Journal of Agricultural Science; Vol. 11, No. 8; 2019
ISSN 1916-9752 E-ISSN 1916-9760
Published by Canadian Center of Science and Education

Evaluation of the American Yam Bean (*Pachyrhizus* spp.) for Storage Root Yield Across Varying Eco-geographic Conditions in Uganda

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Received: May 28, 2018 Accepted: April 7, 2019 Online Published: June 15, 2019
doi:10.5539/jas.v11n8p100 URL: https://doi.org/10.5539/jas.v11n8p100

Abstract

The American yam bean (*Pachyrhizus* spp.) is a legume crop that is exclusively used for its storage roots. The seeds are inedible due to presence of toxic rotenone. It produces high storage root yields comparable of major root crops like cassava or sweetpotato. And flower pruning more than doubles its root yield performance. Using twenty five yam bean accessions, the current study aimed to determine root yield stability and adaptability, and presence of yam bean production mega environments in Uganda. Trials were planted at three stations, Namulonge, Serere, and Kachwekano during two consecutive seasons of 2011. Fresh storage root yields were significantly different ($p < 0.05$) across locations with the ideal location being Namulonge (fresh storage root yield of 10.1 t ha^{-1}), followed by Serere (8.0 t ha^{-1}), and Kachwekano (3.1 t ha^{-1}). Results of AMMI analysis indicated the presence of genotype-by-environment interaction for fresh storage root yield. Through AMMI estimates and GGE visual assessment, genotype 209017 was the highest yielding with mean yield of 20.7 t ha^{-1}. Genotype 209018 with mean yield of 15.5 t ha^{-1} was the most stable and adapted accession in the entire discriminating environment in Uganda. From the environmental focusing plot, the six environments were grouped into two putative mega environments for yam bean production.

Keywords: american yam bean (*pachyrhizus* spp.), accessions, ammi model, and yield stability

1. Introduction

The American yam bean (*Pachyrhizus* spp.) is an underutilized legume crop in the tropics and subtropics producing large storage roots (Jacobsen, Sørensen, Pedersen, & Weiner, 2015). The genus contains three very closely related cultivated species of neo-tropical origin, all of which can be successfully crossed: the Amazonian yam bean (*P. tuberosus*), the Andean yam bean (*P. ahipa*), and the Mexican yam bean (*P. erosus*). Like its close relative the soybean (*Glycine max* [L.]) (Ndirigwe et al., 2017), the yam bean produces large amounts of seeds. The thousand-seed weight of yam bean is high (180 to 230 g) and the seeds themselves have a high protein (26% to 32% by weight) and oil content (22% to 26% by weight) with an interesting fatty acid profile and tocopherol content and composition for the food oil industry (Grüneberg et al., 2014). However, the seeds of the American yam bean are not edible to humans because they contain rotenone and pachyrhizin in toxic quantities (Sørensen, 1996; Ndirigwe et al., 2017). In both small scale and commercial production, the crop is grown exclusively for its storage roots (Sørensen, 1996) and all the flowers are removed, as flower pruning increases storage root production by about 100% (Rizky, Hasani, & Karuniawan, 2013). In cultivation, only a few plants are not flower pruned to produce seeds for the next crop production.

Despite its various potential uses, the American yam beans until today are not yet an African crop. The crop is known to have been disseminated in history by Spanish seafarers and not by the Portuguese a plausible reason why the crop missed early introduction in Africa. In the Philippines, after the introduction of *P. erosus* in the 16th century the crop has become a widely grown root vegetable in all countries of South- and Southeast Asia including

China (Sørensen, 1996). The first research on yam bean in Africa is documented for West Africa (Benin, Senegal and other countries) suggesting the first introductions of the crop on the continent (Heider et al., 2011). For the Eastern and Central Africa, it is possible that just recently introduced yam bean germplasm by the International Potato Center (CIP) in Uganda in 2010 is the first arrival of this crop in this region. It is possible that the great yield potential of the introduced American yam bean germplasm can contribute to solving the food security in the region. Unfortunately, there is no documented information about production of American yam beans in Uganda and this study forms part of the initial studies by CIP and Makerere University about the adaptability of the crop in Uganda. The major focus of American yam bean program in Uganda is to determine its adaptability followed by potential uses by farmers and markets. Some of the supposed and desirable attributes of American yam bean for East African farming systems include: as a root crop it can provide high yields and high yield stability [which is the overall focus of this study (see below)], as a legume it provides more protein than traditional root crops and has the capability to increase soil fertility through N-fixation and a mycorrhiza system which enhances P-efficiency (Sørensen, 1996). It should be noted that *Pachyrhizus* species, although root crops are propagated by true seed, which results in seed system channels much easier and cheaper to handle compared to other root and tuber crops such as cassava, sweetpotato and irish potato.

Overall, the present study sought to know if yam beans can grow under Ugandan growing conditions. The specific objectives were; a) to determine the adaptability of American yam bean accessions to different agro-ecological zones of Uganda; b) to determine suitable production environments (mega-environments) for American yam beans in Uganda; and c) to make recommendations on the most suitable American yam bean accession(s) for production in Uganda.

2. Materials and Methods

2.1 Experimental Sites

The study was conducted at three locations representing different agro-ecological zones of Uganda (Table 1), namely Namulonge in the lake Victoria crescent zone area [1150 m.a.s.l., at the National Crops Resources Research Institute (NaCRRI)], Serere in the north east savanna zone of Uganda [1140 m.a.s.l., at the National Semi Arid Resources Research Institute (NaSARRI)], and Kabale in the south western highlands of Uganda [2220 m.a.s.l., at Kachwekano Zonal Agricultural Research and Development Institute (KaZARDI)]. These locations differ in edaphic and climatic conditions (Table 1).

The study was conducted across two seasons, namely "the first rain season" from April to December in 2011 (season 1), and "the second rain season" from August 2011 to May 2012 (season 2). Each location and season constituted an environment for Additive main effects and multiplicative interaction (AMMI) analysis and constructing Genotype plus Genotype by Environment Interaction (GGE) biplot, resulting in six environments in which data were collected.

Table 1. Description of locations for evaluation of American yam bean accessions

Location	Eco-geographic region	Soil types	Altitude (m.a.s.l)	Rainfall/year (mm)	Temperature (°C)
Namulonge	Tropical rain forest	Sandy clay soils (pH 4.9 to 5.0)	1150	1260	22.4
Kachwekano	Tropical mountain region	Sandy clay loam (pH 5.8 to 6.2)	2220	1317	17.8
Serere	Tall savanna	Sandy loam (pH 5.2 to 6.0)	1140	1208	26.0

Source: Meteorological stations at the study sites.

2.2 Planting Materials and Experimental Design

A total of twenty five accessions (Table 5) belonging to three species (16 *P. ahipa*, 6 *P. erosus*, and 3 *P. tuberosus*) were used in this study. The seeds of the accessions were obtained from the office of the International Potato Centre (CIP) in Uganda. Each accession was planted on two-ridge plots measuring three meters long and one meter apart. Ten seeds were planted 30 cm apart on top of each ridge, one seed per hole (about 2-3 cm deep), and arranged in a randomized complete block design with two replications. The plots were kept weed free by hand weeding and no fertilizer, pesticide, or rhizobial inoculum was applied during the crop growing cycle. *Pachyrhizus tuberosus* and *P. erosus* accessions were staked using sticks to ensure upright plant growth. Flowers were pruned from all accessions weekly to avoid seed production that could easily be picked and eaten by unsuspecting people, and also ensure high root yields (Sørensen, 1996; Zankan et al., 2007). The trials were planted at Namulonge, Serere, and Kachwekano on 9th April, 13th May, and 8th April 2011 (season 1) and 25th October, 20th August, and 8th October 2011 (season 2) respectively.

2.3 Data Collection

The plots were harvested by uprooting all the surviving plants within the plot five months after sowing at Namulonge and Serere (9th September and 13th October 2011 and 25th March and 20th January 2012) for season 1 and season 2 respectively and seven months after sowing at Kabale (13th December 2011 and 8thMay 2012) for season 1 and 2 respectively. Kachwekano is a high altitude site (2220 m.a.s.l.) and its characteristic of cool temperatures contributes to late crop physiological maturity of the crop. The number of plants harvested, number of plants with roots, number of plants without roots, number of roots, weight (kgs) of roots, and fresh weight (kgs) of above ground foliage and stems were recorded. Additional data was recorded for number of roots with nematode symptoms and damage as well as number of roots damaged due to cracking.

Fresh storage root yield (SRFY), storage root dry matter (SRDM), storage root dry matter yield (SRDY), total biomass (BIOM), and harvest index for fresh storage root yield (HI) was calculated using the formulae below (Zanklan et al., 2007):

- SRFY= total weight of fresh storage root divided by total number of plants harvested expressed as tons per hectare;
- SRDM = fraction of dry and fresh weights × 100%;
- SRDY = SRFY × storage root dry matter (SRDM);
- BIOM = SRFY + VLW (fresh Vines and Leaves weight in t ha^{-1}), and
- HI = (SRFY/BIOM) × 100%.

Sample of 3 storage roots per plot, each between 100 and 200 g weight was taken for dry matter determination. The roots were washed of soil particles and rinsed with abundant tap water, peeled, and each root cut open to prepare a 100 g compound sample that was placed in transparent polythene bags and freeze dried at -31 °C for 72 hours. Dry samples were weighed, milled into flour in a stainless steel mill, and stored in kraft paper bags. Percent dry matter was calculated as fraction of dry and fresh weights and multiplied by 100. The dry sample was also used to calculate storage root dry matter (SRDM) that was expressed as a % of fresh storage root yield (SRFY) after measurement.

2.4 Data Analysis

Analysis of variance (ANOVA) for each trait xi (namely, fresh storage root yield, storage root dry yield, biomass, harvest index, damage to storage root by nematodes, and storage root cracking, and storage root dry matter content) was analyzed from each experimental site separately to determine outliers, experimental means, and coefficients of variation and later the analysis of variance across locations was carried out for each trait xi using Genstat 14th edition. The mean of each trait xi was separated using the least significant difference (LSD) test. Damage to storage root by nematodes, and storage root cracking data were normalized by angular transformation prior to ANOVA. Additive main effects and multiplicative interaction (AMMI) and Genotype plus Genotype by Environment Interaction (GGE) biplots were constructed using GenStat 14th Edition statistical software for fresh storage root yield. The AMMI model equation, $Y_{ger} = \mu + \alpha_g + \beta_e + \sum\lambda_n y_{gn}\delta_{en} + p_{ge} + E_{ger}$, was used for this study, where Y_{ger} is the yield of genotype g in environment e for replicate r, μ is the grand mean, α_g is the genotype g mean deviation, β_e is the environment e mean deviation, n is the number of PCA axes retained in the model, λ_n is the singular value for PCA axis n, y_{gn} is the genotype eigenvector value for PCA axis n, δ_{en} is the environment eigenvector values for PCA axis n, pge is the residual, and Eger is the error (Ntawuruhunga et al., 2001). An AMMI3 model was selected, as only the first three interaction principal component axes (IPCAs) were significant ($P < 0.05$).

3. Results

Differences in the experimental means between locations were significantly different ($P < 0.05$) for fresh storage root yield, storage root dry yield, biomass, harvest index and storage root nematode damage but not for storage root cracking except observed traits in Kachwekano (Table 2). Fresh storage root yield means were highest for Namulonge, (10.1 t ha^{-1}), followed by Serere, (8.0 t ha^{-1}) and lowest at Kachwekano (3.1 t ha^{-1}). Similar trends are observed for storage root dry yield, biomass, and harvest index across locations. Serere had the highest mean percentage of SRDM of 17.7% followed by Namulonge with mean percentage of 16.1% and Kachwekano with the lowest mean percentage of 14.3%. The highest percentage of storage root cracking was for Kachwekano followed by Namulonge and Serere (Table 2) though this was not a serious problem since the overall respective means at locations were low.

Table 2. Experimental means (x) and coefficient of variation (CV %) for observed traits at different locations

Traits	Location					
	Namulonge		Serere		Kachwekano	
	Mean	CV %	Mean	CV %	Mean	CV %
Fresh storage root yield (t ha^{-1})	10.1	32.8	8.0	32.6	3.1	88.4
Storage root dry yield (t ha^{-1})	1.4	33.3	1.3	38.1	0.5	87.7
Storage Root Dry Matter (%)	16.1	16.1	17.7	23.0	14.3	12.1
Biomass (t ha^{-1})	11.5	30.9	9.8	32.3	4.7	73.6
Harvest index (%)	84.5	7.8	86.0	7.4	63.8	29.9
Storage root damage by nematodes (%)	31.4	46.8	15.9	47.1	4.7	53.9
Storage root cracking (%)	7.7	36.4	5.4	16.1	8.4	75.4

The lowest damage to storage roots by nematodes for the 25 accessions was observed at Kachwekano and the highest at Namulonge, followed by Serere. At Namulonge, mean for biomass was slightly higher than at Serere and the lowest mean for biomass was at Kachwekano. However, the highest mean for harvest index was for Serere, followed by Namulonge and Kachwekano. The highest percentage of storage root dry matter was for Serere, followed by Namulonge and Kachwekano (Table 2). The coefficients of variation (CV) values for all traits except SRDM, and HI were low to moderate for two locations, Namulonge and Serere but high for Kachwekano (greater than 50%).

The highest accession means for fresh storage root yield was observed for accession 209017 (Table 3) followed by accessions 209018, 209052, 209016 and 209050 respectively but the lowest mean was recorded for accession 209034 followed by 209006. Also the highest storage root dry yield was observed for accessions 209017 and 209018 (2.2 t ha^{-1}). The lowest storage root dry yield was recorded for accession 209006 followed by accession 209034. The highest storage root dry matter was observed for accession 209024 (20.3%) which has low fresh storage root yield while the lowest storage root dry matter was observed for accession 209046 (9.98%) followed by accession 209017 (10.54%) which also had the highest fresh storage root yield (Table 3). The highest mean of biomass was also observed in accession 209017 (23.8 t ha^{-1}) but lowest in accession 209034 (3.4 t ha^{-1}).The populations mean values observed for harvest index, damage to storage root by nematode, and storage root cracking were 78.1%, 17.2%, and 8.0%, respectively. However, the highest harvest index, damage to storage root by nematode, and storage root cracking were 90.7%, 47.9%, and 20.9% for accession 209023, 209060, and 209018 respectively. Observed traits across genotype were significantly different ($P > 0.05$).

Analysis of variance (ANOVA) by AMMI (Table 4) partitioned the main effects of treatments into genotype, environments and genotype x environment (G×E) interaction. All the components of the ANOVA by AMMI were highly significant ($P < 0.000001$) for fresh storage root yield. G×E interactions were also highly significant ($p < 0.000001$). The accessions had the greatest effect that accounted for 37.3% of the treatment Sum of Squares, followed by environment which accounted for 32.6% and G×E interaction, 30.1% of the treatment Sum of Squares respectively. The AMMI analysis also showed that the first interaction principal component axis (IPCA 1) captured 77.2% of the interaction sum of squares and was highly important in explaining the interaction, while IPCA 2 and IPCA 3 explained only 11.1% and 4.2% of the interaction respectively.

Table 3. Observed traits of 25 American yam bean accessions across locations

Accessions	SRFY	SRDY	BIOM	HI	DSN	SRC	SRDM
	$t\ ha^{-1}$			%			
209003	3.5	0.6	4.0	84.5	13.4	6.6	17.23
209004	3.9	0.9	4.2	88.0	13.3	12.3	16.25
209006	3.1	0.5	3.5	85.8	22.8	10.4	16.67
209007	3.4	0.8	4.2	70.2	21.9	4.5	18.79
209016	14.3	1.8	16.8	83.0	3.5	9.4	11.60
209017	20.7	2.2	23.8	85.1	4.3	11.6	10.54
209018	15.5	2.2	17.9	84.8	4.2	20.9	10.91
209022	3.7	0.6	4.2	78.7	15.9	4.7	16.52
209023	4.1	0.7	4.4	90.7	14.6	9.0	17.61
209024	3.6	0.8	4.0	85.5	16.1	6.2	20.31
209025	3.9	0.7	4.1	88.6	25.1	9.6	16.83
209026	3.2	0.6	3.5	83.8	22.8	9.1	18.42
209028	4.0	0.8	4.3	87.8	23.9	7.5	16.53
209030	4.5	0.8	6.2	73.0	13.2	5.9	16.48
209032	6.1	1.1	7.0	80.6	8.1	4.7	17.98
209033	5.0	0.9	6.3	70.1	19.7	4.6	18.68
209034	3.1	0.6	3.4	76.7	15.1	3.3	16.21
209035	5.0	0.9	6.0	83.9	12.5	6.0	18.02
209036	5.5	0.9	7.0	79.2	19.4	5.8	17.83
209046	9.5	0.9	13.4	67.1	3.7	11.1	9.98
209050	13.3	1.6	17.1	77.1	6.5	6.7	12.30
209052	14.5	1.8	16.6	85.8	3.9	11.9	10.67
209055	7.8	1.3	11.9	55.2	44.8	6.5	16.67
209058	7.8	1.5	12.2	53.7	34.2	3.9	18.86
209060	7.0	1.1	10.8	52.7	47.9	7.1	17.36
Mean	7.0	1.1	8.7	78.1	17.2	8.0	15.97
LSD (0.05)	2.358***	0.3859***	2.766***	9.832***	2.94***	1.18*	2.46***
C.V	41.5	44.8	39.6	15.6	52.4	51.2	19

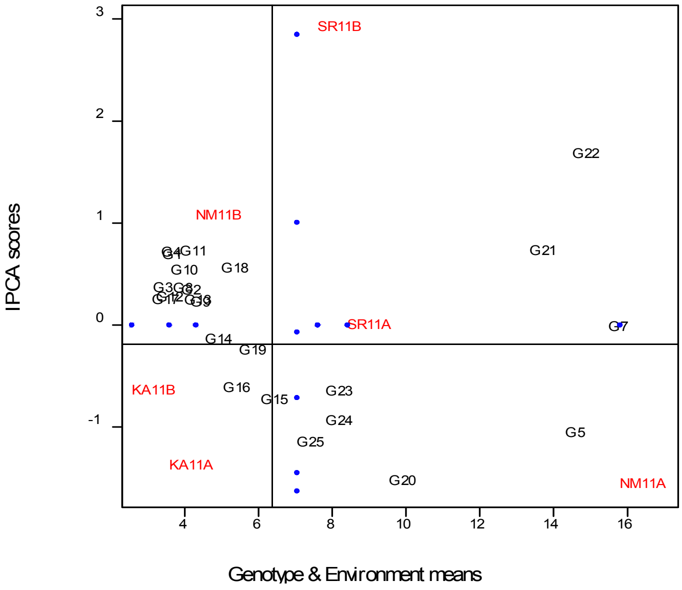
Note. *Significant at the 0.05 level, ***Significant at 0.001 level. SRFY = Fresh storage root yield, SRDY = Storage root dry yield, BIOM = Biomass, HI = Harvest index, DSN = Damage to storage root by nematode, SRC = Storage root cracking, and SRDM = Storage root dry matter.

The combined mean square for the three IPCA axes are 35.4 times that of residual mean square, with the mean square of the first IPCA 27.9 times that of the residual mean square and the second IPCA and third IPCA mean square 4.3 and 3.2 times that of the residual mean square respectively. The AMMI model also contained 93.4% of the treatment sum of squares while the block contained only 1.0% and the error contained 5.6%. The treatment and block sum of squares combined make up 94.4% of the total sum of squares.

Table 4. The AMMI analysis for yield of 25 accessions in six environments in Uganda during 2011A and 2011B seasons

Source	Df	SS	MS	F	F prob
Total	299	19437	65.0		
Treatments	149	18155	121.8	15.88	0.00000
Genotypes	24	6765	281.9	36.73	0.00000
Environments	5	5922	1184.5	38.57	0.00000
Block	6	184	30.7	4.00	0.00098
Interactions	120	5468	45.6	5.94	0.00000
IPCA 1	28	4221	150.7	19.65	0.00000
IPCA 2	26	605	23.3	3.03	0.00001
IPCA 3	24	414	17.3	2.25	0.00180
Residuals	42	229	5.4	0.71	0.90160
Error	143	1097	7.7		

The AMMI biplot (Figure 1) provided a visual expression of the relationships between the first interaction principal component axis (IPCA1) and means of genotypes and environments. The AMMI biplot showed four groupings of accessions; 209034 and 209006, generally low yielding and unstable, 209030, 209023, and 209036 low yielding and the moderately stable, 209018 high yielding and stable, 209052, 209016, and 209050, high yielding but unstable as illustrated in Figure 1.



G1-209003
G2-209004
G3-209006
G4-209007
G5-209016
G6-209017
G7-209018
G8-209022
G9-209023
G10-209024
G11-209025
G12-209026
G13-209028
G14-209030
G15-209032
G16-209033
G17-209034
G18-209035
G19-209036
G20-209046
G21-209050
G22-209052
G23-209055
G24-209058
G25-209060

Figure 1. AMMI biplot of IPCA1 scores versus yield means for 25 Accessions and six environments for 2011A and 2011B seasons

Note. Suffixes 11A and 11B show seasons 2011A, and 2011B respectively, and SR = Serere, NM = Namulonge, and KA = Kachwekano.

The results in the scatter plot (Figure 2) indicated that, the five environments namely NM11A, NM11B, SR11B, KA11A, and KA11B were in one mega environment with the best accession being 209017, followed by 209050, and 209052 in that order. Mega environment II only had the location SR11A, with the best accession being 209016. However accession 209018 was the most adapted accession in the mega environment II. On the other hand, a comparison biplot (Figure 3) that is genotype focused showed that accession 209018 is the most stable accession while 209017 is the most ideal genotype, followed by accessions; 209018, 209016, 209052, and 209050 (Figure 3) as observed in AMMI analysis (Table 6). Figure 4 shows an environment focused comparison biplot where NM 11A was the ideal environment, followed by SR11B, SR11A, NM11B, KA11B and KA11A.

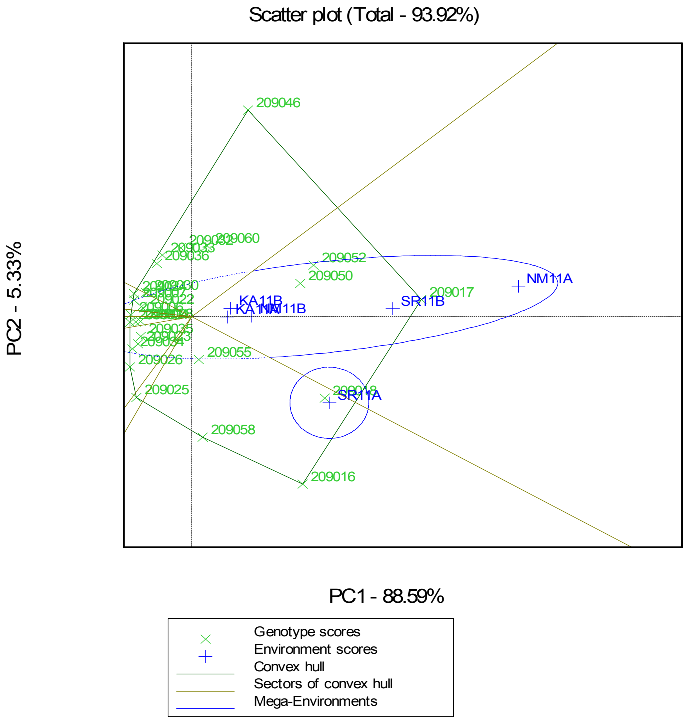


Figure 1. A scatter plot showing PC2 verses PC1 for 25 American yam bean accessions and six environments for 2011A and 2011B seasons

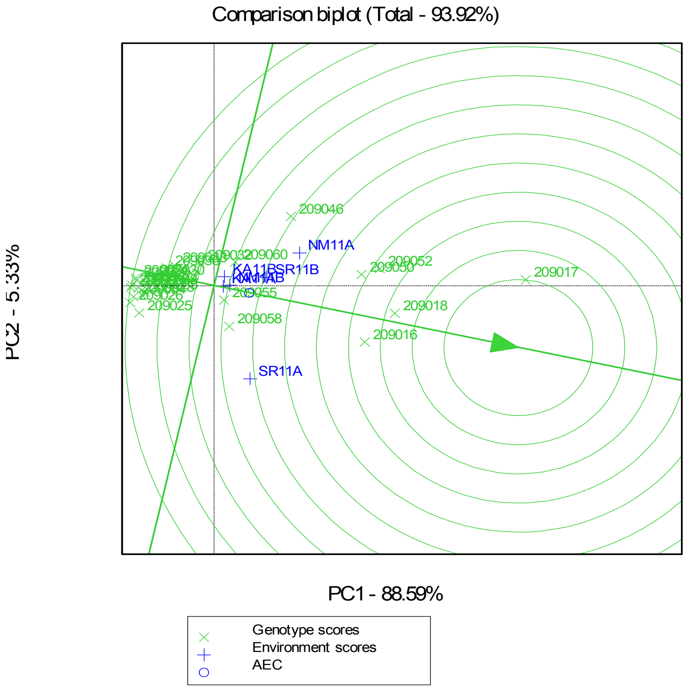


Figure 2. A comparison biplot that is genotype focused showing PC2 verses PC1 for 25 American yam bean accessions and six environments for 2011A and 2011B seasons

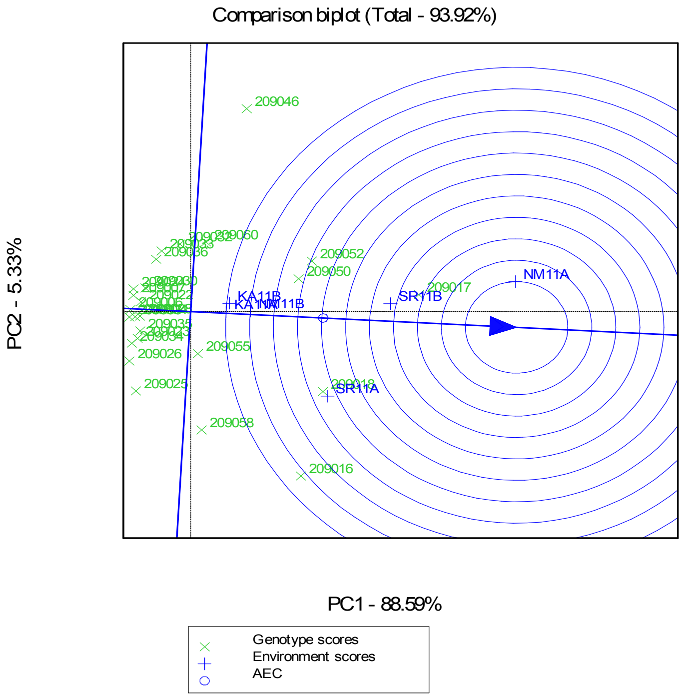


Figure 3. A comparison biplot that is environment focused showing PC2 verses PC1 for 25American yam bean accessions and six environments for 2011A and 2011B seasons

Based on the first IPCA, the accessions with highest G×E interaction were 209017, 209018, 209052, 209050, and 209016 with interaction scores of -3.96, -2.03, -2.01, -1.95, and -1.57 respectively while the least interactive accession was 209032 with IPCA 1 score of 0.01 (Table 5). The best yielding accessions during the two seasons across the different locations were 209017, 209018, 209052, 209016 and 209050. The environments were also highly interactive with NM11A having the highest IPCA 1 score of -5.91 while SR11A was the least interactive environment with IPCA1 score of 0.08 (Table 6). The highest overall storage root fresh yield across accessions was observed at Namulonge (15.80 t ha^{-1}) during the first rains of 2011 followed by Serere (8.41 t ha^{-1}) also in first rains of 2011 (Table 6). The lowest overall environment mean yields were observed at Kachwekano (2.56 t ha^{-1}) during 2011B.

Table 5. Storage root fresh yield and interaction scores of 25 American yam bean accessions across two growing seasons

Accession	Species	Plant type	Mean yield (t ha^{-1})	IPCA1	IPCA2	IPCA3
209003	*P. ahipa*	Bush	3.38	1.08	0.03	0.62
209004	*P. ahipa*	Bush	3.90	1.05	0.07	0.27
209006	*P. ahipa*	Bush	3.14	0.90	0.02	0.29
209007	*P. ahipa*	Climb/Bush	3.36	0.87	0.24	0.64
209016	*P. erosus*	Climb	14.31	-1.57	-2.12	-1.13
209017	*P. erosus*	Climb	20.68	-3.96	0.06	1.11
209018	*P. erosus*	Climb	15.48	-2.03	-1.03	-0.09
209022	*P. ahipa*	Climb	3.68	0.69	0.08	0.29
209023	*P. ahipa*	Bush	4.14	1.05	-0.19	0.15
209024	*P. ahipa*	Bush	3.62	0.99	0.38	0.47
209025	*P. ahipa*	Bush	3.86	1.02	-0.89	0.65
209026	*P. ahipa*	Bush	3.22	1.01	-0.60	0.20
209028	*P. ahipa*	Bush	3.99	0.87	0.00	0.17
209030	*P. ahipa*	Bush	4.54	0.88	0.41	-0.21
209032	*P. ahipa*	Climb	6.06	0.01	0.72	-0.80
209033	*P. ahipa*	Climb	5.04	0.36	0.68	-0.68
209034	*P. ahipa*	Bush	3.11	0.85	-0.46	0.18
209035	*P. ahipa*	Climb	4.98	1.32	0.14	0.48
209036	*P. ahipa*	Climb	5.47	0.81	0.84	-0.32
209046	*P. erosus*	Climb	9.53	-1.43	2.18	-1.60
209050	*P. erosus*	Climb	13.34	-1.95	0.31	0.66
209052	*P. erosus*	Climb	14.51	-2.01	0.70	1.61
209055	*P. tuberosus*	Climb	7.82	0.04	-0.50	-0.72
209058	*P. tuberosus*	Climb	7.81	-0.12	-1.58	-1.01
209060	*P. tuberosus*	Climb	7.03	-0.72	0.05	-1.22

Table 6. Environment mean yields, IPCA 1, IPCA 2, and IPCA 3 scores across genotypes

Environment	Fresh storage root yield	Location Mean	IPCA 1	IPCA 2	IPCA 3
	----------------------- t ha^{-1}	-----------------------			
KA11A	3.58	3.07	2.52	0.57	-1.45
KA11B	2.56		2.43	1.09	-0.71
NM11A	15.80	10.05	-5.19	0.76	-1.63
NM11B	4.30		1.90	0.70	1.01
SR11A	8.41	8.00	0.08	-3.79	-0.07
SR11B	7.60		-1.75	0.66	2.85

Note. Suffixes 11A and 11B show seasons 2011A and 2011B respectively and NM = Namulonge, SR = Serere and KA = Kachwekano.

4. Discussions

The AMMI analysis indicated that there were significant G×E interactions for fresh storage root yield. This is a common phenomenon among many quantitative traits such as yield and complicates breeding efforts by plant breeders (Annichiarico & Perenzin, 1994). Accession 209017 had the highest fresh storage root yield of 20.7 t ha^{-1} followed by accessions 209018 (15.5 t ha^{-1}), 209052 (14.5 t ha^{-1}), 209016 (14.3 t ha^{-1}) and 209050 (13.34 t ha^{-1}) respectively. The observed fresh storage root yields in this study are comparable to those earlier reported in other African countries. For example in Benin, the average fresh storage root yield among 14 *P. erosus* accessions across two locations was 23 t ha^{-1} without pruning and 45 t ha^{-1} with pruning of the reproductive parts (Zanklan, Heiko, & Elke, 2003). In Sierra Leone, storage root fresh yields between 10 and 23 t ha^{-1} and 14 t ha^{-1} without flower pruning were recorded (Belford, Karim, & Schröder, 2001). In Senegal, Annerose and Diouf

(1998) recorded an average SRFY of about 17 t ha^{-1} without flower pruning. Outside Africa, for example in Thailand, Ratanadilok, Suriyawan, and Thanisawanyangkura (1998) reported an average SRFY of 28 t ha^{-1} without flower pruning. The highest fresh storage root yield recorded for accession 209017 (20.7 t ha^{-1}) confirm previous results with the same species (Zanklan et al., 2007). The comparison of yields obtained from some clones in this study with previous studies in and outside Africa suggests that yam bean can grow under Ugandan growing conditions and moreover to a possibility of better yields once the crop has established symbioses with appropriate strains of rhizobia or better agronomic practices.

The observed significant ($P > 0.05$) difference across genotype can probably be explained by many and variable number of accessions used in the present study. This is consistent with other studies (Zanklan et al., 2003, 2007) where significant differences among genotypes for fresh storage root yield were reported and in this present study, the high yielding accessions were all P. erosus and P. tuberous and none in the P.Ahipa species. The highest mean fresh storage root yield observed at Namulonge (10.1 t ha^{-1}) was probably a result of the favorable rain conditions characteristic of the environment and relatively high soil fertility observed at this site. Therefore presence of moisture in the soil during the season and high soil fertility seems to increase storage yield of American yam beans. Tukamuhabwa, Oloka, Sengooba, and Kabayi (2012) reported high soybean yields at Namulonge and attributed them to the high rainfall characteristic of the site. The low means of fresh storage root yields obtained at Kachwekano in this study probably suggest that it is less suitable for yam bean production compared to Namulonge and Serere. Kachwekano represents a distinct agro-ecology characterized by high altitude and low temperatures which probably slow down the physiological growth of the plants (Tumwegamire et al., 2011). It is important to remember that American yam bean was allowed to grow for more two months at Kachwekano than other sites to allow more time to reach physiological maturity. The locations belong to different agro-ecological zones and differed greatly in altitude, crop duration up to harvest (Table 1), and probably poor soil fertility (which is not yet known) might be reason for low values of storage root fresh yield observed in Kachwekano. Such extreme locations are useful in testing accessions adaptability and resistance to pests and diseases, but might be less useful for nutritional quality breeding (Grüneberg et al., 2009). The mean storage root yields were higher in season 2011A (9.3 t ha^{-1}) than in season 2011B (4.8 t ha^{-1}) suggesting that the conditions in the first season were more favorable for American yam bean production than in the second season. In the second season, the rains started late and were erratic, which possibly accounts for the lower yields during the second than first season. The major factor in these favorable conditions is rainfall, which is known to vary more than other factors, suggesting that moisture stress affects American yam bean yields in Uganda to a great extent. The low yield observed at Namulonge during 2011B was probably due to the severe drought that affected production in many regions of the country. The low yields were observed throughout the seasons in Kachwekano (Table 6) though it receives high rain fall which showed that, this site is not favorable for American yam bean production.

The significant difference among the accessions ($P < 0.001$), locations ($P < 0.001$), seasons ($P < 0.001$) and interactions ($P < 0.001$) for storage root dry matter yield in this study is in agreement with Nielsen et al. (2000). The moderate storage root dry matter yield observed in accessions 209017 and 209018 (2.2 t ha^{-1}) is attributed to their high fresh storage root yield (Table 3). The results contradict findings by Zanklan et al. (2003), where he observed that the storage root dry matter yield of *P. tuberosus* and *P. erosus* are about 4.2 t ha^{-1} with no pruning of reproductive parts. These results observed clearly show that American yam bean generally has low storage root dry yield. This is in agreement with previous findings where the root of American yam bean is used as a vegetable and is characterized by high moisture content usually more than 80% of fresh root weight with exception of new yam bean type (Chuin) belonging to *P. tuberosus* that has high root dry matter content (Sørensen, Doeygaard, Estrella, Kvist, & Nielsen, 1997). On the same note, the highest root dry matter contents were also observed among non *P. erosus* accessions with low fresh storage root yields in this trial (Table 3). These accessions should be retained to breed for high dry matter content among the American yam bean accessions. The overall very low total biomass observed in this trial was probably due to flower pruning which was carried out for all the accessions during the growth phase of the experiments resulting into high mean harvest index (78.1%) for fresh storage root yield. This is in agreement with previous studies by Zanklan et al. (2003), where he noted that the harvest index for storage root dry yield increases considerably if flowers are removed with values of 46, 50, and 62% for *P. tuberosus*, *P. erosus* and *P. ahipa*, respectively. Damage to storage roots by nematodes was highest at Namulonge (33.5%) than other locations and reason for this high prevalence of nematodes in Namulonge is not yet known. The damage of American yam beans root by nematodes has been reported (Duke, 1981; Sørensen, 1996; Noda, Bueno, & Silva, 1991). These effects have been noticed in the present study and the roots of *P. ahipa* were more attacked by nematodes than those of *P. erosus* and *P. tuberosus*. The highest mean percentages root cracking observed in accessions 209018 (20.9%) followed by 209017 (11.6%)

was probably due to lack of space for storage root development (crack during expansion). The high percentage of root cracking recorded in season 2011A (10.6%) could probably be attributed to high amount of rain fall received in first season of 2011 that created favorable conditions for storage root development thus big sized storage roots. Root cracking was lowest at Serere (5.6%) probably due to the fact that American yam bean were better adapted to the conditions in Serere as shown by moderately stable environment mean of fresh storage root yield of American yam bean in Serere (Table 6).

The observed highly significant ($P < 0.000001$) G×E interactions from AMMI analysis of variance showed that genotypes responded differently to the environments used during the study (Table 4). It also indicated great diversity among the genotypes with a scale GE interaction. The presence of a scale GE interaction among the American yam bean accessions signifies the need to breed for general adaptability. This is contrary to specific adaption for soybean grain yield (Matus-Cadiz, Hucl, Perron, & Tyler, 2003) in Uganda. Environmental interactions observed in AMMI analysis are due to a number of factors such as rainfall, temperature, soil conditions, and pests and diseases. Studies by Abalo, Hakiza, El-Bedewy, and Adipala (2003) established that temperature was a key factor in creating environmental differences and adaptability of potato varieties. In a related study, Wamatu and Thomas (2002) concluded that altitude and its modulating effect on climatic factors such as temperature play a key role in influencing grain yield of pigeon pea by directly influencing flowering and seed set. Both AMMI and GGE biplots showed that accession 209018 had moderate yield and was stable. This is a desirable trait in plant breeding therefore this accession can be retained to hybridize with low yielding but high dry matter and starch American yam bean accessions. Accession 209018 was outstanding in terms of adaptation and relative stability in all the environments. The dynamic stability exhibited by the genotype is a desirable trait as it performs well irrespective of the site and prevailing environmental conditions. The AMMI results that showed the lowest overall environment mean yields at Kachwekano (2.6 t ha^{-1}) during 2011B probably suggest poor adaptation of American yam bean in Kachwekano (Table 3). In addition, the location (Namulonge), showed high negative interaction during first rains of 2011 (2011A) and a low interaction during 2011B, which suggests that the location is unstable though high yielding. According to Sudaric, Simic, and Vrataric (2006), soybean seed yield was very sensitive to environmental changes and attributed the differences to variations in edaphic and climatic factors. This probably explains the high yields obtained at Namulonge that received high amounts of rainfall during first cropping season of 2011. It was also observed that, environment SR11A had small angle vector with average environment axis (AEA). This shows greater relative stability of this environment across the two seasons 2011A, and 2011B for American yam bean production. Yan and Rajcan (2002) defined an ideal test environment as having small PC2 scores (more representative of the overall environment) and large PC1 scores (power to discriminate). The results in the scatter plot (Figure 2) showed that, the five environments namely NM11A, NM11B, SR11B, KA11A, and KA11B were in one mega environment with the best accession being 209017, followed by 209050, and 209052. Mega environment II only had the location SR11A, with 209016 as the best yielding accession and 209018 as the most adapted accession. Mega environments are test environments with different winning genotypes located at the vertex of the polygon. This implies that the country has two broad regions with unique environmental characteristics with specific high yielding accessions. Therefore, American yam bean accessions respond in a similar way for a greater part of the country; this is further collaborated by presence of a scale GE interaction for fresh storage root yield. However, the test environments within the two putative mega environments were close to one another, implying that targeted breeding for each of them may not be necessary before validation tests are done. SR11A was the only test location representing the second mega environment with mean fresh yield of 8.41 t ha^{-1} (Table 6) probably due to the favorable rain conditions that characterized the site during the period. The results of comparison biplot showed that environment comparison using the AEA identified NM11A as the highest yielding and representative environment (Figure 4). The AEA is a measure of the representativeness of the average environment. The innermost concentric rings represent the most ideal test environment for genotypes with the greatest yield. The high yielding potential of NM11A was consistent with results presented by AMMI estimates (Figure 1).

5. Conclusion

The present study is one of the early studies that report for the first time the performance of an ample number of germplasm representing the three known cultivated sub species under the growing conditions of Uganda. The results clearly show that yam bean can grow in Uganda particularly in areas represented by Namulonge and Serere. The yields seem to be more at Namulonge but stable at Serere. Kachwekano site characterized by high altitude and low temperature cannot favour yam bean production. *P. ahipa* were the worst while the *P. erosus* would require more time to reach physiological maturity, which unfortunately is a disadvantage in an already intensive farming system. Accessions 209017, 209018 and 209016, despite low dry matter can be recommended as the best root and biomass yielding. However, accession 209018 was the most stable and adapted accession in the entire discriminating environment in Uganda. On the other hand accessions 209024, 209007, 209033, 209026, and 209035 despite low root and biomass yields, can be recommended for high dry matter. We can suggest that a cross combination between the two groups of yam mean accessions may offer possibility to improve for root and biomass yields as well as dry matter contents. This would also improve resistance/tolerance to root nematodes most severe among *P. ahipa* accessions. Uganda can be divided into at least two putative mega environments in terms of American yam bean root yield. We recommend agronomic trials to establish the possibility to reduce cracking through higher plant densities or intercropping.

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