South African Journal of Plant and Soil

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tjps20

Yield stability of tropical soybean genotypes in selected agro-ecologies in Uganda

T Obua, M Nabasirye, M Namara, G Tusiime, M Maphosa & P Tukamuhabwa

To cite this article: T Obua, M Nabasirye, M Namara, G Tusiime, M Maphosa & P Tukamuhabwa (2020) Yield stability of tropical soybean genotypes in selected agro-ecologies in Uganda, South African Journal of Plant and Soil, 37:2, 168-173, DOI: 10.1080/02571862.2019.1678687

To link to this article: https://doi.org/10.1080/02571862.2019.1678687

Published online: 06 Aug 2020.

South African Journal of Plant and Soil 2020, 37(2): 168–173
Printed in South Africa — All rights reserved

SOUTH AFRICAN JOURNAL OF PLANT AND SOIL
ISSN 0257-1862 EISSN 2167-034X
https://doi.org/10.1080/02571862.2019.1678687

Yield stability of tropical soybean genotypes in selected agro-ecologies in Uganda

T Obua[1]*, M Nabasirye[1], M Namara[1], G Tusiime[1], M Maphosa[2] and P Tukamuhabwa[1]

[1] School of Agricultural Sciences, College of Agricultural and Environmental Sciences, Makerere University, Kampala, Uganda
[2] Department of Crop and Soil Sciences, Faculty of Agricultural Sciences, Lupane State University, Lupane, Zimbabwe
**Corresponding author, email: obuatonny@gmail.com*

Differential yield response of a genotype is the result of its interaction with the prevailing environment. This makes the task of selecting widely adapted and best soybean genotypes challenging under varied target production environments. The objectives of this study were to; (i) determine the mean performance and stability of 30 elite soybean genotypes in eight different locations, (ii) determine soybean mega-environments in Uganda and (iii) assess the discriminating and representative power of the test environments for soybean seed yield. A field study was conducted for six seasons across eight locations in Uganda. Among the tested 30 soybean genotypes, BSPS 48A-9-2 had the highest mean grain yield of 1 277 kg ha^{-1}; followed by BSPS 48A-28 (1 256 kg ha^{-1}). The genotype and genotype-by-environment (GGE) biplot analyses indicated that the eight test locations can be classified into three mega-environments, while Bulindi was the most discriminating and representative test environment for soybean production in Uganda. Genotypes BSPS 48A-9-2, BSPS 48A-31 and Nam II × GC 44.2 are recommend for further evaluation under farmers' production conditions for selection and release as new soybean varieties in Uganda.

Keywords: biplot, GEI, GGE, yield stability

Introduction

Soybean grain contains about 40% protein, 20% oil, varied essential amino acids and nutrients, and a high calorie value (Singh et al. 2008). Most of the soybean produced in Uganda is processed into soybean meal and vegetable oil. It is therefore an important food and feed resource in Uganda (Tukamuhabwa et al. 2016). Soybean also improves soil fertility through nitrogen fixation and enhanced moisture retention that leads to a more sustainable cropping system (Graham and Vance 2003; Clough et al. 2013). Soybean is a food and cash crop in Uganda; providing farmers cash incomes (Tukamuhabwa et al. 2016). Hence soybean production and consumption has led to increased farmers' income, improved food and nutrition security and poverty reduction at rural household level (SNV 2011; Tukamuhabwa and Obua 2015). Accordingly soybean has the potential to contribute to poverty alleviation in Uganda.

Although area under soybean production has increased in Uganda, the yield has remained low which is about 1 200 kg ha^{-1} compared with mean yield reported in other African countries that reaches up to 2,000 kg ha^{-1} (FAO 2018). The low yields are attributed to several factors including poor soil fertility, inappropriate management practices, limited use of improved varieties and damages caused by various insect pests and diseases (Tukamuhabwa et al. 2016). Currently, soybean rust disease caused by the fungus *Phakopsora pachyrhizi* is the main soybean yield reducing constraint in Uganda (Kawuki 2002; Tukamuhabwa and Maphosa 2011; Murithi et al. 2015). In the past soybean did not have many economically important pests, but in the last five years, there has been emergence of two pests in Uganda; groundnut leaf miners in the field and bruchids during storage. These pests cause considerable economic damage to soybean (Namara 2015). Other abiotic stresses such as drought and low soil fertility have led to extremely low yields of soybean in Uganda.

Despite the challenges highlighted, the Makerere University Centre for Soybean Improvement and Development (MAKCSID) has developed a number of elite soybean genotypes that were evaluated at Advanced Yield Trials (AYT) to assess their adaptability in the major soybean production areas of Uganda (Tukamuhabwa et al. 2011; Tukamuhabwa et al. 2012). MAKCSID has made targeted selections and vital data were collected. The selected genotypes possessed better traits such as high yield and resistance to pests and diseases. Owing to varied climatic conditions coupled with declining soil fertility in Uganda, emphasis has been placed on development of superior soybean varieties that are well adapted to the varied ecological zones (Tukamuhabwa and Oloka 2016). Some of the desirable soybean traits include early maturity, resistance to pod shattering, resistance to lodging, improved nutritional compositional traits, resistance to pests and diseases, high and stable seed yield (Tukamuhabwa and Oloka 2016). Other quantitative soybean traits such as yield remain complex due to genotype environment interactions (GEI) especially if trials are conducted in varied environments (Kaya et al. 2002).

A number of statistical approaches have been developed to analyze Multi Environmental Trial (MET) data. One common approach used by plant breeders is the Genotype and genotype-by-environment interaction (GGE) biplot analysis. The method simultaneously displays the genotype main effect (G) and the genotype by environment interaction (GEI), and has been reported to visually address many questions related to MET data (Yan et al. 2000; Yan 2001; Yan and Kang 2003). A review by Yan et al. (2007) reported that GGE biplot is superior in mega-environment analysis and genotype evaluation. A mega-environment is defined as a group of locations that consistently share the best set of genotypes or cultivars across years (Yan and Rajcan 2002). Therefore, data from multiple years are essential to decide whether or not the target region can be divided into different mega-environments for genotype evaluation or large-scale production.

GGE biplot technique has been widely used in soybean to assess GEI. A study conducted in four different locations of Ethiopia for two consecutive years using thirty two genotypes showed that there was GEI which was crossover type. The same study also identified three genotypes that had both high mean yield and high stability performance across the test environments (Mulugeta et al. 2013). In another study by Adie et al. (2014) who evaluated 10 black seeded soybean genotypes in 16 locations revealed that the genotypes W9837 × Cikuray-66 was stable and recommended for release as a new high-yielding variety. In Zambia, a MET analysis reported that the best genotype for general adaptability was the variety TGX 1988-22F. This genotype was stable across all the locations with high yields and average stability (Cheelo et al. 2017). Therefore, the objectives of this study were to; (i) determine the mean performance and stability of 30 elite soybean genotypes in eight locations that represent the major soybean growing areas of Uganda, (ii) determine soybean mega-environments in Uganda and (iii) assess the discriminating and representative power of the test environments for soybean evaluation and production in Uganda.

Materials and methods

Experimental materials

The experimental materials comprised of 560 families that were constituted from 3 crosses made at Namulonge and Kabanyolo in Uganda. The parental lines were Nam 2 that is a farmer preferred variety; Duiker that is high yielding, adapted and have desirable agronomic traits such as white helium seeds and GC0038-29 that is early maturing and resistant to soybean rust disease. The three bi-parental populations were advanced from F2 to F12 generation using modified single seed descent selection method, where one pod was used instead of a single seed. The test genotypes are presented in Table 1.

From F7 generation, single plant selections were made to identify soybean plants with desirable traits such as high yield, early maturity, resistance to major diseases and insect pests, resistance to lodging and pod shattering. These selected single plants were planted in single rows and seed from each single row was harvested in isolation and used in a replicated preliminary yield trial at Kabanyolo in 2013A. Seed from the preliminary yield trial were evaluated in an intermediate yield trial at two locations in 2013B (Kabanyolo and Namulonge), and the seed from the intermediate yield trial was evaluated further in an advanced yield trial conducted at eight multi locations that represented the major soybean growing areas of Uganda.

Description of the test environments

The study was conducted at eight locations, representing the major soybean growing areas of Uganda (Table 2). Three locations Namulonge, Kabanyolo and Nakabango are situated in the Lake Victoria Crescent; while Bulindi in the Western Grasslands; Ngetta in the north western savannah grasslands; Iki-iki in the Kyoga plains; Abi in North Western Farmlands Wooded Savannah and Mubuku in Western Medium High Farmlands. These locations have different climatic conditions that influence soybean yield (Table 2). Mubuku irrigation scheme was selected in order to assess the adaptability of the soybean genotypes under irrigation conditions.

Experimental design, data collection and analysis

The soybean genotypes included 28 elite breeding lines developed by MAKCSID and two check varieties (Maksoy 3N and Maksoy 4N) (Table 1). Maksoy 3N is a farmer-preferred variety because of large seed, high yields and high oil content, while Maksoy 4N is high yielding soybean variety in Uganda. The soybean genotypes were planted using a randomized complete block design (RCBD) with three replications. Each genotype was represented by three

Table 1: Description of genotypes used in the study

Genotype	Pedigree	Generation	No. families evaluated
BSPS 48A-28	GC0038-29 × Duiker	F12	21
BSPS 48A-9-2	GC0038-29 × Duiker	F12	18
Nam II × GC 44.2	Nam 2 × GC0038-29	F8	19
BSPS 48A-25	GC0038-29 × Duiker	F12	20
BSPS 48A-27-1	GC0038-29 × Duiker	F12	25
BSPS 48A-3B	GC0038-29 × Duiker	F12	26
Nam II × GC 13.2	Nam 2 × GC0038-29	F8	19
MAKSOY 4N	GC0038-29 × Duiker	Check Variety	
BSPS 48A-31	GC0038-29 × Duiker	F12	16
MAKSOY 3N	GC0038-29 × Duiker	Check Variety	
NGDT 8.11-11B	Nam 2 × GC0038-29	F10	23
BSPS 48A-8	GC0038-29 × Duiker	F12	18
BSPS 48A-26	GC0038-29 × Duiker	F12	21
MNG 11.2	Nam 2 × GC0038-29	F9	14
Nam II × GC 35.3	Nam 2 × GC0038-29	F8	15
Nam II × GC 17.3	Nam 2 × GC0038-29	F8	21
Nam II × GC 44.3	Nam 2 × GC0038-29	F8	25
Nam II × GC 43.2	Nam 2 × GC0038-29	F8	19
BSPS 48A-5	GC0038-29 × Duiker	F12	17
Nam II × GC 28.2B	Nam 2 × GC0038-29	F8	22
Nam II × GC 11.2	Nam 2 × GC0038-29	F8	23
NGDT 8.11-4	Nam 2 × GC0038-29	F10	17
Nam II × GC 7.2	Nam 2 × GC0038-29	F8	24
Nam II × GC 20.3	Nam 2 × GC0038-29	F8	23
Nam II × GC 4.8	Nam 2 × GC0038-29	F8	19
NGDT 8.11-19	Nam 2 × GC0038-29	F8	18
NGDT 4.11-5	Nam 2 × GC0038-29	F8	18
Nam II × GC 30B	Nam 2 × GC0038-29	F8	17
Nam II × GC 32.6	Nam 2 × GC0038-29	F8	21
Nam II × GC 43.1	Nam 2 × GC0038-29	F8	21

Table 2: Description of the locations used to evaluate soybean genotypes for yield in six seasons in Uganda

Location in Uganda	Position	Region	Altitude (masl)	Mean annual temperature (°C)	Mean Annual rainfall (mm)
Namulonge	0°32′ N 32°37′ E	Central	1 160	22.6	1 400
Nakabango	0°29′ N 33°14′ E	Eastern	1 210	22.8	1 400
Iki-Iki	1°06′ N 34°00′ E	Eastern	1 156	24.7	1 200
Ngetta	2°17′ N 32°56′ E	Northern	1 103	24.7	1 200
Mubuku	0°13′ N 30°08′ E	Western	1 007	27.8	750
Kabanyolo	0°28′ N 32°36′ E	Central	1 180	21.4	1 234
Bulindi	1°41′ N 31°42′ E	Mid-West	1 122	22.9	1 355
Abi	3°04′ N ′30°56′ E	West Nile	1 214	22.9	1 404

Source: Meteorological station data at the study locations

Table 3: Analysis of variance of 30 soybean genotypes evaluated in eight locations and six seasons in Uganda

Source of variation	df	SS	MS	VR	*p*-value
Location	7	5.76×10^7	8 235 565	2.7801	0.034
Season	5	2.41×10^7	4 825 029	89.3027	<0.001
Location × Season	20	5.92×10^7	2 962 221	56.3143	<0.001
Genotype	29	772×10^6	266 482	2.8179	<0.001
Location × Genotype	203	1.91×10^7	94 566	1.7977	<0.001
Season × Genotype	145	7.83×10^6	54 030	1.0271	0.408
Residual	610	3.20×10^7	52 601		
Total	1 019	2.08×10^8	203 989		

df = degrees of freedom; SS = sum of squares; MS = mean square; VR= variance ratio

rows measuring 5 m long with spacing of 60 cm between rows and 5 cm between plants within a row. The multi locational trial was conducted for six consecutive seasons; first rains of 2014 (2014 A), second rains of 2014 (2014 B), first rains of 2015 (2015A), second rains of 2015 (2015 B), first rains of 2016 (2016A) and second rains of 2016 (2016 B). The trials were kept weed free by regular weeding and no agrochemicals were used on the trials to control pests. At maturity, each genotype was harvested separately, threshed and corrected to 10% moisture content before determining yield per hectare. Separate analysis of variance were conducted per location for the 30 genotypes across the six seasons prior to combined analysis of variance. Yield data was analyzed using GGE model in GenStat 13th Edition (Payne et al. 2010). Certain locations had missing yield data, therefore the data were filtered using the Restricted Maximum Likelihood (REML) with the genotypes being fixed factor and replicates as random factor in the model.

Results

Results showed highly significant differences among genotypes, locations, seasons and the following interactions; Genotype × Location, Location × Season for seed yield (Table 3). The results also showed that genotype BSPS 48A-9-2 had the highest mean yield of 1 277 kg ha⁻1 with a yield advantage of 85 kg ha^{-1} and 65 kg ha^{-1} compared with Maksoy 3N and Maksoy 4N respectively (Table 4). Maksoy 3N is farmer preferred, while Maksoy 4N is the highest yielding soybean variety in Uganda. Genotypes BSPS 48A-28, Nam II × GC 44.2 and BSPS 48A-25 had mean yields of 1 256, 1 250, 1 240 kg ha^{-1} respectively. Bulindi had the highest mean yield of 1 426 kg ha^{-1}; followed by Ngetta and Nakabango with yields of 1 402 kg ha^{-1} and 1 380 kg ha^{-1} respectively (Table 4).

A ranking GGE biplot analysis showed that genotype BSPS 48A-9-2 was the best performer, though it was relatively unstable across the eight locations (Figure 1). This genotype was the highest performer as it was farthest from the mean along the 'average environment axis' (Yan

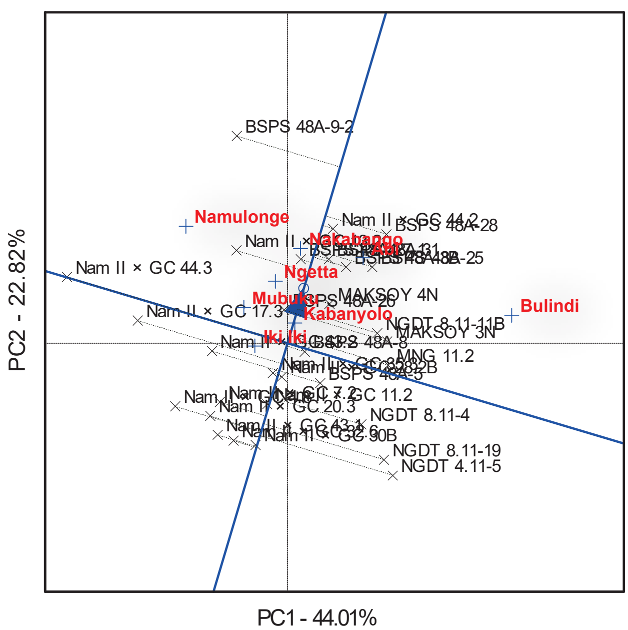

Figure 1: A GGE ranking biplot showing mean performance and stability for seed yield of 30 soybean genotypes evaluated in eight locations and six seasons

Table 4: Seed yield (kg ha⁻¹) of 30 soybean genotypes evaluated in eight locations and six seasons in Uganda

Genotype	Location									Yield advantage	
	Abi	Bul	Iki	Kab	Mub	Nak	Nam	Nge	Mean	vs Maksoy 3N	vs Maksoy 4N
BSPS 48A-9-2	1 144	1 346	851	936	1 400	1 525	1 509	1 506	1 277	85	65
BSPS 48A-28	1 316	1 709	869	947	1 389	1 571	812	1 437	1 256	64	44
Nam II × GC 44.2	903	1 652	856	930	1 411	1 714	961	1 577	1 250	58	38
BSPS 48A-25	1 180	1 674	980	1 014	1 302	1 560	800	1 408	1 240	48	28
Nam II × GC 13.2	892	1 215	866	1 023	1 564	1 599	960	1 645	1 221	29	9
BSPS 48A-27-1	1 013	1 384	892	1 020	1 372	1 686	814	1 574	1 220	28	8
BSPS 48A-3B	999	1 728	875	936	1 359	1 381	1 048	1 428	1 219	27	7
MAKSOY 4N	858	1 590	981	1 030	1 316	1 500	807	1 611	1 212	20	0
MAKSOY 3N	945	1 797	883	1062	1 335	1 314	712	1 487	1 192	0	−20
BSPS 48A-31	790	1 798	773	895	1 259	1 400	1 336	1 250	1 188	−4	−24
NGDT 8.11-11B	952	1 779	908	954	1 339	1 369	788	1 369	1 182	−10	−30
BSPS 48A-26	802	1 393	880	1 002	1 348	1 480	830	1696	1 179	−13	−33
BSPS 48A-8	596	1 610	1 015	972	1 524	1 524	865	1 271	1 172	−20	−40
MNG 11.2	837	1 814	881	996	1 306	1 405	697	1 334	1 159	−33	−53
Nam II × GC 17.3	638	901	1 103	958	1 528	1 465	1 096	1 484	1 147	−45	−65
Nam II × GC 35.3	613	1 465	929	969	1 648	1 347	849	1 343	1 145	−47	−67
Nam II × GC 43.2	783	1 086	971	891	1 572	1 448	819	1 458	1 128	−64	−84
Nam II × GC 44.3	772	743	1 028	917	1 483	1 127	1641	1 298	1 126	−66	−86
Nam II × GC 28.2B	861	1 310	940	950	1 177	1 353	782	1 431	1 101	−91	−111
BSPS 48A-5	664	1 548	814	940	1 192	1 420	784	1 419	1 098	−94	−114
Nam II × GC 11.2	655	1 438	889	806	1 463	1 044	900	1 534	1 091	−101	−121
Nam II × GC 20.3	619	1 130	1 150	918	1 414	1 319	822	1 340	1 089	−103	−123
NGDT 8.11-4	705	1 733	880	821	1 185	1 258	739	1 273	1 074	−118	−138
NGDT 8.11-19	849	1 763	899	898	1 260	1 079	626	1 153	1 066	−126	−146
Nam II × GC 4.8	493	1 009	975	1 008	1 312	1 331	944	1 431	1 063	−129	−149
Nam II × GC 7.2	651	1 124	825	928	1 520	1 422	818	1 196	1 061	−131	−151
Nam II × GC 30B	637	1 282	1 022	837	1 256	1 256	777	1 268	1 042	−150	−170
Nam II × GC 32.6	530	1 180	795	957	1 271	1 294	782	1 379	1 023	−169	−189
NGDT 4.11-5	1 052	1 641	751	911	1 143	1 042	510	1 112	1 020	−172	−192
Nam II × GC 43.1	931	951	865	807	1 157	1 176	751	1 338	997	−195	−215
Mean	823	1426	912	941	1 360	1 380	886	1 402	1 141		

Bul = Bulindi; Iki = Iki-Iki; Kab = Kabanyolo; Mub = Mubuku; Nak = Nakabango; Nam = Namulonge; Nge = Ngetta

et al. 2007). On the other hand, Nam II × GC 30B was the most stable genotype yet very low yielding, while Nam II × GC 44.3 was the least stable genotype. In comparison, Nam II × GC 44.2 was both high yielding and stable genotype (Figure 1).

The GGE polygon plot (Figure 2) gave good visual assessment of GE with both PCA1 and PCA2 explaining about 67% of total GE sum of squares. The scatter plot indicated that the eight locations were grouped into three major mega-environments. The first mega environment included Namulonge, Mubuku and Iki-Iki with the best genotype being Nam II × GC 44.3. The second mega environment included Ngetta, Nakabango and Kabanyolo with the best genotype being BSPS 48A-9-2. The last mega environment included Abi and Bulindi with the best genotype being BSPS 48A-28.

The GGE scatter plot (Figure 3) showed that Bulindi was the most discriminating environment, while Iki-Iki was the least of the eight locations. This was revealed by the long and short environment vectors of Bulindi and Iki-Iki, respectively. Of all the eight test environments, Bulindi was the most representative of the mega-environment than the rest due to the small angle from the average environment axis.

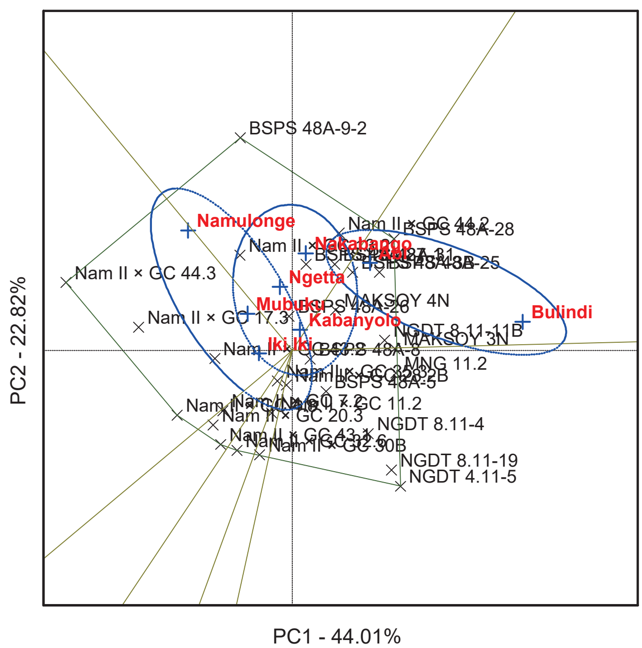

Figure 2: Polygon views of the GGE-biplot based on symmetrical scaling for the 'which-won-where' pattern of 30 soybean genotypes evaluated in eight locations and six seasons

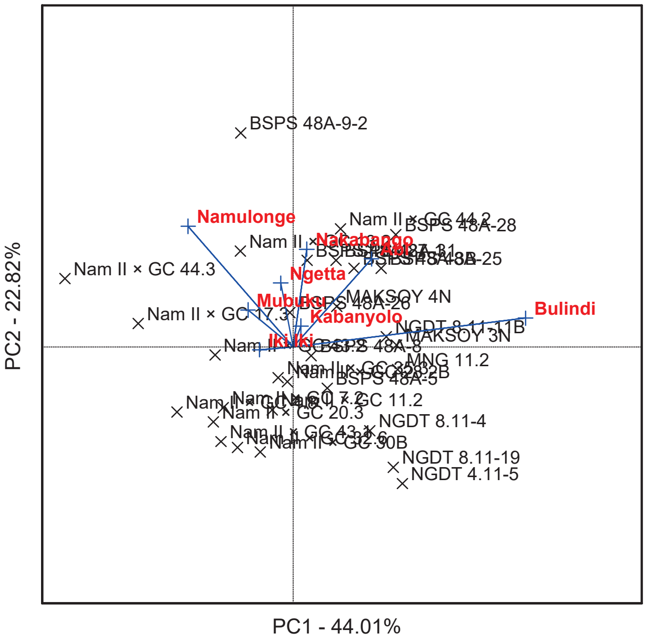

Figure 3: A GGE biplot showing discriminating power and representativeness of test environments involving 30 soybean genotypes evaluated in eight locations and six seasons

Discussion

Mean performance and stability

The present study showed that there were a number of genotypes that performed better than Maksoy 3N and Maksoy 4N that are the most farmer-preferred and high yielding varieties in Uganda, respectively. This study also showed that BSPS 48A-9-2 derived through single plant selection from BSPS 48A had the highest yield level compared to all the other genotypes. BSPS 48A was released in Uganda as Maksoy 3N as the highest yielding genotype (Tukamuhabwa et al. 2012). However, through continuous single plant selection, the yields of this variety has been greatly improved and stabilized. BSPS 48A-9-2 had greater yield stability, implying that its yield responds in accordance to the prevailing conditions. Such genotypes that display average stability tend to have higher yields when the prevailing conditions like moisture and soil fertility are favorable. Therefore, with increased input use such as fertilizer such genotypes tend to have high yields useful for both smallholder and commercial farmers. On the other hand, Nam II × GC 44.2 was consistent in yield performance irrespective of the prevailing conditions because it displayed narrow adaption (Lin et al. 1986; Becker and Leon 1988). Thus genotype Nam II × GC 44.2 will have stable yields irrespective of the prevailing conditions. Such genotypes are recommended for low input farming systems because their performance does not change with the prevailing environmental conditions (Lin et al. 1986).

Clustering test environments

Bulindi had the highest mean seed yield compared to the other seven locations. This was probably because of the high moisture content in the soil since this location receives much rainfall for most of the time in the season. This contradicts a previous study by Tukamuhabwa et al. (2011) that reported that Namulonge had highest yields due to the high rainfall received through the different seasons. Yet another study by Tukamuhabwa et al. (2012) showed that Nakabango was instead highest yielding test environment across five locations due to high soil fertility and high amounts of rainfall received. According to Obua (2013) Mubuku was reported as the highest yielding environment compared to the other four test locations because of the available water in the soil through flood irrigation. These results suggest that soil moisture and soil fertility during the cropping season are the major drivers of soybean seed yield in Uganda.

Three mega-environments were observed in this study (Figure 2). This is contrary to the observations by Tukamuhabwa et al. (2012) which showed that Uganda had two mega environments for soybean seed yield when evaluating 24 soybean genotypes for three seasons in five locations. However, in the current study, evaluations were conducted in six seasons and eight locations that represented the diverse agro-ecological zones than reported by Tukamuhabwa et al. (2012). The three mega-environments observed in this study suggest that successful soybean breeding and selections must be done in at least each one of the selected mega-environments.

Bulindi was the most discriminating test environment for soybean yield in Uganda in this study (Figure 3). This implies that Bulindi provides much information about the differences among the genotypes being evaluated, which was in agreement with a study conducted by Tukamuhabwa et al. (2012) that reported Bulindi as the most discriminating test environment. The test genotypes used in the current study are different from those reported by Tukamuhabwa et al. (2012) yet Bulindi was the most discriminating environment. The high discriminating power of Bulindi makes it a good location to be used as a primary testing location for differentiating the soybean genotypes for yield, and can be used as a "culling environment" for quick elimination of unstable genotypes during the evaluation process (Yan and Kang 2003). On the other hand, Bulindi was also the most representative environment because it had the smallest angle between its vector and "average-environment axis". This implies that Bulindi can be used to represent the other test environments used in this study for soybean yield.

Conclusion and recommendations

Genotypes BSPS 48A-9-2, BSPS 48A-31 and Nam II × GC 44.2 should be further tested under farmers' production condition for selection and release as new soybean varieties in Uganda because of their high and stable yields. BSPS 48A-9-2 is recommended for high input farming systems because it had broad stability, while Nam II × GC 44.2 for low input production systems because it had narrow stability. Therefore, genotypes with broader stability should be recommended for commercial farmers who have access to production inputs, while genotypes with narrow stability should be recommended for resource poor farmers who have limited access to suitable production technologies. Highly discriminating environment such as Bulindi should be used as a primary location for evaluation or seed production of soybean genotypes.

Geolocation

The study was conducted at eight locations, representing the major soybean growing areas of Uganda. Three locations Namulonge (0°32′ N, 32°37′ E), Kabanyolo (0°28′ N, 32°36′ E) and Nakabango (0°29′ N, 33°14′ E) are situated in the Lake Victoria Crescent; while Bulindi (1°41′ N, 31°42′ E) in the Western Grasslands; Ngetta (2°17′ N, 32°56′ E) in the north western savannah grasslands; Iki-iki (1°06′ N, 34°00′ E) in the Kyoga plains; Abi (3°04′ N, 30 56′E) in North Western Farmlands Wooded Savannah and Mubuku (0°13′ N, 30°08′ E) in Western Medium High Farmlands.

Acknowledgements — The authors are grateful to the Alliance for a Green Revolution in Africa – Program for Africa's Seed System and the Vegetable Oil Development Project for financial support. Makerere University (Soybean Breeding and Seed Systems Program) is thanked for providing the germplasm and facilities.

ORCID

Tonny Obua – https://orcid.org/0000-0003-1134-3255

References

Adie MM, Ayda K, Gatut-Wahyu AS. 2014. Assessment of genotype × environment interactions for black soybean yield using AMMI and GGE Biplot. *International Journal of Agriculture Innovations and Research* 2: 2319−1473.

Becker HC, Leon J. 1988. Stability analysis in plant breeding. *Plant Breeding* 101: 1−23.

Cheelo P, Lungu D, Mwala M. 2017. GGE biplot analysis for identification of ideal soybean [*Glycine max* L. Merrill] test and production locations in Zambia. *Journal of Experimental Agriculture International* 15: 1−15.

Clough TJ, Condron LM, Kammann C, and Mueller C. 2013. A review of biochar and soil nitrogen dynamics. *Agronomy* 3: 275–293.

FAO. 2018. FAOSTAT. avaialble at http://www.fao.org/faostat. [accessed 20 June 2020].

Graham PH, Vance CP. 2003. Legumes: importance and constraints to greater use. *Plant Physiology* 131: 872–877

Kawuki R. 2002. Soybean germplasm reaction to rust in Uganda, associated yield loss and rust control using fungicides. M.Sc. thesis. Makerere University, Uganda

Kaya Y, Palta C, Taner S. 2002. Additive main effects and multiplicative interactions analysis of yield performances in bread wheat genotypes across environments. *Turkish Journal of Agriculture and Forestry*. 26: 275–279.

Lin CS, Binns MR, Lefkovitch LP. 1986. Stability analysis: where do we stand? *Crop Science* 26: 894–900.

Mulugeta A, Sisay K, Seltene A, Zelalem F. 2013. GGE biplots to analyze soybean multi-environment yield trial data in north-western Ethiopia. *Journal of Plant Breeding and Crop Science* 5: 245–254.

Murithi HM, Beed F, Tukamuhabwa P, Thomma BPJ, Joosten MHAJ. 2015. Soybean production in eastern and southern Africa and threat of yield loss due to soybean rust caused by *Phakopsora pachyrhizi*. *Plant Pathology* 65: 176–188.

Namara M. 2015. Resistance of soybean germplasm to the groundnut leaf miner (*Aproaerema modicella*) in Uganda. MSc. thesis. Makerere University, Uganda.

Obua T. 2013. Soybean Rust Diversity and Adaptation of Elite Soybean Lines to the Ugandan Environment. MSc. thesis. Makerere University, Uganda.

Payne RW, Harding SA, Murray DA, Soutar DM, Baird DB, Glaser AI, Channing IC, Welham SJ, Gilmour AR, Thompson R, Webster R. 2010. *The Guide to GenStat Release 13, Part 2: Statistics*. Hemel Hempstead UK: VSN International.

Singh P, Kumar R, Sabapathy SN, Bawa AS. 2008. Functional and edible uses of soy protein products. *Reviews in Food Science and Food Safety* 7: 14–28.

SNV. 2011. Increased competitiveness of the oilseed value chain through improved information on the markets for soybean in Uganda. Final report submitted to SNV Rwenzori Portfolio, Kampala, Uganda.

Tukamuhabwa P, Obua T. 2015. Soybean production guide in Uganda. Makerere University Agricultural Research Institute, Kabanayolo – Kampala, Uganda.

Tukamuhabwa P Maphosa M. 2011. State of knowledge on breeding for durable resistance to soybean rust disease in the developing world. FAO plant production and protection paper 204.

Tukamuhabwa P, Asiimwe M, Nabasirye M, Kabayi P, Maphosa M. 2011. Genotype by environment interaction of advanced generation soybean lines for grain yield in Uganda. *African Crop Science Journal* 20: 107–115.

Tukamuhabwa P, Oloka HK, Sengooba T, Kabayi P. 2012. Yield stability of rust-resistant soybean lines at four mid-altitude tropical locations. *Euphytica.* 183:1–10

Tukamuhabwa P, Obaa B, Obua T, Namara M, Okii D, Kabayi P. 2016. Status of soybean production and impact indicators of new soybean varieties in Uganda. Makerere University Agricultural Research Institute, Kabanyolo (MUARIK), Makerere University, Kampala.

Tukamuhabwa P, Oloka HK. 2016. Soybean research and development in Uganda. A case of paradigm shift in an African University. Makerere University Agricultural Research Institute, Kabanyolo (MUARIK), Makerere University, Kampala.

Yan W, Hunt LA, Sheng Q, Szlavnics Z. 2000. Cultivar evaluation and mega-environment investigation based on the GGE biplot. *Crop Science* 40: 597–605.

Yan W, Rajcan I. 2002. Biplot evaluation of test sites and trait relations of soybean in Ontario. *Crop Science* 42: 11–20.

Yan W. 2001. GGE Biplot—A Windows application for graphical analysis of multi-environment trial data and other types of two-way data. *Agronomy Journal* 93: 1111–1118.

Yan W, Kang MS. 2003. *GGE biplot analysis: A graphical tool for breeders, geneticists, and agronomists*. Boca Raton, FL: CRC Press.

Yan W, Kang MS, Ma B, Woods S, Cornelius PL. 2007. GGE Biplot vs. AMMI analysis of Genotype-by-Environment data. *Crop Science* 47: 643–655.

Received 7 June 2018, revised 3 October 2019, accepted 7 October 2019
Associate Editor: Hussein Shimelis