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SOIL & CROP SCIENCES | RESEARCH ARTICLE

Analysis of genotype by environment interaction for grain yield of intermediate maturing drought tolerant top-cross maize hybrids under rain-fed conditions

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Abstract: Maize plays a crucial role in combating food insecurity in Ghana due to its high yield potential and wide adaptability. Thirty five intermediate maturing maize hybrids were evaluated at eight locations in Ghana for two years (i) to determine grain yield performance, stability and adaptability, (ii) to determine the representativeness and discriminating ability of the test locations and (iii) identify core testing sites for selection of superior maize hybrids. Genotype, environment and genotype \times environment interactions were significant ($p < 0.01$) for grain yield and most other traits measured. Grain yield of the hybrids ranged from 3.3 to 4.7 t ha⁻¹ for in the present study. The GGE biplot analysis identified genotype M1326-17 as the most stable and high yielding hybrid followed by M1326-14 and M1326-4. Test locations were divided into three groups; Ejura and Damongo constituting the first

ABOUT THE AUTHORS

Maize, the most widely cultivated and consumed cereal crop in Ghana is grown mainly under rain-fed conditions. Even though maize is a warm season crop, it becomes susceptible to inadequate moisture thereby, low yield. Additionally, low-fertility soils, pests, diseases and use of low-yielding varieties increase the risk of crop failure that negatively affects income, food security and sustenance of majority of farm households. The group's research activity seeks to develop and deploy high yielding stress-tolerant varieties to increase maize productivity in the country. These include:

- Evaluating stress tolerant materials from the CGIAR centres, identifying high yielding varieties with wide adaptability and releasing them for cultivation.
- Developing new hybrids from existing inbred lines and varieties, evaluating them and consequently, release.
- Developing new inbred lines and populations.

The research reported in this paper relates to issues of easy detection of genetic differences among genotypes through efficient and less costly variety testing.

PUBLIC INTEREST STATEMENT

Maize has a high yield potential and grows successfully under wide range of environmental conditions in Ghana. With this advantage, it has the potential of combating food insecurity in the country. However, yields from farmers' fields are low due to the use of low yielding varieties, poor soils, pests, diseases and drought. Hybrid maize production is one of the best ways of improving maize productivity in Ghana. The research objective was therefore to find out the consistency in grain yield of 35 hybrid maize, their adaptability to different locations and also to identify test environments representative of optimum hybrid maize production locations in Ghana. From the study, grain yield of the hybrids ranged between 66 – 94 bags of 50kg per hectare. It also identified Damongo, Fumesua and Nyankpala as perfect test environments for optimum maize production which can assist in the identification of superior hybrid maize to reduce testing cost.

group; Kpeve, Fumesua, Nyankpala, Pokuasi and Yendi the second and Wa standing alone as the third. Damongo was highly discriminating and representative in the first group and was identified as a core test site in that group. Fumesua and Nyankpala were identified as core test sites within group two while Wa was identified as the only test site in group three. The core testing sites identified would be used to facilitate the identification of superior maize hybrids to reduce testing cost in the country.

Subjects: Environment & Agriculture; Bioscience; Environmental Studies & Management; Food Science & Technology

Keywords: core testing sites; genotype × environment interaction; grain yield; discriminating ability; yield stability

1. Introduction

Maize (*Zea mays* L.) is an important cereal crop cultivated for its high economic importance as a staple food crop and an industrial raw material. It is the third most important crop in the world, after wheat and rice, in terms of growing area, production and grain yield (Shiri, Choukan, & Aliyev, 2010). Maize is the major staple crop grown in sub-Saharan Africa and plays a critical role in combating food insecurity in the sub-region due to its high yield potential, wide adaptability and relative ease of cultivation (Badu-Apraku, Akinwale, et al., 2011a). Globally more than 160 million hectares of maize is produced under rain-fed condition (Edmeades, 2013) and on nearly 13 million hectares of land in West and Central Africa (WCA) under rain-fed conditions (FAOSTAT, 2014).

Maize is one of the most important crops for Ghana's agricultural sector and for food security. It is the most widely cultivated crop produced on nearly 1.04 million hectares of land (Statistics, Research & Information Directorate, 2013) mostly under rain-fed conditions and accounting for 50–60% of total cereal production in the country (Millennium Development Authority, 2010). Mean annual production growth rate of maize in the country has increased at an estimated rate of 13.86% per annum from 2007 to 2012 at an average yield of 1.9 t/ha in 2012 (Statistics, Research & Information Directorate, 2013). Even though this is quite low compared to the achievable average yield of 6 t/ha (Statistics, Research & Information Directorate, 2013), the increased production of maize is proving an important step in achieving food security in the country. The low yields of maize in Ghana can be attributed to biotic and abiotic stresses, including recurrent drought, low soil fertility, limited use of fertilizers, low plant population and *Striga hermonthica* (Delile) Benth. parasitism.

Ghana has a great potential to be self-sufficient and net-exporter of maize due to high yield potential maize production ecologies with high solar radiation, low night temperatures and low incidence of diseases. The Development and deployment of hybrid maize adapted to diverse production environments is one of the best ways of improving the production and productivity of maize in Ghana as they are more responsive to fertilizer application and other production inputs. Generally, top-cross hybrids are extra productive than open-pollinated varieties (OPVs) and are expected to increase production per unit area, which is the primary objective in maize breeding programmes. Top-cross hybrids are formed by crossing open-pollinated maize varieties (OPVs) with inbred lines and can be developed fairly quickly from existing adapted germplasm. They are characterized by heterogeneity that provides them with greater flexibility to minimize risks associated with disease and pest outbreaks. They can also encourage indigenous seed companies that are currently producing only open pollinated maize varieties to start hybrid seed production since the production and maintenance of parents of top-cross hybrids are comparatively less complex and cheaper than conventional hybrid (Bidinge et al., 2005).

Genotype by environment interactions (GEI) refers to differential responses of genotypes or cultivars across a range of environments (Kang, 1998, 2004). Grain yield being quantitative in nature

normally demonstrates GEI and therefore call for genotype evaluation in multi-environments trials (MET) in the advanced stages of selection (Annicchiarico, 2002; Fan et al., 2007; Kang, Balzarini, & Guerra, 2004). GEI are of major significance to the plant breeder in developing enhanced genotypes but at the same time a challenge because they pose difficulties in selecting genotypes evaluated in varied environments. Different kinds of gene actions in the maize genotype interact differently in the inheritance of the various plant attributes. In addition, the maize crop grows on a wide range of environmental conditions with regard to water balance, solar radiation, and temperatures (Hill, Becker, & Tigerstedt, 1997). The greater part of GEI observed in yield responses of maize genotypes in multi-location trials may be contributed by varying environmental conditions prevailing at different agro-ecological zones where maize is grown, often hampering the identification of high yielding and stable maize hybrids across varying agro-ecological zones (Akçura, Taner, & Kaya, 2011). According to Badu-Apraku, Abamu, Menkir, Fakorede, and Obeng-Antwi (2003), the magnitude of genotype by location interaction are often greater than genotype by year interaction in multi-location trials and this complicates the identification of superior genotypes for a single location due to GEI.

A number of statistical methods have been developed to reveal patterns of GEI, such as joint regression (Eberhart & Russell, 1966; Perkins & Jinks, 1968), sum of squared deviations from regression (Eberhart & Russell, 1966), stability variance (Shukla, 1972), coefficient of determination (Pinthus, 1973), coefficient of variability and type B genetic correlation (Burdon, 1977). The most predominant being the additive main effects and multiplicative interaction (AMMI) model projected by Zobel, Wright, and Gauch (1988) and Gauch and Zobel (1997), and the GGE biplot methodology by Yan, Hunt, Sheng, and Szlavnic (2000). The AMMI model has led to more insight in the complicated patterns of genotypic responses to different environments (Zobel et al., 1988). The GGE biplot is efficient in identifying the best performing genotype in a given environment and the most suitable environment for each genotype (Yan et al., 2000). It also compares any pair of genotypes in individual environments, identifies the best genotype for each environment and mega-environment differentiation, the yield and stability of the genotypes, and the discriminating ability and representativeness of the environments (Yan & Kang, 2003; Yan, Kang, Ma, Woods, & Cornelius, 2007; Yan & Tinker, 2006). It is therefore a useful tool for identifying locations that optimized hybrid genotypes performance and for making better use of limited resources available for maize testing programmes (Fan et al., 2007). The GGE biplot allows visual analysis of the relationships among the test environments, genotypes and the GE interactions by using singular value decomposition to break the data matrix into component matrices. The first two principal components (PC1 and PC2) are used to produce a two-dimensional GGE-biplot. If a large portion of the variation is explained by these components, a rank-two matrix, represented by a GGE-biplot, is appropriate (Yan & Kang, 2003). Using a mixed model analysis may offer superior results when the regression of genotype by environment interaction on environment effect does not explain all the interaction (Yan & Rajcan, 2002).

The objectives of the present study was to use the GGE-biplot technique to; (i) examine the grain yield performance, stability and adaptability of the hybrids, (ii) determine the representativeness and discriminating ability of the test locations found in different agro-ecological zones in Ghana used for the evaluation of the hybrids and (iii) identify core testing sites for selection of superior maize hybrids.

2. Materials and methods

This study was carried out at eight locations in the Guinea, Sudan and coastal savannas, the forest and forest-savanna transition zones of Ghana. Thirty-five intermediate maturing (110 days) top-cross hybrids (Table 1) were evaluated in 2013 and 2014 under rain-fed conditions at Damongo, Nyankpala, Wa and Yendi in the Guinea savanna, Pokuase in the coastal savanna, Fumesua and Kpeve in the forest and Ejura in the forest-savanna transition (Table 2) to determine their yield potential. Trials were established when the rains at each location had come to stay or stabilised. All genotypes evaluated were drought tolerant materials from the Drought Tolerant Maize for Africa (DTMA) Project of the International Institute of Tropical Agriculture (IITA). A standard protocol was adopted at each location during the 2 years of genotype evaluation. The trials at all locations were

Table 1. Names and codes of 35 intermediate maturing top-cross maize hybrids evaluated across eight locations in Ghana in 2013 and 2014

Code	Hybrid	Code	Hybrid
1	M1326-1	19	M1326-19
2	M1326-2	20	M1326-20
3	M1326-3	21	M1326-21
4	M1326-4	22	M1326-22
5	M1326-5	23	M1326-23
6	M1326-6	24	M1326-24
7	M1326-7	25	M1326-25
8	M1326-8	26	M1326-26
9	M1326-9	27	M1326-27
10	M1326-10	28	M1326-28
11	M1326-11	29	M1326-29
12	M1326-12	30	M1326-30
13	M1326-13	31	M1326-31
14	M1326-14	32	M1326-32
15	M1326-15	33	M1326-33
16	M1326-16	34	M1326-34
17	M1326-17	35	Local check
18	M1326-18		

Table 2. Description of the test locations for the intermediate maturing top-cross maize hybrids conducted in eight locations in Ghana in 2013 and 2014

Location	Code	Agro-ecological zone	Latitude	Longitude	Altitude (m asl)	Rainfall during growing season (mm)
Damongo	DAM	GS	09° 01' N	01° 49' W	189.1	1,050
Ejura	EJU	FST	07° 38' N	01° 37' E	90	1,460
Fumesua	FUM	F	06° 41' N	01° 28' W	150	1,345
Kpeve	KPE	CST	06° 41' N	00° 21' E	513	1,198
Nyankpala	NYA	GS	09° 25' N	00° 58' E	340	1,090
Pokuase	POK	CS	05° 36' N	00° 10' E	78	1,100
Wa	WA	GS	10° 04' N	02° 30' W	323	966
Yendi	YEN	GS	09° 26' N	00° 10' W	157	1,128

Notes: GS, Guinea Savanna; CS, Coastal Savanna; CST, Coastal-savanna transition; F, Forest; FST, Forest-savanna transition; asl, Above sea level.

evaluated using randomized incomplete block design with three replications. A plot consisted of two rows spaced 0.75 m apart. Each row measured 5 m with 0.50 m spacing between plants within the row. Three seeds were planted per hill and later thinned to two plants per hill, giving a final population density of about 64,000 plants/ha. Pre- and post-emergence herbicides were used to control weeds and application of a combination of Pendimethalin [N-(1-ethylpropyl)-3, 4-dimethyl-2, 6-dinitrobenzenamine] and Gesaprim [2-chloro-4-(ethylamino)-6-(isopropylamino)-s-triazine] at 1.5 and 1.0 l ha⁻¹ active ingredient, respectively at planting. Hand weeding was also done when necessary to control weeds during the growing period. NPK 15-15-15 fertilizer was applied at the rate of 60 kg N ha⁻¹, 60 kg K₂O and 60 kg P₂O₅ ha⁻¹ as basal fertilizer at two (2) weeks after planting and

top-dressed with additional N at 40 kg N ha⁻¹ at four weeks after planting. Other management practices were done according to the recommendations for the respective locations.

2.1. Data collection

Data were recorded for grain yield and other agronomic traits from the two rows. These traits were days to 50% silking (DS), as the number of days from planting to when 50% of the plants had emerged silks, and days to anthesis (DA) when 50% had shed pollen. The anthesis-silking interval (ASI) was estimated as the difference between days to 50% silking and 50% anthesis. Plant height (PH) was measured as the distance from the base of the plant to the height of the first tassel branch and ear height (EH) as the distance from the base of the plant to the node bearing the upper ear. Plant aspect (PASP) was rated on a scale of 1 to 5 based on plant type, where 1 = excellent and 5 = poor. Ear aspect (EASP) was rated on a scale of 1 to 5, where 1 = clean, uniform, large, and well-filled ears and 5 = ears with undesirable features. Husk cover (HC) was scored on a scale of 1 to 5, where 1 = husks tightly arranged and extended beyond the ear tip and 5 = ear tips exposed. The number of ears per plant (EPP) was obtained by dividing the total number of ears per plot by the number of plants harvested. Grains from five randomly selected cobs were shelled to measure the percent grain moisture at harvest for each plot. Grain yield (GY) was computed based on 80% (800 g grain kg⁻¹ ear weight) shelling percentage and adjusted to 150 g kg⁻¹ moisture content.

2.2. Statistical analysis

The data were analysed separately for each location, and then combined across locations for grain yield and other measured traits with PROC GLM in SAS using a RANDOM statement with the TEST option (SAS Institute, Inc, 2002) to determine the genotype × environment (G × E) interaction. In the combined analyses of variance, replications, year, location, and year by location interaction were considered random factors, while genotypes were considered fixed. The combined ANOVA was done considering year-location combination as the environment to determine the effect of the environment [consisting of year (Y), location (L), and Y × L interaction], genotype, and all possible interactions among these sources of variation. Mean grain yields were separated using the standard error (SE).

The means from the ANOVA for grain yield across years in each site was used to determine the stability of hybrids in the various environments using the top 15 and bottom 10 genotypes generated from the base index. The GGE Biplots were generated using the R graphic interface 'GGEBiplotGUI' package (Yan & Kang, 2003). The biplots were constructed from the first two principal components (PC1 and PC2, also referred to as primary and secondary effects, respectively) derived from subjecting environment centred yield data (yield variation due to GGE), to singular value decomposition (SVD), (Yan et al., 2000). The data used were not transformed (Transform = 0), not standardized (Scale = 0), and were tester-cantered (Centering = 2). This provided information on the genotypes that were suitable for the different locations and investigation of stability of genotypes in the various locations and years. The GGE biplot Model equation used is as follows:

$$Y_{ij} - Y_j = \lambda_1 \xi_{i1} \eta_{j1} + \lambda_2 \xi_{i2} \eta_{j2} + \epsilon_{ij}$$

where Y_{ij} is the average yield of genotype i in location j , Y_j is the average yield across all genotypes in location j , λ_1 and λ_2 are the singular values for PC1 and PC2, respectively, ξ_{i1} and ξ_{i2} are the PC1 and PC2 scores, respectively, for genotype i , η_{j1} and η_{j2} are the PC1 and PC2 scores, respectively, for location j , ϵ_{ij} is the residual of the model associated with genotype i in location j .

3. Results and discussion

3.1. Analysis of variance

The combined ANOVA across locations and years showed that mean squares for location (L) and year by location interaction were significant ($p < 0.01$) for grain yield and all other measured traits of the hybrids studied (Table 3). Year mean squares were significant ($p < 0.05$) for grain yield and all other traits measured except for ear height. Genotypes (G), genotype by year, genotype by location

Table 3. Mean squares for grain yield and other agronomic traits of intermediate maturing maize hybrids evaluated across eight locations in Ghana in 2013 and 2014

Source	DF	Grain yield (t ha ⁻¹)	% CTV	Days to anthesis	Days to silking	ASI	Plant height	Ear height	Plant aspect	Ear aspect	Husk cover	EPP
Year (Y)	1	5.9*	4.0	49.5**	9.1*	101.0**	7,532.7**	18.7 ns	38.8**	3.6**	31.1**	0.2**
Location (L)	7	68.8**	47.1	1,459.5**	1,346.0**	68.3**	54110.0**	20901.1**	33.9**	33.4**	17.8**	1.6**
Genotype (G)	34	3.3**	2.2	9.3**	8.1**	0.6**	406.4*	301.5**	0.5 ns	0.7*	0.3 ns	0.03**
Block (L × Y)	320	1.3**	0.9	7.3**	7.3**	0.4**	967.6**	440.9**	0.6**	0.6**	0.3 ns	0.02**
L × Y	7	61.6**	42.2	1,189.4**	963.7**	31.6**	43830.0**	1,722.0**	18.5**	5.0**	6.7**	0.7**
G × L	238	1.1**	0.8	2.7**	2.5*	0.4**	326.8*	175.7*	0.4 ns	0.5*	0.3 ns	0.02**
G × Y	34	2.2**	1.5	6.2**	5.9**	0.3**	528.9**	309.5**	0.4 ns	0.7**	0.4 ns	0.01 ns
G × L × Y	238	1.1*	0.8	3.1**	3.0**	0.4**	384.7**	217.3**	0.4 ns	0.4 ns	0.3 ns	0.01 ns
Error	800	0.8	0.5	2.0	2.0	0.3	259.3	134.8	0.4	0.4	0.3	0.01

Notes: ns = not significant; %CTV = percentage contribution to total variation; ASI = anthesis-to-silking interval; EPP = number of ears per plant.

*Significant at 0.05 probability level.

**Significant at 0.01 probability level.

and genotype by year by location mean squares were significant ($p < 0.05$) for GY, DTA, DTS, ASI and PH (Table 3). Genotype and genotype by location mean squares were also significant ($p < 0.01$) for EPP. The significant mean squares recorded in the current study for genotypes for most traits, except for husk cover and plant aspect indicated that the genotypes responded differently to the test locations (environments) and thus, call for the need to identify high-yielding and stable genotypes across the locations (Badu-Apraku et al., 2003; Moghaddam & Pourdad, 2009). Also, the highly significant genotype by location interaction (GEI) for grain yield of the intermediate maturing top-cross hybrids seeks to justify the need for the testing of the hybrids in multiple locations over years before recommendation.

Environment had the highest impact on yield, accounting for 94.2% ($Y + L + \text{Blks } (Y \times L) + Y \times L$) of the total variation, followed by the GEI, accounting for 3.1% ($G \times Y + G \times L + G \times Y \times L$) and genotype alone accounted for the least variation of 2.2% (Table 3). Fan et al. (2007) and Mitrović et al. (2012), reported similar findings in multi-environment trials on maize where the largest proportion of total variation was attributed to locations and relatively smaller sources of variation to G and GEI. In their research whereby GGE biplot was used for targeting early maturing maize cultivars to mega-environments in West Africa, Badu-Apraku, Oyekunle, et al. (2011b) also reported similar result for which environment contributed about 83.4% of the total sources of variation in grain yield while G and GEI accounted for about 1.5% and 11% respectively. The large sum of squares associated with the environment in the present study indicates that the selected environments were diverse. The smaller $G \times E$ interaction and large environmental effect implies that the genotypes are stable across environments and the maximum variation in hybrid performance is contributed by the environmental differences. Grain yield of the hybrids ranged from 3.3 t ha⁻¹ for M1326-12 and M1326-26 to 4.7 t ha⁻¹ for M1326-30. The highest yielding top-cross hybrid (M1326-30) out-yielded the local check by 17.5% (Table 4).

3.2. GGE biplot analysis of grain yield response and stability of intermediate maturing top-cross maize hybrids

The highly significant $G \times E$ mean squares for grain yield across the test locations justified the use of the GGE biplot to decompose the $G \times GEI$ effects. The GGE biplot for grain yield of the best 15, the worst 10 and the hybrid check of the 35 intermediate maturing top-cross maize hybrids evaluated at eight locations across the forest, forest transition, Guinea and Sudan savannas zones of Ghana in

Table 4. Grain yield and other agronomic traits of intermediate maturing maize hybrids evaluated across eight locations in Ghana in 2013 and 2014

Code	Hybrid	Grain yield (t/ha)	Days to anthesis	Days to silking	ASI	Plant height	Ear height	Husk cover	Plant aspect	Ear aspect	EPP
1	M1326-1	3.8	56.1	58.0	1.9	180.3	86.1	1.6	2.0	2.0	1.0
2	M1326-2	4.1	55.4	57.4	2.0	179.9	81.0	1.8	1.8	2.0	0.9
3	M1326-3	4.2	55.5	57.3	1.9	179.7	81.6	1.8	1.9	1.9	0.9
4	M1326-4	4.6	55.7	57.5	1.8	177.4	83.5	1.8	1.9	1.9	1.0
5	M1326-5	4.1	55.0	56.9	1.9	172.8	77.3	1.7	1.8	1.9	1.0
6	M1326-6	3.8	55.5	57.4	1.9	174.7	80.0	1.9	2.0	2.3	0.9
7	M1326-7	4.1	55.8	57.5	1.7	175.2	78.8	1.7	1.9	1.9	0.9
8	M1326-8	3.9	54.4	56.6	2.3	174.9	81.6	1.7	2.1	2.1	0.9
9	M1326-9	4.0	55.8	57.6	1.8	177.3	82.5	1.6	1.9	1.9	0.9
10	M1326-10	4.1	55.9	57.7	1.8	174.3	77.5	1.7	2.0	2.0	0.9
11	M1326-11	3.6	55.5	57.3	1.8	172.9	77.3	1.8	2.3	2.0	0.9
12	M1326-12	3.3	56.0	57.9	2.0	170.4	77.0	1.6	2.1	2.1	0.9
13	M1326-13	3.8	55.9	57.9	2.0	173.6	76.5	1.8	2.0	2.2	0.9
14	M1326-14	4.3	55.6	57.5	1.8	173.9	76.3	1.7	1.9	2.0	0.9
15	M1326-15	4.1	55.7	57.6	1.8	176.5	76.0	1.8	2.0	1.9	0.9
16	M1326-16	4.1	54.8	56.8	2.0	177.0	81.1	1.8	1.9	2.3	0.9
17	M1326-17	4.1	55.8	57.7	1.9	172.0	77.9	1.6	2.1	2.0	0.9
18	M1326-18	3.5	56.0	57.8	1.8	172.7	75.8	1.9	2.1	2.3	0.9
19	M1326-19	4.1	55.5	57.6	2.1	175.5	82.5	1.8	2.1	2.0	0.9
20	M1326-20	3.8	55.7	57.6	1.9	174.2	79.9	1.6	1.9	1.9	0.9
21	M1326-21	4.0	55.9	57.9	2.0	171.3	77.8	1.8	2.0	2.2	0.9
22	M1326-22	3.6	56.1	58.1	2.0	174.8	77.9	1.8	2.0	2.1	1.0
23	M1326-23	4.1	56.4	58.1	1.7	181.7	85.3	1.7	2.0	2.1	0.9
24	M1326-24	4.1	55.6	57.7	2.1	177.5	81.2	1.8	2.0	2.2	0.9
25	M1326-25	3.8	55.8	57.8	2.0	174.8	81.7	1.8	1.9	2.2	1.0
26	M1326-26	3.3	55.0	56.9	1.9	171.7	76.7	1.8	2.0	2.1	1.0
27	M1326-27	3.6	56.1	57.8	1.8	173.4	80.1	1.8	2.0	2.3	0.9
28	M1326-28	3.7	57.1	58.9	1.9	175.2	79.8	1.7	2.0	1.9	0.9
29	M1326-29	3.7	55.7	57.6	2.0	174.7	80.1	1.7	2.1	2.2	0.9
30	M1326-30	4.7	56.2	58.0	1.8	172.8	77.4	1.7	1.9	1.9	0.9
31	M1326-31	4.3	56.3	58.2	1.9	172.3	78.1	1.6	2.1	2.0	0.9
32	M1326-32	3.8	56.1	58.3	2.2	170.2	77.4	1.8	2.2	2.3	0.9
33	M1326-33	4.3	56.0	57.8	1.8	176.2	80.2	1.9	2.3	2.4	0.9
34	M1326-34	4.0	56.4	58.4	2.0	169.6	75.7	1.6	2.1	2.2	0.8
35	Locdl check	4.0	55.9	58.0	2.1	165.7	74.1	1.8	2.3	2.3	0.9
	Mean	4.0	55.8	57.7	1.9	174.5	79.3	1.7	2.0	2.0	0.9
	SE	0.03	0.1	0.1	0.02	0.7	0.5	0.01	0.02	0.02	0.003
	CV	22.3	2.6	2.5	27.7	9.2	14.6	30.9	30.3	29.8	12.4

2013 and 2014 are shown in Figures 1 and 2. The principal component axis 1 (PC1) accounted for 51.75% of total variation and principal component axis 2 (PC2) also accounted for 15.53%. Cumulatively, these two principal components explained 67.28% of the total variation for grain yield (Figures 1 and 2). The polygon in Figure 1 is formed by connecting the markers of the hybrids that are farthest away from the biplot origin, such that all other hybrids are contained in the polygon. The polygon view also contains a set of lines perpendicular to each side of the polygon. These perpendicular lines divide the biplot into several sectors. The vertex hybrid in each sector represents the highest yielding hybrid (the winning hybrid) in the location that falls within that particular sector (Yan et al., 2010; Yan & Tinker, 2005). There are seven sectors in (Figure 1) with hybrids 10, 11, 12, 23 and 30 as the vertex hybrids. Locations DAM and EJU fell in the sector in which hybrids 23 and 30 were the vertices hybrids implying that, hybrids 23 and 30 were the best hybrids for DAM and EJU. Hybrid 10 was the highest yielding hybrid at NYA, KPE, POK, YEN and FUM while hybrid 11 was the highest yielding hybrid in WA. No location fell into sector with hybrid 12 as the vertex. This implies that it was the poorest hybrid in some or all of the locations. Hybrids within the polygon, notably hybrids 2, 7, 15, 19, 20, 26, 27, 32, 33 and 34 were less responsive than the vertex hybrids. The eight locations fell into three sectors. This pattern suggests that the target locations may consist of three different mega-environments and that different hybrid should be selected and deployed for each.

Figure 1. A “Which won where/what” of genotype × environment biplot of the best 15 and the worst 10 and the hybrid check of 35 intermediate maturing top-cross maize hybrids evaluated under rain-fed conditions at eight locations in Ghana in 2013 and 2014. Principal components PC1 and PC2 explained 67.28% of the variation among genotypes.

Location abbreviations:
 DAM = Damongo,
 NYA = Nyankpala, EJU = Ejura,
 KPE = Kpeve, POK = Pokuase,
 YEN = Yendi, FUM = Fumesua
 and WA = Wa.

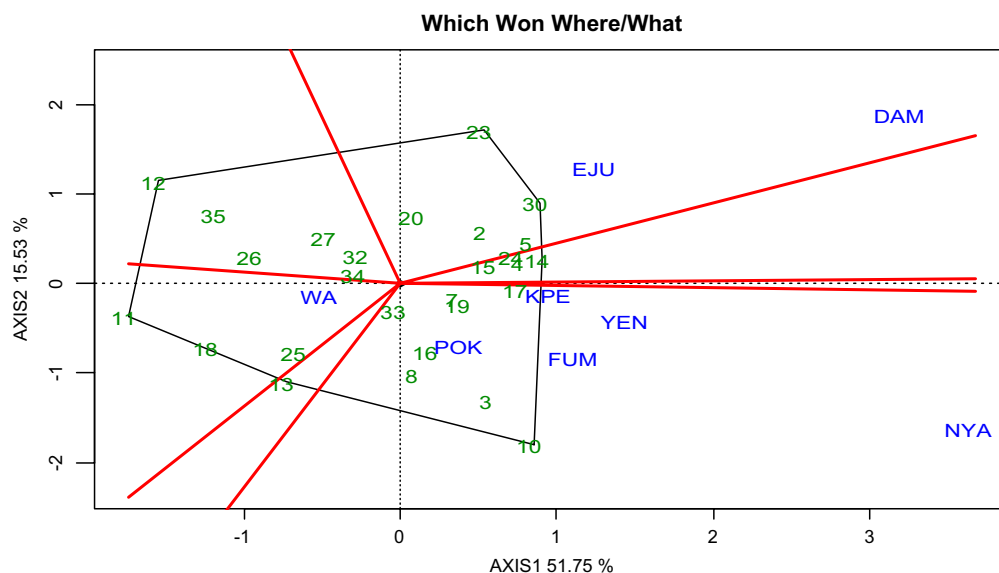
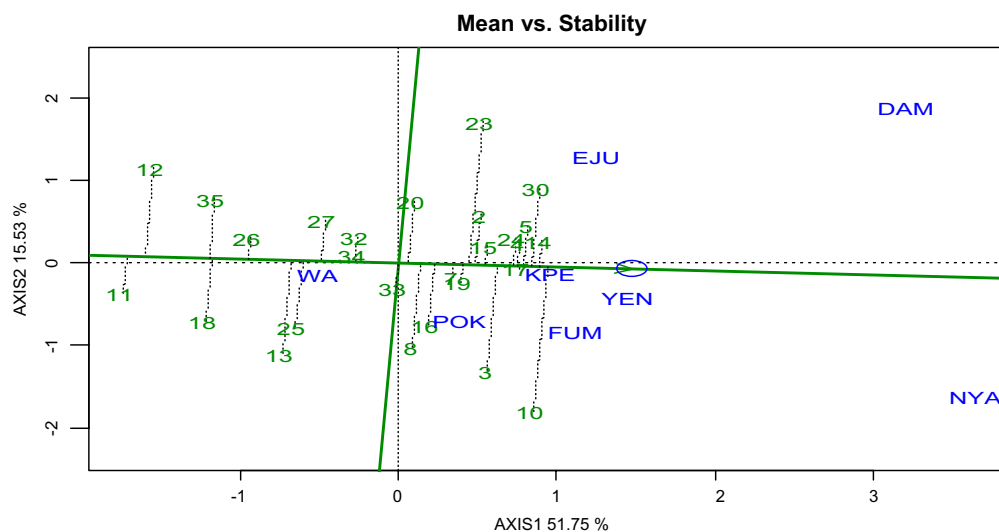


Figure 2. An entry/tester genotype × environment biplot of the best 15 and worst 10 and the hybrid check of 35 intermediate maturing top-cross maize hybrids evaluated under optimum conditions at eight locations in Ghana in 2013 and 2014. Principal components PC1 and PC2 explained 67.28% of the variation among genotypes.

Location abbreviations:
 DAM = Damong,
 NYA = Nyankala, EJU = Ejura,
 KPE = Kpeve, POK = Pokwase,
 YEN = Yendi, FUM = Fumesua
 and WA = Wa.



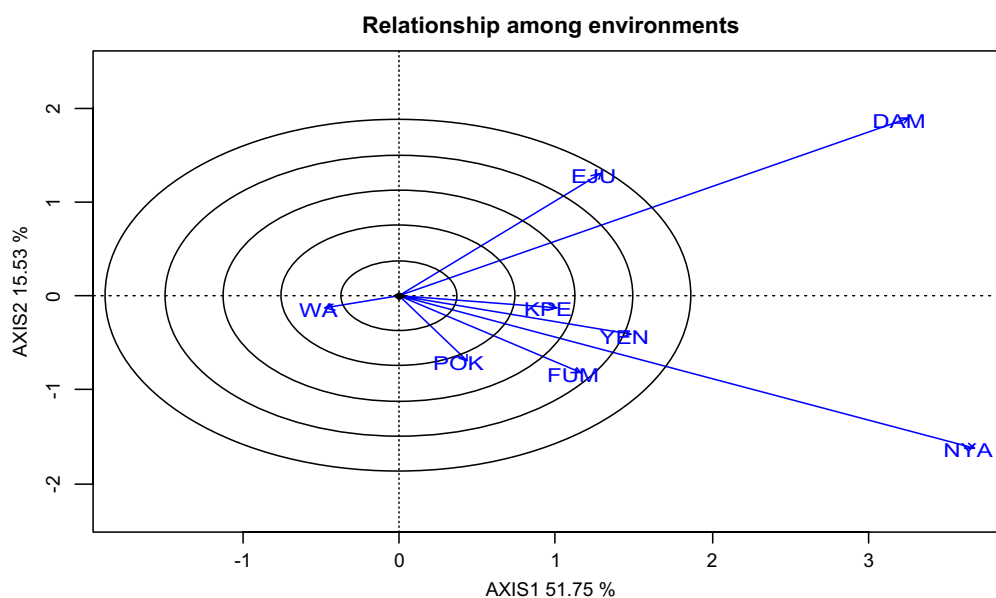
Using the stability GGE biplot of grain yield for the best 15 and the worst 10 and the hybrid check of the 35 intermediate maturing top-cross maize hybrids as shown in Figure 2, the hybrids were ranked along the average-tester axis (ATC abscissa), with the horizontal line based on their average performance across the eight locations. This figure is the average-environment coordination (AEC) view of the GGE biplot. The single-arranged line is the AEC abscissa (or AEA) and points to higher mean yield across environments. The vertical line separates entries with below-average means from those with above-average means. The mean yield of the hybrids is estimated by the projections of their markers on the average-tester axis. The stability of the hybrids is determined by their projection onto the middle horizontal line. The greater the absolute length of the projection of a hybrid, the less stable it is. Thus hybrid 10 was the highest yielding but most unstable hybrid while hybrid 11 was the lowest yielding but very stable. In contrast, hybrids 30, 24, 17, 14, 5 and 4 were the high yielding and most stable hybrids and therefore identified as the best hybrids across locations in the present study. Hybrid 35, the local check, was low yielding but relatively stable whilst hybrid 12 was not only low yielding but also one of the least stable hybrids.

3.3. Relationship among environments (test locations)

The eight test locations showed significant variation. Each location provided different conditions for expression of yield for the hybrids tested. The vector view of the GGE biplot in Figure 3 shows the interrelationships between the test locations. The lines connecting the biplot origin and the markers for the locations are termed environment vectors. The cosine of the angle between the environmental vectors indicates the correlation coefficient between them (Yan, 2002). The smaller the angle, the more highly correlated the environments (Yan & Kang, 2003; Yan & Tinker, 2006). The cosine of the angle between the vectors of environment point to near-zero correlations between WA and EJU, DAM, KPE, YEN and NYA. When the angle between two environments is less than 90°, the correlation coefficient between them is positive (Yan, 2002). There is therefore a positive correlation between EJU and DAM as well as among POK, FUM, NYA, YEN and KPE. From the vector view of the GGE biplot in Figure 3 the eight environments in this study were clustered into three groups: EJU and DAM constitute the first group, then KPE, YEN, NYA, FUM and POK the second group while WA stands alone as the third group.

Figure 3. Vector view of the GGE biplot showing relationships among locations.

Location abbreviations:
 DAM = Damongo,
 NYA = Nyankpala, EJU = Ejura,
 KPE = Kpeve, POK = Pokuase,
 FUM = Fumesua, YEN = Yendi
 and WA = Wa.



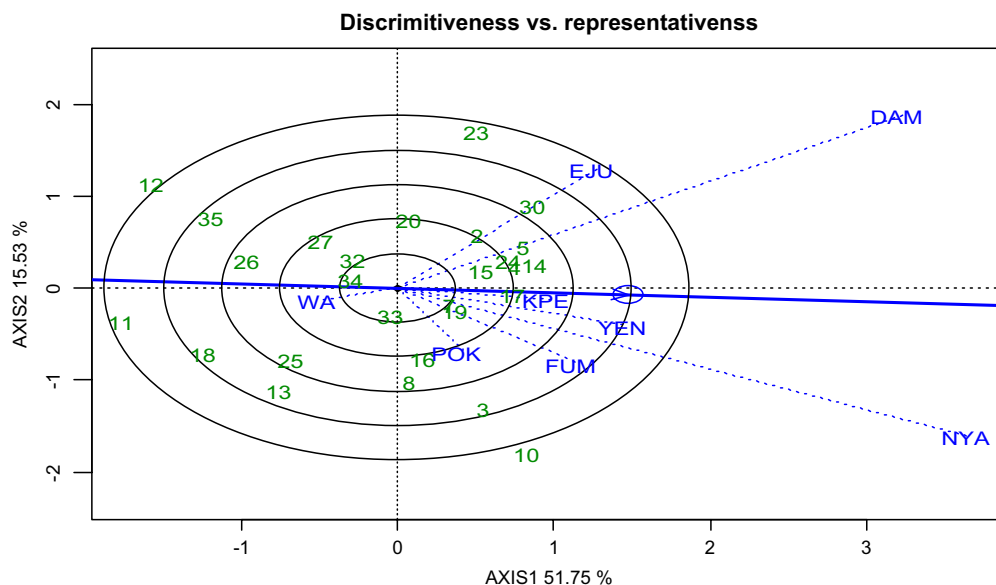
3.4. Ranking test locations based on both discriminating ability and representativeness

Figure 4 represents the discriminating ability and representativeness of the test locations. The ability of an environment to identify an ideal test environment is referred to as the discriminating power of an environment (Badu-Apraku, Oyekunle, et al., 2011) and the distance between the markers of the environment to the biplot origin, is a measure of its discriminating ability (Frutos, Galindo, & Leiva, 2013). The ability of a test environment to represent the mega-environment is referred to as the representativeness (Badu-Apraku, Oyekunle, et al., 2011) and the magnitude of the projection from the marker of the environment onto the average environment coordinate (AEC) axis is the measurement of its representativeness (Frutos et al., 2013). The small circle is the average-environment axis (AEA), and according to Yan and Tinker (2005) the arrow pointing to it is used to indicate the direction of the AEA. Test environments having large angles with the AEA are less representative of the mega-environment than those having small angles with it. Environments with longer vectors are more informative compared to those with shorter vectors and offer more information about the genotypes. Environments with shorter vectors could therefore be excluded when choosing test environments since they offer little or no information about the genotypes. Test environments with shorter environmental vectors indicate weak correlation with test environments with longer vectors. Consequently, the short-vector environments WA, POK and KPE may be regarded as independent research environments and may be treated as unique and, therefore, essential research environments. In contrast, the long-vector test environments DAM, NYA, FUM, EJU, and YEN were more powerful in discriminating among the cultivars, DAM and NYA being the most discriminative environments.

Test environments with long vectors and small angles with the AEC abscissa are ideal for selecting superior genotypes while test environments with long vectors and large angles with the AEC abscissa are useful in culling unstable genotypes (Yan et al., 2007, 2010). EJU and DAM had long vectors and large angles with the AEC abscissa suggesting that they may not be used in selecting superior genotypes, but may be used in culling unstable genotypes. Furthermore, the distance between two test environments measures their dissimilarity in discriminating the genotypes and presence of close associations among test environments suggest that the same information can be obtained from the fewer environments and this will reduce the testing cost. In the present study EJU and DAM were closely associated, confirming that these locations produced similar information about the genotypes and thus implying that a promising intermediate maturing top-cross hybrid in this study selected in one of these locations will also be suitable for production in the other locations. Hence, one of these testing sites can be dropped in this case. The discriminativeness versus representativeness biplot (Figure 4) strongly suggests, DAM test environment is better discriminating and

Figure 4. The discriminating ability and representativeness of the test locations.

Location abbreviations:
 DAM = Damongo,
 NYA = Nyankpala, EJU = Ejura,
 KPE = Kpeve, POK = Pokuase,
 FUM = Fumesua, YEN = Yendi
 and WA = Wa.



representative than EJU. Similarly, FUM and POK produced similar information about the genotypes (were closely associated) implying that a promising intermediate maturing top-cross hybrid in this study selected in one of these locations will also be suitable for production in the other location. Hence, one of these testing sites can be dropped, in this case POK since FUM is more discriminating and representative than POK. Test locations KPE, YEN and NYA were highly correlated in their ranking of the genotypes and were thus, grouped into the same mega-environment also suggesting that, a promising intermediate maturing top-cross hybrid in this study selected in one of these locations will more likely be adapted to the other locations.

An ideal test environment is one that is most discriminating for genotypes and is representative of other environments (Tonk, Ilker, & Tosun, 2011; Yan & Kang, 2003). From the biplot display in Figure 4, test locations DAM and NYA were most discriminating because of their longest distances from the biplot origin but were less representative due to their large angles with the AEC abscissa as compared to KPE that seemed to be the most representative location followed by YEN. Therefore, test location KPE has been identified as the ideal test environment in Ghana in this study, whilst YEN was close to the ideal. Based on their discriminating power and representativeness the order of ranking the other test locations was as follows: NYA, DAM, EJU \approx FUM, POK and WA. Similar results were obtained by Badu-Apraku, Oyekunle, et al. (2011) in their ranking of test locations on the basis of their discriminating power and representativeness in their work targeting early maturing maize cultivars to mega-environments in West Africa, YEN was followed by NYA followed by EJU.

4. Conclusion

The results of the present study showed that $G \times E$ influences the ranking of the genotypes in different locations with some locations better for genotype evaluations than others. Test locations were divided into three groups; Ejura and Damongo constituting the first group; Kpeve, Fumesua, Nyankpala, Pokuasi and Yendi the second and Wa standing alone as the third. Damongo was highly discriminating and representative in the first group and was identified as a core test site in that group. Fumesua and Nyankpala were identified as core test sites within group two while Wa was identified as the only test site in group three. The core testing sites identified would be used to facilitate the identification of superior maize hybrids to reduce testing cost in the country. Hybrid M1326-17 was identified as the most stable and high yielding in the present study followed by hybrids M1326-14 and M1326-4. The superior hybrids identified from the present study should be promoted for adoption and commercialization to contribute to mitigation of food insecurity and poverty in Ghana.

Abbreviations

AMMI	additive main effects and multiplicative interaction
ANOVA	analysis of variance
ASI	anthesis-silking interval
DT	drought tolerant
$G \times E$	genotype \times environment
GGE	genotype main effect and genotype \times environment interaction
MET	multi-environments trials

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