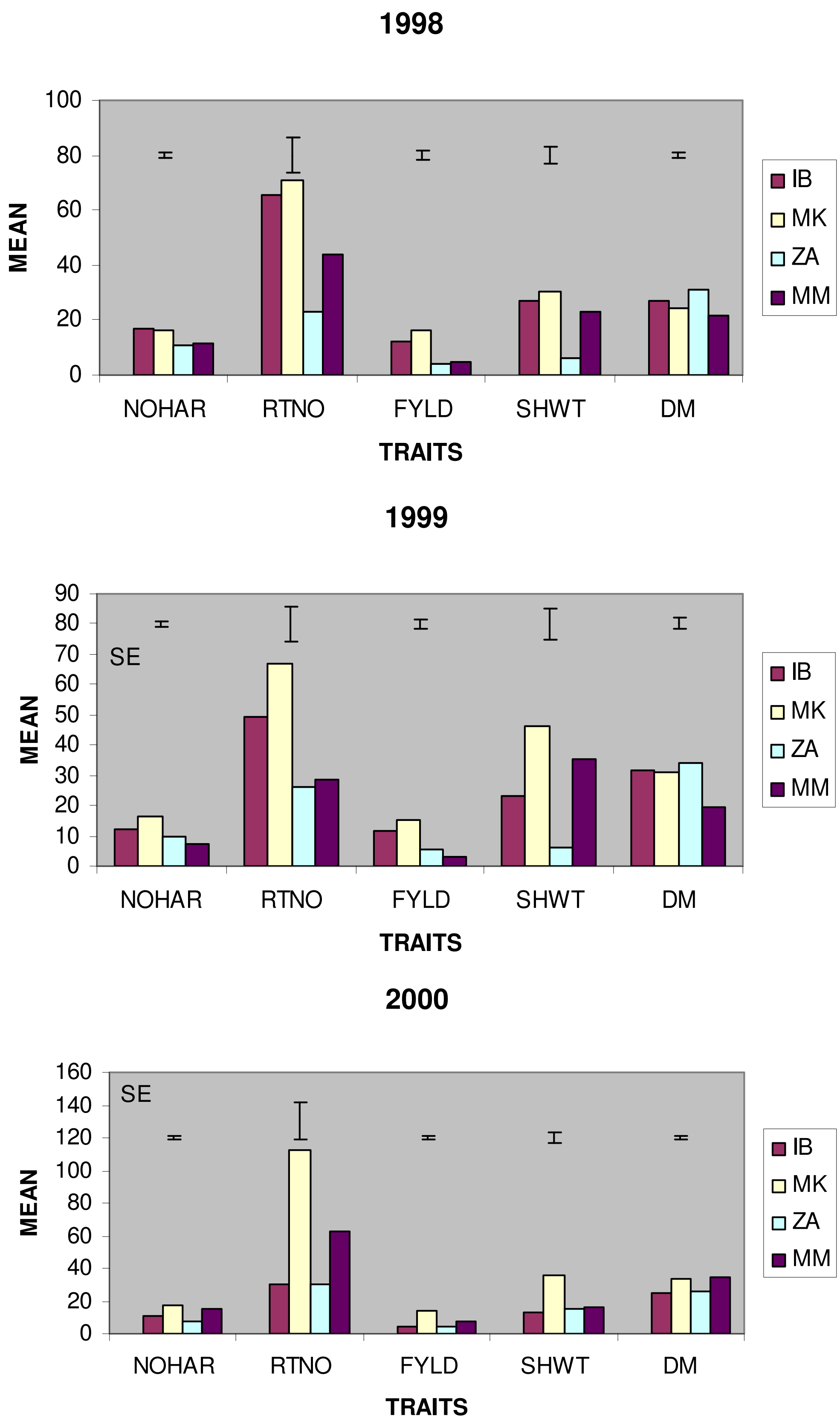

Figure 1. Comparative yield and yield components of 12 cassava landraces and 6 improved genotypes in 4 locations and 3 seasons in Nigeria. IB = Ibadan, MK = Mokwa, ZA = Zaria, MM = Mallamadori.

Table 5. Climatic and soil characteristics of experimental sites.

Climatic factors	Ibadan	Mokwa	Zaria	Mallamadori
Latitude	7°26´N	9°29´N	11°11´N	11°78´N
Longitude	3°54´E	5°04´E	7°38´E	9°34´E
Altitude (masl)	243	152	610	472
Radiation (Mj/m^2/day)	17.25	17.41	18.33	20.38
Mean annual Temp. (°C) (Minimum to maximum)				
1999	22.47 - 31.52	21.41 - 32.42	20.79 - 32.88	19.87 - 33.61
2000	21.86 -31.75	21.40 - 32.36	20.60 - 33.27	18.31 - 31.52
2001	22.24 -31.84	21.40 - 32.34	18.93 - 30.53	19.20 - 33.06
Mean annual rainfall (mm)				
1999	1653.00	1386.00	991.60	52.70
2000	1315.70	1352.70	989.10	653.00
2001	1269.68	1275.50	1060.80	720.20
Agroecological zones	Forest savanna transition	Southern Guinea savanna	Northern Guinea savanna	Sudan savanna
Length of growing period (days)	211 - 270	181 - 201	151 - 180	< 150
Soil type	Ferric luvisol	Ferric luvisol	Orthic luvisol	Eutric regosol

masl = Meters above sea level.

Table 6. AMMI analysis for 12 cassava landraces and 6 improved genotypes grown in 12 environments in Nigeria.

Source	duff	SS	MS	Probability
Total	839	39115.69	46.62	
TRT	215	27736.79	129.01	***
GEN	17	2975.37	175.02	***
ENV	11	19488.58	1771.68	***
G × E	187	5272.83	28.19	***
IPCA 1	27	3513.42	130.12	***
IPCA 2	25	637.01	25.48	ns
IPCA 3	23	358.16	15.57	ns
Residual	40	95.64	2.39	ns
Error	624	11378.90	18.23	

Grand mean 8.46723, Fresh yield (t/ha).
TRT = Treatment, GEN = Genotype, ENV = environment.
*** Significant at $P < 0.001$, ns = not significant.

GGE biplot comparing performance of cultivars with respect to 2 check cultivars

The performance of 2 check cultivars 30572 (G1) and 4(2)1425 (G3) were compared across all the environments to indicate their response across environments. The GGE biplot (Figure 7) showed that tester environments ENV 5 and ENV1 were on the G1 side of the perpendicular indicating that G1 was better in these environments. G3 was better in ENV3, ENV4, ENV8 and ENV 12.

Conclusion

High variability existed among cassava landraces for

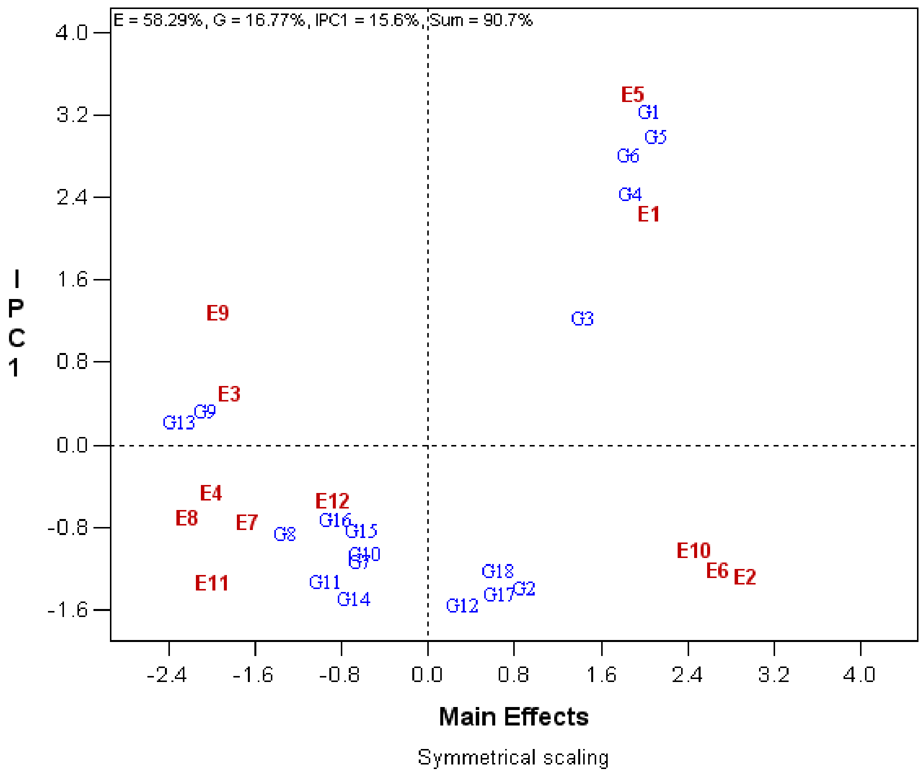

Figure 2. GGE biplot for AMMI showing distribution of genotypes and environments. (The identification for G (genotypes) and E (environments) is as depicted in Table 7).

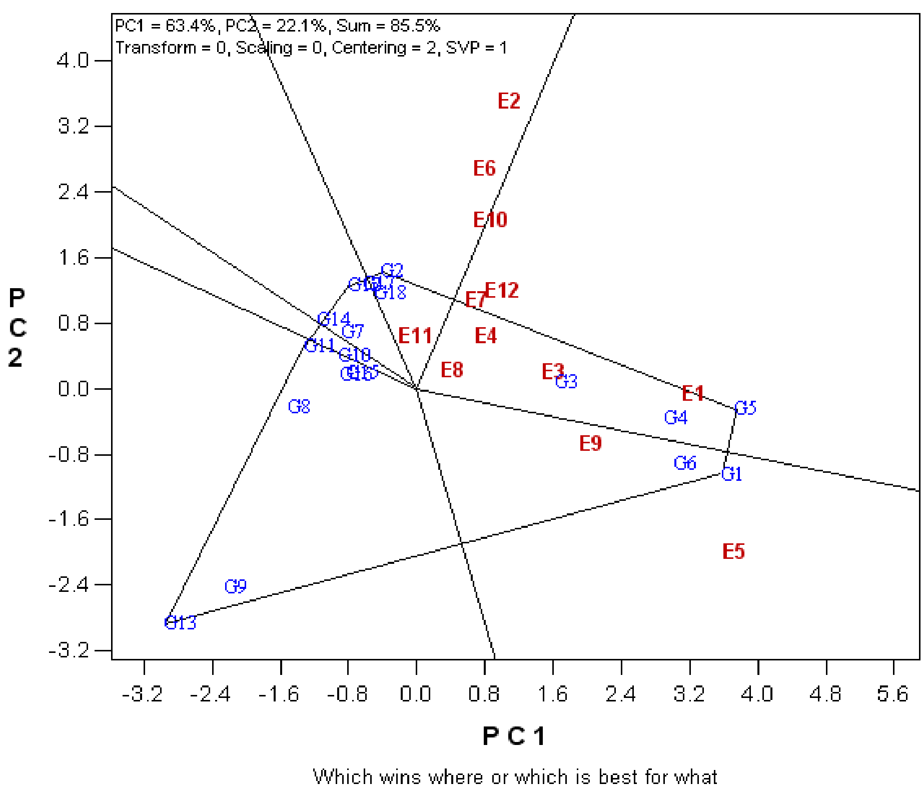

Figure 3. GGE biplot for best cultivars in different environments.

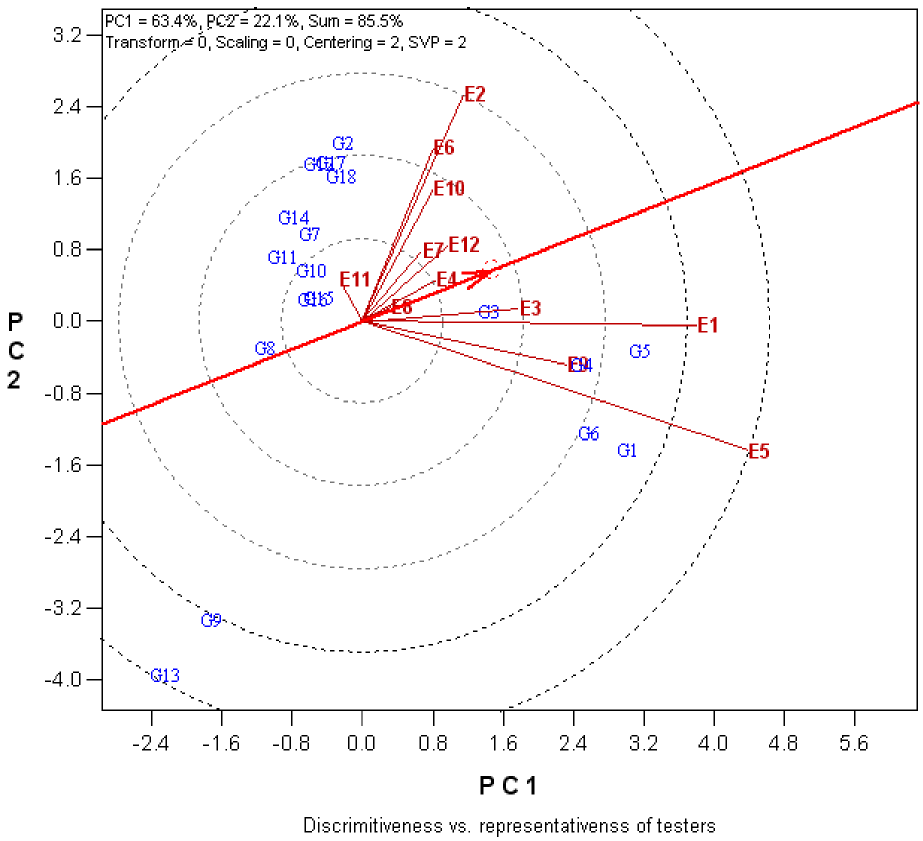

Figure 4. GGE biplot for representativeness and discriminating ability of environments.

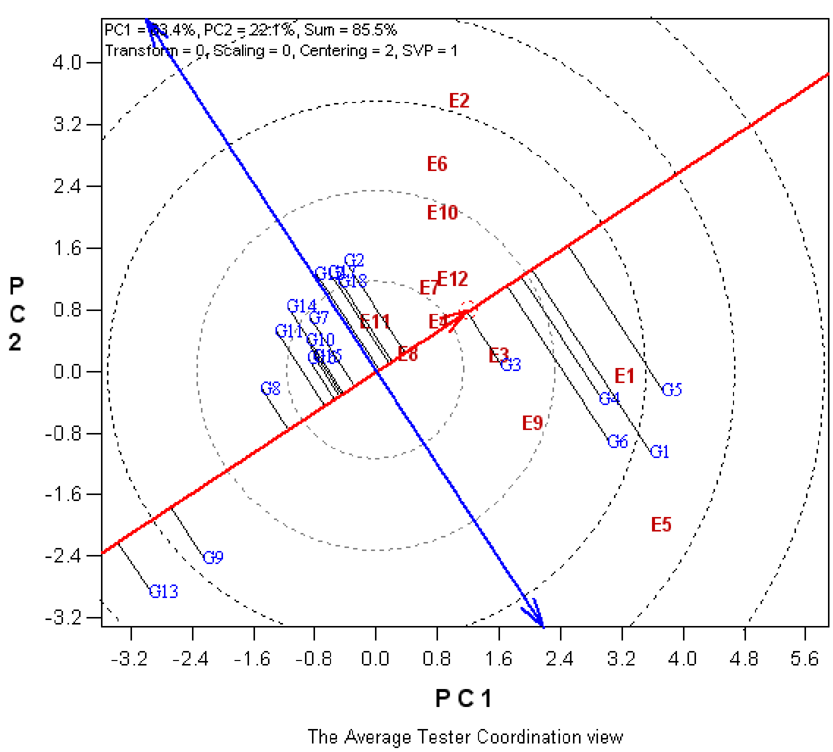

Figure 5. GGE biplot for average yield and stability of different landrace cultivars.

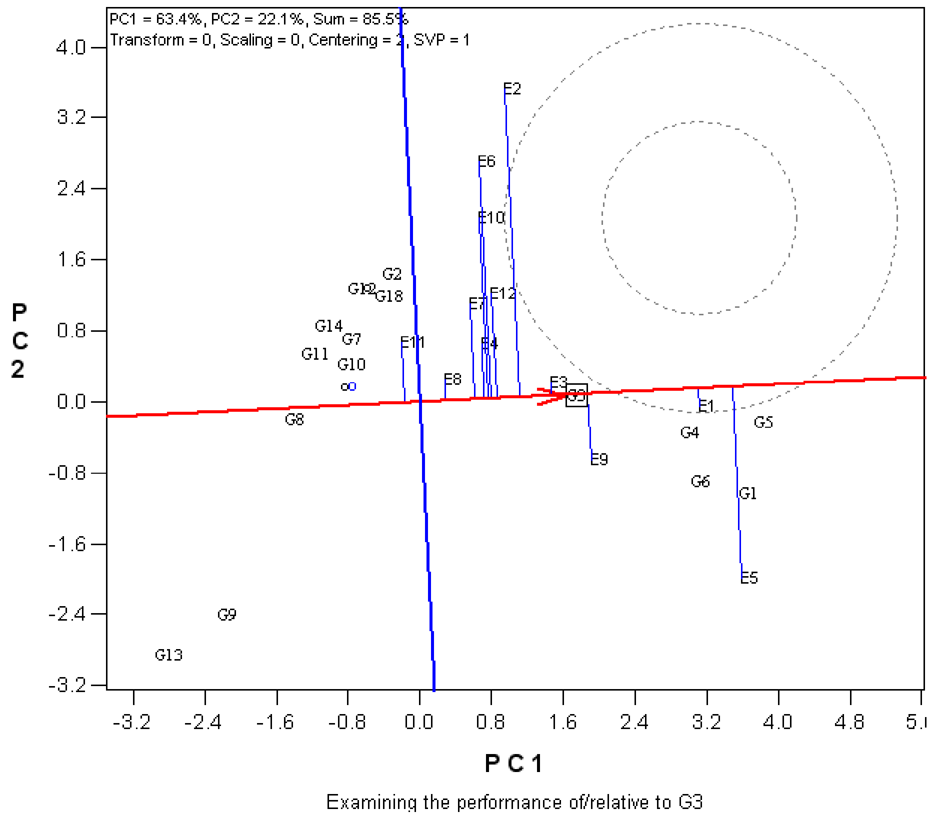

Figure 6. GGE biplot examining the performance of cultivars relative to a check cultivar (G3).

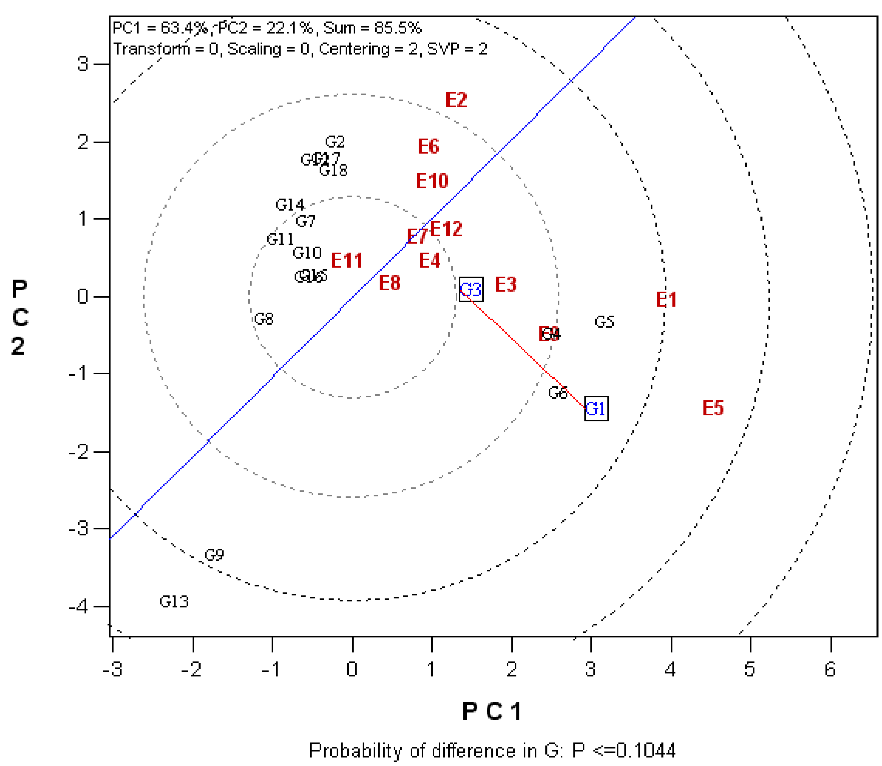

Figure 7. GGE biplot comparing performance of cultivars in respect to two check cultivars, G1 (30572) and G3 (4(2)1425.

Table 7. AMMI mean fresh yield (FRSH) and unadjusted mean yield for 12 cassava landraces and 6 improved genotypes grown in 12 environments in Nigeria.

Cultivar	Id No	AMMI mean FRSH (t/ha^{-1})	Unadjusted mean FRSH (t/ha^{-1})
30572	GEN1	10.56	12.24
2ND-AGRIC	GEN2	10.14	9.20
4(2)1425	GEN3	7.13	10.19
81/00110	GEN4	8.40	11.54
82/00058	GEN5	9.21	12.47
82/00661	GEN6	12.07	11.69
ABBEY-IFE	GEN7	6.56	7.90
ALICELOCAL	GEN8	6.72	6.61
AMALA	GEN9	8.75	4.08
ANTIOTA	GE10	9.96	8.01
ATU-IWO	GE11	9.34	7.30
BAGI-WAWA	GE12	6.44	8.45
ISU	GE13	6.55	2.90
LAPA1-1	GE14	8.12	7.80
MS20	GE15	8.37	7.85
OFEGE	GE16	6.56	7.43
OKO-IYAWO	GE17	6.63	8.71
TOKUNBO	GE18	7.88	8.68
Environments			
Ibadan Year 1	ENV1	12.17	12.17
Mokwa Year 1	ENV2	16.43	16.43
Zaria Year 1	ENV3	4.69	4.22
Mallamadori Year 1	ENV4	4.10	4.83
Ibadan Year 2	ENV5	11.62	11.62
Mokwa Year 2	ENV6	14.98	14.98
Zaria Year 2	ENV7	5.21	5.27
Mallamadori Year 2	ENV8	2.97	2.94
Ibadan Year 3	ENV9	4.34	4.30
Mokwa Year 3	EN10	13.71	13.71
Zaria Year 3	EN11	3.80	3.79
Mallamadori Year 3	EN12	7.60	7.60

yield and yield-related traits. Mean FYLD were higher for improved cultivars than for the local landraces. Root yield obtained for the landraces were, however, high enough to produce appreciable economic yield. The landraces, showed a higher level of tolerance to CMD and CBB than the improved lines indicating that such available desirable traits within the germplasm could be exploited for breeding purposes. The GGE biplot provides an excellent graphical presentation of MET data. It gives a reliable graphical display of the yield stability of cultivars in different environments, ranked environments based on relative performance of a given cultivar, identified the best cultivar in each environment, identified mega-environments and evaluated environments based on discriminating ability and representativeness. Three mega-environments were identified for evaluating cassava landraces in Nigeria.

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