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RESEARCH

Genotype × Environment Interaction of Quality Protein Maize Hybrids under Contrasting Management Conditions in Eastern and Southern Africa

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ABSTRACT

Drought and low soil fertility are major abiotic stresses limiting yield of maize (*Zea mays* L.) in eastern and southern Africa. The present study was undertaken to determine genotype by environment interaction (GEI) and grain yield stability of quality protein maize (QPM) experimental hybrids. A total of 108 hybrids, including two commercial checks, were tested across 13 environments under drought, low N, and optimal environments in Ethiopia, Zambia, and Zimbabwe in 2015 and 2016. Environment, hybrid, and hybrid × environment interaction effects were significant ($P < 0.01$) across environments and within management conditions. The highest yielding hybrids were H40, H41, H56, and H58 under optimum management; H2, H9, H40, and H87 under low N; H3, H10, H11, and H94 under drought; and H9, H10, H40, H56, and H94 across environments. The GEI and grain yield stability analysis using different models indicated that additive main effects and multiplicative interaction (AMMI), and genotypic main effects plus GEI (GGE) models were more efficient and precise compared to the linear regression stability model in identifying high-yielding hybrids with stable performance. Based on the AMMI and GGE biplots, the most promising QPM hybrids were identified under different management conditions. Hybrid H40 was the most outstanding genotype under various management conditions and could be used in breeding programs or commercialized in target areas. Gwebi optimum and Bako low N were identified as the most discriminating and representative environments under the contrasting management conditions. In general, results of the present study depicted the possibility of developing high-yielding and stable QPM hybrids for stress and nonstress conditions.

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Abbreviations: AEC, average environment coordinate; AMMI, additive main effects and multiplicative interaction; ASV, additive main effects and multiplicative interaction stability value; GEI, genotype × environment interaction; GGE, genotypic main effects plus genotype × environment interaction; IPCA, interaction principal component analysis; MET, multienvironment trial; PCA, principal component analysis; QPM, quality protein maize; SSA, sub-Saharan Africa.

Maize (*Zea mays* L) is an important crop for food security and economic wellbeing of hundreds of millions of households in sub-Saharan Africa (SSA) (Fisher et al., 2015). In most SSA countries, maize covers >50% of the land area allocated for cereal production (Masuka et al., 2017). Maize accounts for 45% of the total calories and 43% of the total protein derived from cereals in eastern and southern Africa (Shiferaw et al., 2011). Despite its importance in the region, maize yields in SSA are still the lowest compared with other regions of the world (Masuka et al., 2017) due to several environmental and socioeconomic factors (Shiferaw et al., 2011). Smallholder subsistence farmers in the region grow maize under suboptimal management and rainfed conditions, which expose the crop to unpredictable stresses at different growth stages (Ertiro et al., 2017).

Drought and low soil N stresses have been identified as the common constraints to maize production in the subregion (Weber et al., 2012). When the two abiotic factors occur simultaneously, the combined effect can result in a significant yield reduction (Badu-Apraku et al., 2013). Research results have shown that ~40% of the maize fields in Africa experience random drought

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stress, which can cause a yield loss of between 10 and 25%. About a quarter of the maize area suffers from recurrent drought that results in yield losses as high as 50% of the expected harvest, and under severe drought, total crop failure is common (CIMMYT, 2013). Under such circumstances, it is justifiable to embark on stress tolerance breeding as an economically feasible option (Bänziger et al., 2006), as maize varieties that tolerate drought stress and low soil fertility could minimize smallholders' risk (Shiferaw et al., 2011), maximize crop productivity, and improve household food security and livelihoods (Tesfaye et al., 2016). In addition, low cultivar turnover (Abate et al., 2017) and genotype × environment interaction (GEI) predominantly contribute to low yield in small-scale farming systems (Abakemal et al., 2016).

For decades, CIMMYT has conducted research aimed at improving nutritional quality of maize and has developed nutritionally enhanced varieties such as quality protein maize (QPM) (Wegary et al., 2014). The QPM genotypes possess about twofold the levels of lysine and tryptophan, which have higher biological value than the normal endosperm (non-QPM) maize genotypes. The CIMMYT has also generated several drought- and low-N-stress-tolerant QPM inbred lines for eastern and southern Africa (Wegary et al., 2014; Ertiro et al., 2017). Assessing GEI of the available hybrids across a range of stress and optimum environments will facilitate the identification of hybrids adapted to different abiotic stress conditions (Badu-Apraku et al., 2016). Hence, increasing the production and utilization of QPM varieties among the low-income households can help improve food security and minimize the risk of malnutrition (Wegary et al., 2014).

Multienvironment trials (METs) are useful for accurate identification of potential genotypes and representative variety testing environments (Yan et al., 2007) to improve the efficiency of breeding activities (Yan and Holland, 2010). The GEI complicates the identification of desirable genotypes and ideal testing environments that can be used for the selection of superior cultivars; thus, conduct of multilocation testing over years prior to cultivar recommendation would suffice (Badu-Apraku et al., 2012). Over years, several studies have been conducted on GEI and stability of non-QPM germplasm under various management conditions. Information on GEI and stability of QPM germplasm to identify commercially acceptable hybrids across SSA under contrasting environment is very limited. Agronomic performances and quality characteristics of QPM germplasm are greatly affected by environmental conditions such as drought and low N (Wegary et al., 2011; Njeri et al., 2017; Setimela et al., 2017). Information on GEI and stability of QPM genotypes across different management conditions in eastern and southern Africa would therefore provide a scientific basis to develop future breeding strategies that target the development of QPM germplasm for release and marketing across countries. Various methods could be used for the analysis and interpretation of MET data. The additive main effects and multiplicative interaction (AMMI) (Gauch and Zobel, 1997; Zobel et al., 1988), genotypic main effects plus GEI (GGE) biplot (Yan et al., 2000, 2007; Yan, 2001), and joint regression (Eberhart and Russell, 1966) analyses are the most commonly used univariate and multivariate methods for analysis of MET data. Among these statistical tools, Yan et al. (2007) indicated that AMMI and GGE biplots are the most powerful models for the analysis and interpretation of MET data. However, GGE biplot is superior to AMMI in accommodating different data scaling and weighting options and delineating mega-environment, genotype, and test environment evaluation (Yan et al., 2007), whereas the AMMI biplot is superior to GGE in separating genotypic and environmental main effects and the GEI effects (Gauch et al., 2008) when analyzing MET data.

The CIMMYT in collaboration with National Agricultural Research Systems (NARS) in eastern and southern Africa has developed well-adapted elite QPM inbred lines that are tolerant to major abiotic stresses in the region. Promising QPM hybrids derived from crosses involving these stress-resilient inbred lines need to be evaluated for their GEI and grain yield stability patterns under optimum and stress environments. Therefore, the present study was undertaken to determine GEI and grain yield stability of QPM experimental hybrids under stress and nonstress environments for cultivar development and recommendation in eastern and southern Africa.

MATERIALS AND METHODS

Germplasm

The germplasm used for the study included 106 F_1 QPM hybrids developed by crossing 28 late-maturing QPM inbred lines to four QPM inbred testers (Table 1) using the line-by-tester mating design proposed by Kempthorne (1957), along with two commercial check hybrids (ZS261 and SC627). In addition, two popular standard checks were included for the purpose of comparison in each environment. The standard checks included hybrids AMH760Q and AMH851 at Ambo, BHQPY545 and BH546 at Bako, and SC403 and SC513 in all other test environments. The inbred lines selected for this study (Table 1) were identified through careful phenotypic performance evaluations in breeding nurseries and evaluation for endosperm modification using the light table to select hard vitreous endosperm kernels. This was followed by biochemical analysis of tryptophan and protein contents following the method of Villegas et al. (1984). Most of the QPM inbred lines with the desirable endosperm modification used for the present study were developed by converting popular non-QPM stress-resilient inbred lines as suggested by Vivek et al. (2008) and by recycling advanced QPM inbred lines. The testers were well-adapted QPM inbred lines (Wegary et al., 2013, 2014) and had previously been proven useful in hybrid combinations at CIMMYT for tropical

and subtropical mid-altitude environments. The commercial checks used represent medium-maturing QPM (ZS261) and non-QPM (SC627) three-way cross hybrids widely grown in eastern and southern Africa. Among the standard checks, AMH760Q (QPM) and AMH851 (non-QPM) are medium-maturing three-way cross hybrids and widely adopted in the highland and transitional highland agroecologies of Ethiopia. A single-cross, yellow-endosperm QPM hybrid (BHQPY545) released for the mid-altitude major maize growing areas of Ethiopia and a high-yielding, medium-maturing, non-QPM, three-way cross hybrid (BH546) released for the mid-altitude, high-rainfall maize growing areas were included as checks. In

Table 1. Names, pedigrees, and protein quality profiles of 32 medium- to late-maturing quality protein maize (QPM) inbred lines used in the line-by-tester crosses.

Parent	Name	Pedigree	Prot†	Trp‡	QI§	DA¶
			%			d
Line						
L1	TL156579	([NIP25-100-1-1-B-1-B*5/[GQL5/[GQL5/CML202]F2-3sx]-11-1-3-2-B*4]- 3/CML395IR)-BBB(IR)-1-B-B-B-B	9.54	0.07	0.73	63
L2	TL156580	([NIP25-100-1-1-B-1-B*5/[GQL5/[GQL5/CML202]F2-3sx]-11-1-3-2-B*4]-3/CML395IR)-BBB-1-2-1-B-B-B-B	11.05	0.06	0.54	68
L3	TL156583	(CML312IR/[[[CLQRCWQ83/CML312SR//CML312SR]/CML312SR]-26-B/(CLQRCWQ50/CML312SR)-2-2-1-BB]-BB)F2-B-7-2-2-B-B-B-B	11.64	0.09	0.74	62
L4	TL156584	([CML389/GQL5]-B-22-1-1-1-B*5/[CML205/CML176]-B-2-1-1-2-B*5)-B-1-1-2-1-B-B-B	9.63	0.08	0.83	65
L5	TL156587	[[CML202/CML144]F2-1-1-3-B-1-B*6/CZL066]-B*5-3-B-B-B-B	10.34	0.08	0.79	69
L6	TL156593	(([CML511*/[CML390//[CML390/GQL5]-B-3sx]-B-1-1-2-BBB]-3/CML390IR)-B)F2-B-6-1-1-1-B-B-B	10.58	0.08	0.76	69
L7	TL156594	([CML205/CML176]-B-2-1-1-2-B*5/CML511//CML511)-1-1-1-1-1-B-B-B	10.61	0.09	0.85	69
L8	VL05118	CML159-B	11.76	0.07	0.58	64
L9	TL101711	[CML159/[CML159/[MSRXPOOL9]C1F2-205-1(OSU23i)-5-3-X-X-1-BB]F2-3sx]-8-1-1-BBB-4-B-B-B	11.01	0.07	0.68	66
L10	TL156602	(CZL083/[[CLQRCWQ83/CML312SR//CML312SR]/CML312SR]-26-BB-1-B)F2-19-1-1-2-B-B-B	11.66	0.08	0.70	63
L11	TL102715	[CML202/CML144]F2-1-1-3-B-1-B*5-1-1-B-B	9.40	0.08	0.82	67
L12	TL116956	[[CML202/CML144]F2-1-1-3-B-1-B*6/CML442]-B*5-4-B-B-B	9.65	0.07	0.71	65
L13	TL156603	[[CML202/CML144]F2-1-1-3-B-1-B*6/CZL066]-B*5-2-B-B-B	10.98	0.08	0.74	67
L14	TL156606	(CML489/[CML202/CML144]F2-1-1-3-B-1-B*6)-B-14-2-2-2-B-B-B	10.61	0.08	0.75	66
L15	TL135470	([NAW5867/P49SR(S2#)//NAW5867]F#-48-2-2-B*5/([CML144/[CML144/CML395]F2-8sx]-1-2-3-2-B*4-1-B/[INTA-2-1-3/INTA-60-1-2]-X-11-6-3-BB)F2)-B-B-34-2-B	10.44	0.07	0.62	61
L16	TL147070	(CML197/(CML197/[(CLQRCWQ50/CML312SR)-2-2-1-BB/CML197]-BB)F2)-B-B-44-2-B	10.44	0.07	0.66	72
L17	TL156607	(CML197/(CML197/(CLQRCWQ50/CML312SR)-2-2-1-BBB)F2)-B-B-6-4-B	11.90	0.10	0.84	73
L18	TL147078	(CML197/(CML197/(CLQRCWQ50/CML312SR)-2-2-1-BBB)F2)-B-B-36-2-B	11.91	0.11	0.95	68
L19	TL147129	(CML395/(CML395/CML511)F2)-B-B-11-1-B	12.15	0.11	0.88	65
L20	TL155810	(CML395/(CML395/[NAW5867/P49SR(S2#)//NAW5867]F#-48-2-2-B*4)F2)-B-B-17-2-B	10.33	0.08	0.78	66
L21	TL147114	(CML395/(CML395/S99TLWQ-B-8-1-B*4-1-B)F2)-B-B-20-2-B	12.06	0.10	0.84	67
L22	TL156595	[(CLQRCWQ50/CML312SR)-2-2-1-BB/[CML390//[CML390/GQL5]-B-10sx]-B-6-1-BBB]-B*5-2-B-B-B-B	11.04	0.10	0.87	65
L23	TL156596	((CLQRCWQ50/CML312SR)-2-2-1-BBB/[CML390//[CML390/GQL5]-B-10sx]-B-6-1-BBB)-B-18-1-2-2-B-B-B	10.44	0.08	0.77	68
L24	VL06373	(CLQRCWQ01/CML312SR)-4-2-1-BB-1-B-B-B	11.35	0.07	0.62	70
L25	TL156598	([CML390//[CML390/GQL5]-B-3sx]-B-1-1-2-BBB/[CML202/CML144]F2-1-1-3-B-1-B*6//[CML390//[CML390/GQL5]-B-3sx]-B-1-1-2-B)-1-4-3-2-2-B-B	10.74	0.08	0.74	66
L26	TL156610	([CML181/[CML181/[MSRXPOOL9]C1F2-174-1(OSU31ss)-1-7(I)-X-X-1-B]F2-2sx]-1-3-3-1-BB-2-1/CML181-2-1)-47-B-6-2-2-1-B-B-B	10.60	0.09	0.85	70
L27	TL156611	([CML181/[CML181/[MSRXPOOL9]C1F2-174-1(OSU31ss)-1-7(I)-X-X-1-B]F2-2sx]-1-3-3-1-BB-2-1/CML181-2-1)-47-B-6-2-3-2-B-B-B	9.72	0.07	0.72	66
L28	VL05117	CML144-B	11.94	0.09	0.75	66
Tester						
T1	TL156587	[[CML202/CML144]F2-1-1-3-B-1-B*6/CZL066]-B*5-3-B-B-B-B	10.34	0.08	0.79	60
T2	VL05552	CML491	10.53	0.08	0.76	68
T3	TL148289	[WWO1408-1-1-2-B*4-#/[CML202/CML144]F2-1-1-3-B-1-B*6]-B*4-4-1-B-B-B	10.41	0.09	0.85	65
T4	TL149662	[[[CZL083/CML509]F2-1/[GQL5/[GQL5/[MSRXPOOL9]C1F2-205-1(OSU23i)-5-3-X-X-1-BB]F2-4sx]-11-3-1-1-B*4]-9-B-1-BBB-1-B-B-B	10.92	0.10	0.93	65
Mean			10.80	0.08	0.76	66

† Prot, Protein content in whole grain.

‡ Trp, Tryptophan content in whole grain.

§ QI, quality index (calculated as the ratio of tryptophan to protein concentrations in whole grain).

¶ DA, days to anthesis.

addition, the early- and medium-maturing, non-QPM, three-way hybrids SC403 and SC513, widely marketed in many SSA countries, were included as checks.

Environments and Experimental Design

The 110 hybrids (106 QPM experimental hybrids, two commercial, and two standard hybrid checks) were evaluated across 13 environments—six optimum (well-watered and well-fertilized), four low N stress, and three managed drought stress environments—during 2015 and 2016 in Ethiopia, Zambia, and Zimbabwe (Table 2). The experimental sites were representative of the subhumid mid-altitude and dry-lowland maize production mega-environments of SSA (Hartkamp et al., 2000), except Ambo, which represented the highland subhumid maize growing agroecology (Abakemal et al., 2016). All the optimum management and low soil N experiments were conducted during the respective main growing season of each country, whereas the controlled drought stress experiments were conducted during the off-seasons entirely under irrigation. Fertilizer rates in each environment were applied based on site-specific recommendations (Table 2). The trial sites were all managed through crop rotation and incorporation of residues to maintain good soil health, except for the low N plots. All low N trials were planted on N-depleted plots and received no N fertilizer. Nitrogen depletion was achieved by continuously planting maize at high density on the same plot for at least 5 yr without N fertilizer application and removing residues at harvest. In an effort to detect crossover effects, Bolaños and Edmeades (1996) recommended that target yields for low N stress should be between 20 and 30% of what the average yield under optimum management in the same environment. To induce drought stress, irrigation was withheld 2 wk ahead of the anticipated date of flowering through to maturity. The entries were hand planted in single-row plots of 4.8-m length at Bako, 4.25-m length at Ambo, and 4-m length in all other environments. The spacing used was 0.75 m between rows and 0.25 m between plants, except at Bako, where 0.3-m spacing between hills was used following the agronomic recommendations of the respective environments. Initially, two seeds were planted per hill and later thinned to one plant to achieve the target plant densities of 44,444 plants ha^{-1} at Bako and 53,333 plants ha^{-1} in all the other environments (Table 2).

The 110 hybrids were planted in a 5 × 22 α-lattice design (Patterson and Williams, 1976) replicated twice at each test environment. Data were recorded on several agronomic characteristics, but only grain yield was used for the present study. Under all the three management conditions, the total grain weight from harvested ears of each hybrid was used to calculate grain yield per hectare after adjusting to 12.5% moisture content (Magorokosho et al., 2009). Measurements were taken on well-bordered plants by excluding the plant nearest to the alley of each row.

Data Analysis

Data for each environment were analyzed using the PROC MIXED procedure of SAS (SAS Institute, 2002). Genotypes were considered as fixed effects, whereas replications and blocks within replications were considered as random effects. Adjusted entry means from each environment analysis according to the lattice design (Cochran and Cox, 1960) were used to perform the combined analyses using PROC GLM procedure of SAS (SAS Institute, 2002) to test the significance of GEI. The two local checks included in each environment were different and thus excluded from combined analysis. In the combined analysis, the significance of genotype mean squares was tested using GEI mean square as the error term, whereas the GEI was tested using the pooled error. Upon confirming the presence of significant GEI in the combined analysis (Table 3), further partitioning of the GEI and stability analyses was conducted using suitable models. Broad-sense heritability (H) was computed for different management conditions and across environments based on entry means following the method suggested by Hallauer et al. (2010).

Joint linear regression of the mean of genotype on the environmental mean as an independent variable was performed according to the method described by Eberhart and Russell (1966). According to this model, stable varieties were defined as those having high mean grain yield, regression coefficient (b_i) = 1.0 and deviation from regression (s^2d_i) = 0. The AMMI model, which combined the standard ANOVA with principal component analysis (PCA) (Zobel et al., 1988), was also used to investigate the agronomic nature of GEI. The AMMI analysis was computed using adjusted means from each management

Table 2. Description of the environments used to evaluate the quality protein maize single-cross hybrids.

Code	Location	Management	Country	Year	Latitude	Longitude	Altitude	Fertilization			Grain yield ± SE
								N	P_2O_5	K	
							m asl	kg ha^{-1}			t ha^{-1}
BKOP	Bako	Optimum	Ethiopia	2015	9°06′ N	37°09′ E	1650	92	69	0	6.42 ± 0.66
BKLN	Bako	Managed LN	Ethiopia	2015	9°06′ N	37°09′ E	1650	0	46	0	3.02 ± 0.83
AMOP	Ambo	Optimum	Ethiopia	2015	8°57′ N	38°07′ E	2225	166	69	0	5.29 ± 1.05
AMLN	Ambo	Managed LN	Ethiopia	2015	8°57′ N	38°07′ E	2225	0	0	0	4.73 ± 0.98
HALN	Harare	Managed LN	Zimbabwe	2016	17°49′ S	31°1′ E	1489	0	56	24	4.02 ± 0.72
HAOP	Harare	Optimum	Zimbabwe	2016	17°49′ S	31°1′ E	1489	166	56	24	5.22 ± 1.12
GWLN	Gwebi	Managed LN	Zimbabwe	2016	17°13′ S	31° E	1406	0	56	24	2.00 ± 0.65
GWOP	Gwebi	Optimum	Zimbabwe	2016	17°13′ S	31° E	1406	166	56	24	6.56 ± 1.00
GLOP	Glendale	Optimum	Zimbabwe	2016	17°31′ S	31°3′ E	1147	166	56	24	4.05 ± 0.75
MPOP	Mpongwe	Optimum	Zambia	2016	13°32′ S	28°03′ E	1300	208	35	21	6.94 ± 1.36
CHDS	Chisumbanje	Managed drought	Zimbabwe	2015	20°48′ S	32°14′ E	455	148	56	24	4.04 ± 0.97
CZDS	Chiredzi	Managed drought	Zimbabwe	2015	21°02′ S	31°58′ E	395	148	56	24	1.00 ± 0.11
SVDS	Save Valley	Managed drought	Zimbabwe	2015	20°22′ S	32°17′ E	556	148	56	24	2.73 ± 0.56

condition and across the 13 environments for the 108 hybrids (excluding the standard checks). To compare the stability of the hybrids, AMMI stability value (ASV) was also computed for each hybrid, as described by Purchase et al. (2000). Hybrids with lower ASV values (closer to zero) were considered more stable than hybrids with higher ASV values. Additive main effects and multiplicative interaction biplots were constructed for each management condition and across environments using mean values of the top-yielding 25 hybrids and the two commercial checks (SC627 and ZS261), as it was difficult to visualize all the 108 hybrids in the AMMI biplot. Biplots of the first PCA and mean grain yields of the genotypes and environments were therefore used to construct the biplots that illustrated all the relationships among genotypes and environments.

In addition, the variation due to genotypes and GEI for grain yield under each management condition was assessed using a GGE biplot based on the PCA of environment-centered data to obtain information on genotype and GEI, referred to as a GGE biplot (Yan et al., 2000; Yan, 2001; Yan and Kang, 2003). The GGE biplots were generated using a singular value decomposition model of the first two principal components (Yan, 2002). The adjusted hybrid means across each management condition and across environments for the 25 top-yielding hybrids and the two commercial checks were used for the GGE biplot analysis. The relationships of GEI as represented by the which-won-where pattern (Gauch and Zobel, 1997; Yan, 2002), associations among test environments (Yan and Rajcan, 2002) and hybrids (Yan, 2001) were visualized using environment-centered GGE biplot. An average environment coordinate (AEC) was drawn to observe the mean performance and stability of the hybrids (Yan and Kang, 2003) and to identify ideal test environments and hybrids. GenStat 17 statistical software (Payne et al., 2007) was used for the analyses of joint linear regression, AMMI, and GGE biplot models.

RESULTS

ANOVA and Hybrid Performance under Different Management Conditions

Individual environment ANOVA showed highly significant variations for grain yield among the hybrids (Supplemental Table S1). Mean grain yields for the hybrids ranged from 1.0 t ha^{-1} under the drought-stressed environment CZDS to 6.9 t ha^{-1} under optimum environment MPOP (see Table 2 for definition of environment codes). A number of new QPM hybrids exhibited higher grain yield than the best check hybrids under managed stress and nonstress conditions (Supplemental Tables S1 and S3). Highly significant mean squares were observed due to environment, hybrid, and hybrid × environment interaction for grain yield across optimum, low N, drought, and across all environments (Table 3). Heritability for grain yield was high for all management conditions (i.e., 0.65, 0.69, 0.88, and 0.91 across drought, low N, optimum, and across environments, respectively). Mean grain yield across optimum environments was 5.68 t ha^{-1}, with a range between 1.97 and 7.90 t ha^{-1} (Table 3). As presented in Table 4 and Supplemental Table S2, higher yielding hybrids under optimum management were H56 (7.92 t ha^{-1}), H58 (7.63 t ha^{-1}), H40 (7.57 t ha^{-1}), and H41 (7.20 t ha^{-1}). Under low N, grain yield of the hybrids ranged from 1.12 to 4.89 t ha^{-1}, with a mean of 3.44 t ha^{-1}, whereas H87 (4.86 t ha^{-1}), H40 (4.77 t ha^{-1}), H2 (4.65 t ha^{-1}), and H9 (4.59 t ha^{-1}) showed higher grain yield. Across drought conditions, mean grain yield was 2.56 t ha^{-1}, with a range from 0.67 to 4.29 t ha^{-1}. Hybrids H11 (4.29 t ha^{-1}), H10 (4.00 t ha^{-1}), H94 (3.98 t ha^{-1}), and H34 (3.84 t ha^{-1}) were higher yielding than the other hybrids and the checks (Tables 3 and 4).

Across environments, grain yield ranged from 1.40 to 5.77 t ha^{-1}, with an overall mean of 4.29 t ha^{-1}. The best QPM hybrids across environments were H40 (5.77 t ha^{-1}),

Table 3. Combined ANOVA and means for grain yield of 106 quality protein maize hybrids and two commercial check hybrids tested across 13 stress and nonstress environments during 2015 and 2016.

	Optimum†		Low N		Drought		Across	
Source of variation	df	Mean square	df	Mean square	df	Mean square	df	Mean square
		t ha^{-1}		t ha^{-1}		t ha^{-1}		t ha^{-1}
Environment (E)	5	123.78**	3	155.62**	2	252.54**	12	348.49**
Hybrid (H)	107	6.86**	107	2.00**	107	1.65**	107	8.48**
H × E	535	0.92**	321	0.60**	214	0.60**	1284	0.80**
Pooled error	642	0.59	428	0.38	321	0.22	1391	0.44
Mean		5.68		3.44		2.56		4.29
Minimum		1.97		1.12		0.67		1.40
Maximum		7.90		4.89		4.29		5.77
SE (m)		0.31		0.31		0.27		0.18
LSD $_{(0.05)}$		0.61		0.60		0.53		0.36
Heritability (*H*)		0.88		0.69		0.65		0.91
CV (%)		13.41		17.91		18.24		15.44

** Significant at the 0.01 probability level.

† Optimum, optimum management; Low N, low-nitrogen stress; Drought, drought stress; Across, across all environments.

Table 4. Mean grain yield of the 25 top-yielding quality protein maize hybrids and two commercial checks evaluated across optimal, low N and drought environments in Eastern and Southern Africa in 2015 and 2016.

		Optimum management§						Low N stress						Drought stress					
Hybrid†	GY‡	IPCA1 (27.6%)	IPCA2 (25.8%)	ASV	b_i	s^2d_i	Hybrid	GY	IPCA1 (49.4%)	IPCA2 (32.4%)	ASV	b_i	s^2d_i	Hybrid	GY	IPCA1 (61%)	IPCA2 (39%)	ASV	b_i	s^2d_i
	t ha^{-1}							t ha^{-1}							t ha^{-1}					
H56	7.92	0.64	0.06	0.69	1.56	0.52	H87	4.86	0.27	−0.20	0.46	1.26	1.39	H11	4.29	0.66	0.07	1.04	1.80	0.35
H58	7.63	0.21	−0.11	0.25	1.34	1.07	H40	4.77	0.26	−0.28	0.48	1.22	−0.03	H10	4.00	0.67	−0.26	1.08	1.96	−0.15
H40	7.57	0.26	0.12	0.30	1.26	−0.06	H2	4.65	0.16	−0.08	0.26	0.87	1.67	H94	3.98	0.55	0.36	0.94	1.60	1.59
H41	7.20	0.47	−0.67	0.84	1.44	1.04	H9	4.59	0.35	0.27	0.59	1.52	0.87	H34	3.84	0.38	0.20	0.63	1.41	0.62
H59	7.06	0.69	0.35	0.82	1.35	0.79	H11	4.50	0.87	−0.16	1.33	2.23	0.06	H12	3.78	0.59	−0.09	0.93	1.76	−0.08
H10	7.00	0.43	−0.06	0.47	1.21	0.44	H85	4.38	0.34	0.05	0.52	1.58	−0.27	H3	3.76	0.43	−0.14	0.70	1.62	−0.18
H26	6.90	0.14	0.12	0.19	1.08	0.65	H57	4.38	0.07	−0.16	0.19	1.13	−0.25	H77	3.71	0.32	0.48	0.69	1.26	1.89
H94	6.89	−0.44	0.36	0.60	1.01	0.63	H81	4.35	0.22	0.05	0.34	1.30	−0.03	H40	3.52	0.34	−0.14	0.56	1.49	−0.17
H57	6.88	0.17	−0.29	0.35	1.32	0.62	H89	4.24	0.00	−0.15	0.15	1.04	−0.27	H2	3.47	0.45	−0.47	0.85	1.73	0.68
H9	6.88	0.22	0.16	0.28	1.18	0.15	H10	4.24	−0.17	0.09	0.27	1.12	0.15	H22	3.38	0.23	0.79	0.87	1.01	4.49
H76	6.70	−0.05	−0.33	0.33	1.26	0.37	H41	4.20	0.04	−0.40	0.40	0.98	1.33	H59	3.37	0.35	−0.05	0.55	1.46	−0.15
H2	6.68	−0.24	0.05	0.26	1.08	0.48	H90	4.17	−0.13	0.15	0.24	1.04	0.89	H86	3.35	0.38	−0.03	0.59	1.50	−0.15
H82	6.64	0.15	0.25	0.29	1.02	0.85	H93	4.17	0.41	−0.11	0.63	1.59	−0.27	H4	3.34	0.38	0.02	0.59	1.48	−0.08
H83	6.64	0.11	0.40	0.42	1.18	0.22	H20	4.15	−0.17	−0.28	0.38	0.71	−0.02	H1	3.33	0.30	−0.31	0.56	1.46	0.13
H42	6.63	0.06	−0.14	0.15	1.21	0.21	H79	4.13	−0.18	0.20	0.34	1.04	−0.21	H82	3.32	0.31	−0.03	0.49	1.40	−0.11
H45	6.55	0.05	0.21	0.22	1.17	−0.06	H92	4.11	−0.26	−0.42	0.58	0.56	−0.07	H33	3.29	0.25	0.18	0.43	1.24	0.34
H87	6.55	−0.33	−0.54	0.64	1.13	0.86	H16	4.10	0.07	−0.54	0.55	0.82	1.60	H35	3.28	0.14	0.41	0.46	1.06	1.15
H79	6.53	−0.18	0.13	0.23	1.02	0.05	H3	4.10	0.44	−0.08	0.67	1.70	0.00	H9	3.27	0.29	−0.15	0.49	1.41	−0.16
H85	6.51	0.30	0.16	0.36	1.12	0.07	H61	4.10	−0.08	−0.34	0.37	0.77	−0.20	H27	3.25	0.25	0.09	0.40	1.25	0.06
H90	6.49	0.32	0.13	0.37	1.16	0.10	H56	4.06	0.34	−0.09	0.52	1.48	0.02	H75	3.24	0.27	0.07	0.42	1.32	0.01
H65	6.47	−0.25	−0.37	0.46	1.17	0.29	H27	4.02	0.40	0.07	0.61	1.48	−0.24	H55	3.22	0.24	0.18	0.42	1.26	0.18
H68	6.47	−0.03	−0.57	0.57	1.18	0.21	H94	3.99	0.18	−0.01	0.28	1.24	−0.26	H93	3.19	0.22	−0.09	0.36	1.30	−0.17
H75	6.45	−0.46	−0.07	0.50	1.05	0.03	H33	3.97	−0.10	−0.08	0.17	0.60	−0.17	H85	3.18	0.14	0.32	0.39	1.09	0.77
H62	6.45	−0.18	−0.19	0.27	1.21	0.07	H18	3.97	0.02	0.49	0.49	1.28	0.33	H64	3.16	0.21	0.44	0.55	1.13	1.52
H47	6.44	0.84	0.17	0.91	1.07	1.05	H65	3.96	−0.22	−0.25	0.41	0.64	−0.16	H26	3.13	0.21	−0.07	0.33	1.30	−0.18
Mean	6.81							4.25							3.47					
LSD $_{(0.05)}$¶	0.61							0.6							0.53					
NLOC#	6							4							3					
Commercial checks																				
SC627	6.5	−0.47	−0.33	0.6	1.17	0.35	SC627	3.82	0.4	0.34	0.69	1.74	−0.04	SC627	3.02	0.25	0.15	0.43	1.26	0.34
ZS261	5.05	−0.06	0.22	0.23	0.84	0.01	ZS261	2.8	−0.11	0.04	0.17	0.82	0.02	ZS261	2.77	0	0.03	0.03	0.96	−0.14

† H, hybrid.

‡GY, grain yield.

§ IPCA1 and IPCA2, first and second interaction principal component; ASV, additive main effects and multiplicative interaction stability value; b_i, slope of linear regression; s^2d_i, deviation from regression.

¶ LSD is from 108 hybrids.

NLOC, number of environments used in the combined analysis.

H56 (5.49 t ha^{-1}), H10 (5.46 t ha^{-1}), H9 (5.34 t ha^{-1}), and H94 (5.33 t ha^{-1}) (Supplemental Table S3). These crosses outyielded the best non-QPM commercial check (SC627) by 18.5, 12.7, 12.1, 9.7, and 9.5%, respectively. A total of 23 hybrids showed higher grain yield than the best check (SC627), of which eight hybrids significantly outyielded SC627 (Supplemental Table S3). Furthermore, the QPM check hybrid (ZS261) was significantly outyielded by 49 new QPM hybrids. Hybrids H2 (L1 × T2), H9 (L3 × T1), H10 (L3 × T2), H40 (L12 × T1), H85 (L23 × T3), and H94 (L25 × T4) were among the 25 top-yielding hybrids under each management condition (Table 4), and across environments (Supplemental Table S3). In addition, hybrids H13, H10, and H11 were common for optimum management and low N, optimum management and drought, and low N and drought, respectively (Table 4).

Joint Linear Regression Analysis

Most of the top-yielding hybrids displayed higher slope of linear regression ($b_i > 1.0$) and deviation from regression ($s^2d_i \neq 0$) (Table 4, Supplemental Table S2). Across optimum management, b_i for the selected top-yielding hybrids ranged from 1.01 (H94) to 1.56 (H56), and absolute values of s^2d_i ranged from 0.03 (H75) to 1.07 (H58). Under low N, b_i ranged from 0.56 (H92) to 2.23 (H11), with the absolute values of s^2d_i ranging from zero (H3) to 1.67 (H2). Similarly, b_i ranged from 1.01 (H22) to 1.96 (H10), whereas absolute values of s^2d_i ranged from 0.01 (H75) to 4.49 (H22) under drought environments. Among the highest yielding hybrids, H40 ($s^2d_i = -0.06$) under optimum management, H40 ($s^2d_i = -0.03$) and H11 ($s^2d_i = 0.06$) under low N, and H12 ($s^2d_i = -0.08$) under drought showed lower s^2d_i values (Table 4). Across environments, good levels of stability were exhibited by H92 ($b_i = 1.02$, $s^2d_i = -0.04$), but it had lower mean grain yield of 4.93 t ha^{-1} and was ranked 17th (Supplemental Table S3).

AMMI Analysis

The GEI effects were partitioned into interaction principal component analysis (IPCA) axes using the AMMI model for each management condition and across environments (Supplemental Tables S2 and S3). The first two IPCA axes explained about 53, 82, 100, and 37% of the GEI across optimum management, low N, drought, and all environments for the 108 hybrids, respectively (Supplemental Table S4). The ASV of each hybrid exhibited variations in grain yield stability among the 108 hybrids under different management conditions and across environments (Supplemental Tables S2 and S3). In Table 4, the ASV is presented for the 25 top-yielding hybrids and the two commercial checks and ranged from 0.15 to 0.91 under optimum management conditions. Hybrids H42 (0.15), H26 (0.19), H45 (0.22), H79 (0.23), and ZS261 (0.23) were the most stable, with relatively low ASV values. Across low N, ASV ranged from 0.15 to 1.33, and H89 (0.15), H33 (0.17), ZS261 (0.17), and H57 (0.19) had lower ASV values. Under drought, the ASV ranged between 0.33 and 1.08, whereas hybrids ZS261 (0.03), H26 (0.33), H93 (0.36), and H85 (0.39) had relatively low ASV values. Across management conditions, ZS261 was among the hybrids with low ASV but produced the least grain yield. Hybrids H41 (0.84), H11 (1.33), and H10 (1.08) that had the highest ASVs under optimum management, low N, and drought, respectively, were the least stable. As IPCA1 explained the largest proportion of GEI across management conditions, hybrids with positive IPCA1 score interacted positively with environments with positive IPCA1 scores, but negatively with environments with negative IPCA1 scores (Table 4).

The AMMI biplots of 25 top-yielding hybrids and two commercial checks across optimum management, low N, and drought are presented in Fig. 1a to 1c. The AMMI biplot of these hybrids across the 13 stress and nonstress environments is shown in Supplemental Fig. S1a. In this study, IPCA1 explained nearly 34, 46, and 76% of the variation attributed to GEI under optimum, low N, and drought conditions, respectively (Fig. 1a–1c). Under optimum management, hybrids H47, H56, and H59 had larger positive IPCA1, whereas H68, H75, SC627, and H87 had larger negative IPCA1 (Fig. 1a). Hybrids H40, H41, and H58 were high yielding (above grand mean) and relatively stable, with IPCA1 close to zero. Hybrid H56 had the highest grain yield but showed high positive IPCA1. This hybrid interacted positively with high-yielding environments (MPOP and GWOP) that had IPCA1 score of the same sign. Under low N, hybrids H92 and H11 had the largest positive and negative IPCA1s, respectively (Fig. 1b). Higher-yielding and stable hybrids under low N were H2, H40, and H87, which had above average grain yield and low IPCA1. Under drought, hybrid H22 had the highest positive IPCA1 and interacted positively with SVDS, whereas H2 and H10 had larger negative IPCA1s. (Fig. 1c). Hybrids H11, H34, and H94 had outstanding performance in terms of high grain yield and stability under drought environments. Across management conditions, most hybrids showed mean grain yield higher than or close to the grand mean, except ZS261, which consistently had the lowest grain yield. H10 and H40 were the highest yielding and were more stable hybrids (Supplemental Fig. S1a). Most of the test environments had larger IPCA1 scores, as shown in the longest distance from the IPCA1 line. Only GLOP and AMOP (optimum), HALN (low N stress), and CZDS (drought stress) had low IPCA1 scores. However, these environments had lower mean grain yields than other environments with the same management conditions. Environments MPOP, GWOP, AMLN, and CHDS had higher grain yield under the three management conditions, but larger IPCA1 scores.

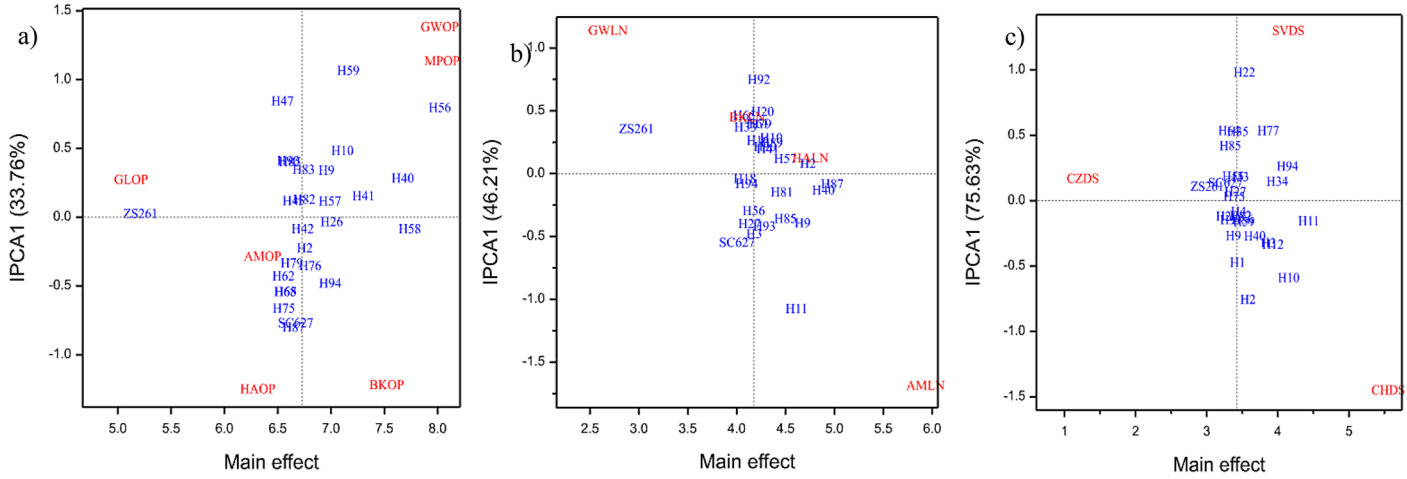

Fig. 1. Additive main effect and multiplicative interaction (AMMI) biplot for grain yield of selected quality protein maze hybrids across environments: (a) optimum management, (b) low N, and (c) drought. See codes of environments in Table 2 and genotypes in Supplemental Table S1. IPCA1, first interaction principal component axis.

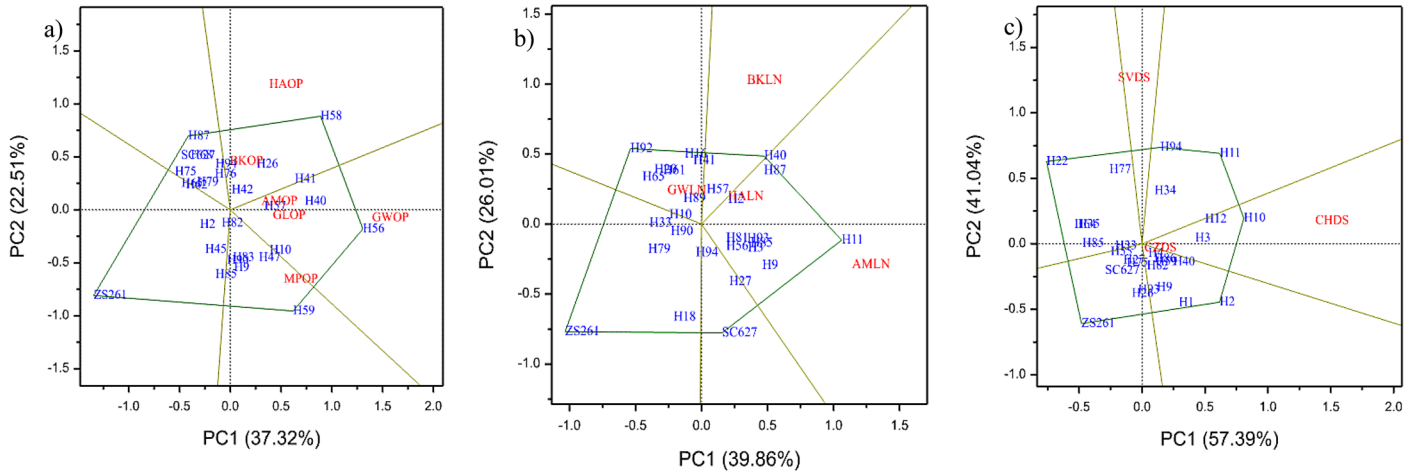

Fig. 2. A "which-won-where" view of the genotypic main effects plus genotype × environment interaction (GGE) biplot for 25 high-yielding quality protein maize hybrids and two commercial checks evaluated across environments: (a) optimum management, (b) low N, and (c) drought. See codes of environments in Table 2 and genotypes in Supplemental Table S1. PC, principal component.

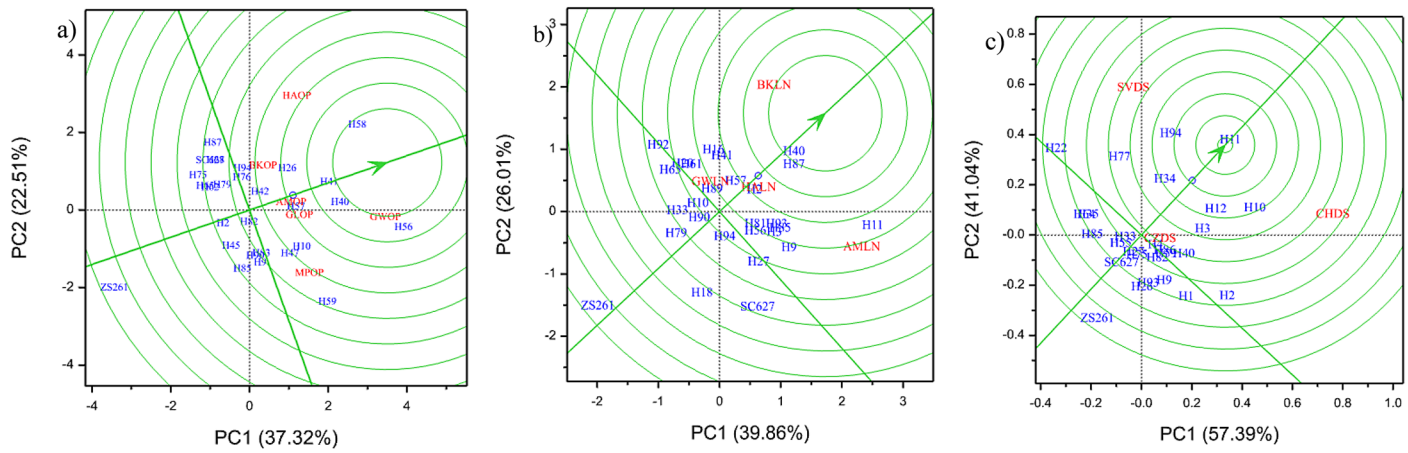

Fig. 3. The genotypic main effects plus genotype × environment interaction (GGE) biplot view showing ranking of selected quality protein maize hybrids relative to an ideal genotype under different management conditions: (a) optimum management, (b) low N, and (c) drought. See codes of environments in Table 2 and genotypes in Supplemental Table S1. PC, principal component.

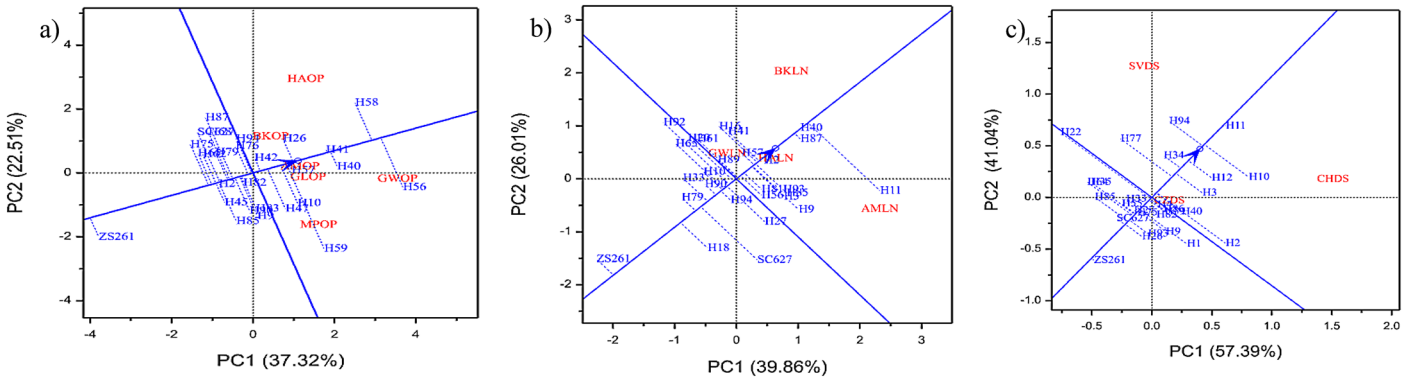

Fig. 4. The "mean vs. stability" view of the genotypic main effects plus genotype × environment interaction (GGE) biplot view of selected quality protein maize hybrids evaluated across environments: (a) optimum management, (b) low N, and (c) drought. See codes of environments in Table 2 and genotypes in Supplemental Table S1. PC, principal component.

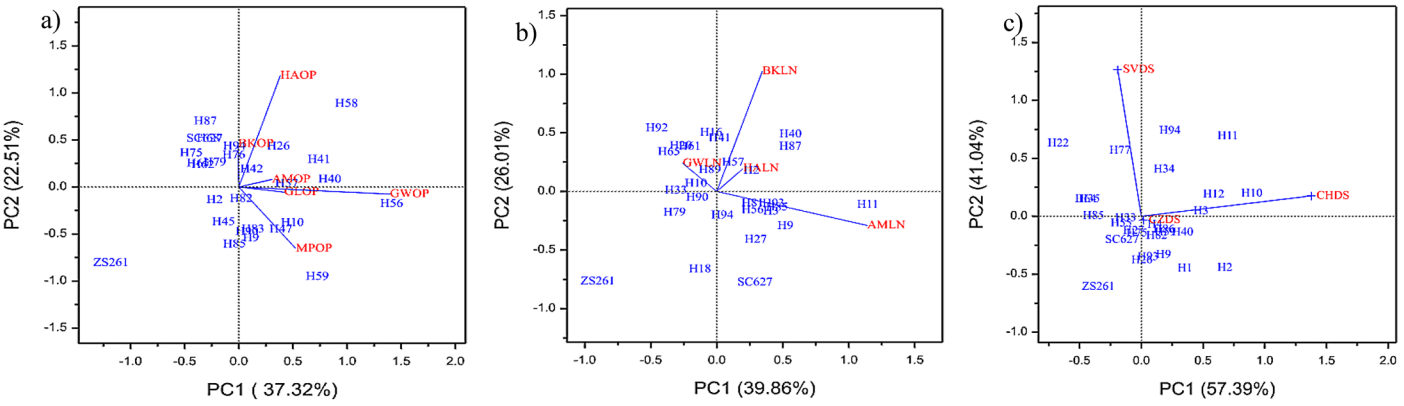

Fig. 5. The vector view of genotypic main effects plus genotype × environment interaction (GGE) biplot showing the "discriminating power and representativeness" of the test environments used to evaluate selected quality protein maize hybrids across environments: (a) optimum management, (b) low N, and (c) drought. See codes of environments in Table 2 and genotypes in Supplemental Table S1. PC, principal component.

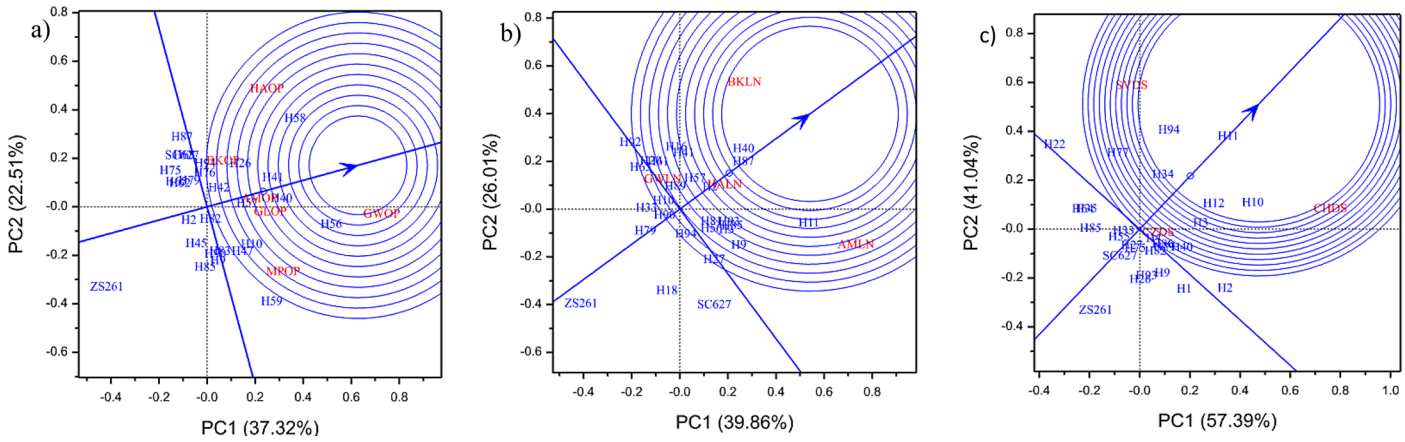

Fig. 6. The biplot view showing ranking of environments relative to the ideal environment" (a) optimum management, (b) low N, and (c) drought. See codes of environments in Table 2 and genotypes in Supplemental Table S1. PC, principal component.

GGE Biplot

Which-Won-Where Pattern

The GGE biplots for grain yield of 27 selected hybrids are shown in Fig. 2 to 6. The first (PC1) and the second (PC2) principal component scores were used as the *x* axis and *y* axis, respectively. Figure 2a to 2c presents a "which-won-where" polygon view of the biplot displaying which hybrid performed well in which environment. The GGE biplot based on environment-standardized (scaled by the SD of genotype means within environments) grain yield data of selected hybrids across the 13 test environments is presented in Supplemental Fig. S1b to S1f. The biplots accounted for approximately 60, 66, and 98% of the total variation related to genotype and GEI under

optimum (Fig. 2a), low N (Fig. 2b), and drought (Fig. 2c) environments, respectively. The vertex hybrids in each sector of the biplots represented the top-yielding hybrid in the environments that fell within that sector. Hybrids located closer to the origin of the biplot were more stable (less responsive) than the vertex hybrids. Hybrids that formed the corners of the polygon in the optimum management (H58, H56, H59, ZS261, and H87), low N (H40, H11, SC627, ZS261, and H92), and drought (H11, H10, H2, ZS261, H22, and H94) experiments were among the most responsive hybrids to environments in their respective directions compared with the other hybrids. The line that starts from the origin of the biplot and passes perpendicular to the sides of the polygon classified the biplot into different sectors. Under optimum environments, H58 was the highest yielding hybrid at HAOP and BKOP; H56 was the winner hybrid at GWOP, AMOP, and GLOP; and H59 was the highest yielding hybrid at MPOP. None of the environments fell into the sector where ZS261 and H87 were the vertex hybrids (Fig. 2a). Under low N, H11 at HALN, H40 at BKLN and HALN, and H92 at GWLN were the winner hybrids, but ZS261 and SC627 did not win in any of the environments (Fig. 2b). Hybrids H10 and H12 had higher grain yield under drought environment of CHDS (Fig. 2c).

Mean Grain Yield and Stability of Hybrids

An AEC was drawn to visualize mean and stability of the hybrids. The AEC ordinate separate hybrids that had below average grain yield from those showing higher grain yields than the average. An ideal hybrid is defined by the greatest vector length and low GEI and is represented by the center of the concentric circle with an arrow pointing to it (Fig. 3a–3c), indicating its highest mean grain yield and stability. In this study, the most desirable hybrids with closer proximity to the ideal genotypes were H40, H41, and H58 under optimum management (Fig. 3a), H40 and H87 under low N (Fig. 3b), and H11 under drought (Fig. 3c). Hybrids H41 and H57 under optimum management (Fig. 4a), H2, H40, and H87 under low N (Fig. 4b), and H11 under drought (Fig. 4c) that had above average yield were located on the AEC abscissa with zero (very low) projection onto the AEC ordinate and were the most stable hybrids. On the other hand, hybrids H58 and H56 under optimum management, H11 under low N, and H10 and H94 under drought were among the highest yielding but were less stable, as evident from greater projection onto the AEC ordinate.

Relationships, Discriminating Power, and Representativeness of the Test Environments

The vector view of the GGE biplot, portraying how the interrelationships among the environments are connected to the biplot origin through the vectors, is shown in Fig. 5. Under optimum management environments, negative association (>90°) was observed between BKOP and MPOP (Fig. 5a), whereas no association was observed between HAOP and MPOP. Strong positive association was observed among AMOP, GWOP, and GLOP. Among the low N environments, negative association was observed between GWLN and AMLN (Fig. 5b). Both GWLN and AMLN had weak association with BKLN and HALN, but strong positive association was observed between BKLN and HALN. Under drought, no association was observed between SVDS and CZDS (Fig. 5c). In the vector view of the GGE biplot, the length of the vector approximates the SD within each test environment and is a measure of the environment's ability to discriminate among the hybrids. Shorter environmental vectors indicated that the specific environments were not strongly associated with environments with longer vectors. The short-vector environments (BKOP, AMOP, GLOP, GWLN, HALN, and CZDS) were less informative and provided little or no information about the hybrids compared with environments with longer vectors (HAOP, GWOP, BKLN, AMLN, SVDS, and CHDS) (Fig. 5a–5c).

In Fig. 6, the circle at the center of the concentric circle represents the "ideal environment," and it is a virtual environment with the longest vector (most discriminating) of all environments and is absolutely representative (i.e., it has no significant contribution to GEI and thus is positioned on the AEC abscissa). The nearer an environment is to the ideal environment, the more desirable that environment is for selecting superior genotypes. Consequently, the GGE biplot identified GWOP, BKLN, and CHDS as ideal environments under optimum management (Fig. 6a), low N (Fig. 6b), and drought (Fig. 6c), respectively.

DISCUSSION

The variations observed among the experimental hybrids for grain yield at individual environments and across stress and nonstress environments indicated the possibility of selecting preferred hybrids under stress and nonstress environments. In addition, high heritability values observed under all management conditions indicated that grain yield is highly heritable, and selection for grain yield improvement would be effective in the set of QPM hybrids studied. Previous studies also reported the presence of significant variations among QPM hybrids evaluated under contrasting management conditions for grain yield (Wegary et al., 2014; Abakemal et al., 2016; Njeri et al., 2017). Significant effects of environment confirmed that each of the target environments were distinctly different from each other, as expected. Significant hybrid × environment interactions, in combination with stability estimates from the AMMI and GGE biplot results, indicated the existence of a crossover interaction and change in the response and ranking of the QPM hybrids across contrasting environments. This could

seriously limit gain in selecting superior QPM hybrids with outstanding performance across a range of environments. Thus, a suitable breeding strategy should be devised to develop varieties with stable performance across a range of environments or varieties with specific adaptation. Similar findings were reported in previous studies conducted on maize hybrids under stress and nonstress environments (Sserumaga et al., 2016; Badu-Apraku et al., 2017; Ertiro et al., 2017).

Environment effects were significant for each management condition and across environments (Table 3), as the result of inclusion of contrasting testing environments, which is in line with the findings of previous investigations (Badu-Apraku et al., 2012; Ertiro et al., 2017). Grain yields of the evaluated hybrids varied considerably across different management conditions (Table 4). As expected, lower mean grain yields were observed under low N and drought compared with optimum management. Different levels of yield reduction could be expected under low N and drought conditions as a result of the intensity of stress to which the crop is exposed (Derera et al., 2008; Pswarayi and Vivek, 2008).

Several QPM hybrids used in this study had higher grain yields than both the QPM and non-QPM commercial check hybrids, indicating the potential for developing and commercializing QPM hybrids with superior yield advantage over the existing commercial hybrids in SSA. Yield advantage of newly developed QPM hybrids over the commercial checks has been previously reported in southern Africa (Setimela et al., 2017) and in eastern and southern Africa (Wegary et al., 2014; Njeri et al., 2017). This implied that the newly developed QPM single-cross hybrids were superior in drought and low N tolerance to the commercial checks. Most hybrids that had higher grain yield under different management conditions and across environments contained inbred lines L1, L3, L12, and L16 and testers T1, T2, and T3 as parents. Some of these hybrids include H40 (L12 × T1), H41 (L12 × T1), H56 (L16 × T1), and H58 (L16 × T3) across optimum management environments; H2 (L1 × T2), H9 (L3 × T1), and H40 (L12 × T1) across low N stress environments; H3 (L1 × T3), H10 (L3 × T2), and H11 (L3 × T3) across drought stress environments; and H9 (L3 × T1), H10 (L3 × T2), H40 (L12 × T1), and H56 (L16 × T1) across all environments (Supplemental Table S3). The use of stress-tolerant QPM inbred lines selected simultaneously under stress and nonstress conditions can offer the advantage of producing high-yielding and stress-resilient QPM hybrids. This study also corroborated the possibility of developing and identifying QPM hybrids that can perform well across stress and nonstress conditions, as most of the 25 top-yielding hybrids identified showed outstanding performance under different management conditions. In SSA, where maize is the major source of daily dietary intake, identification of high-yielding QPM hybrids with superior performance over commercial and conventional maize hybrids would enhance achievement of QPM and protein security. In SSA, yield gains have been mainly attributed to increased stress tolerance to random drought and improvement of poor soil fertility (Setimela et al., 2017). The findings of this study highlighted interesting progress made by CIMMYT in collaboration with its partners to improve tropical maize germplasm for both drought and low N (Bänziger et al., 2000, 2006; Makumbi et al., 2011). Feasibility for simultaneous improvement of grain yield of maize under stress and nonstress conditions has previously been reported by other researchers (Ndhlela et al., 2014; Ertiro et al., 2017).

Most high-yielding hybrids evaluated in the present study had higher b_i values, indicating better adaptability of these hybrids to high-yielding environments (Eberhart and Russell, 1966). Consistent with these findings, positive association between high mean grain yield and regression coefficient was reported by Betrán et al. (2003) for maize hybrids evaluated under contrasting growing conditions. In this study, H40, H11, and H12 were identified as the most desirable hybrids for higher grain yield and stability (low s^2d_i value) under optimum, low N, and drought stress environments, respectively.

In this study, some hybrids showed strong interaction with the environments, as evident from the larger positive and negative IPCA1 scores, while having comparable grain yields, suggesting the existence of variation among hybrids in response to the contrasting environments. Accordingly, hybrids that had larger IPCA1 scores were likely to be adapted to specific environments and were less stable. In line with this study, specific adaptation of tropical maize hybrids was reported by previous studies (Abakemal et al., 2016; Ertiro et al., 2017; Njeri et al., 2017). As indicated in Fig. 1a to 1c, the AMMI biplot identified some desirable hybrids with higher grain yield (well above the grand mean) and stable (IPCA1 scores close to zero) performances across optimum, low N, and drought stress environments. Across management conditions, however, most hybrids concentrated around the origin of the biplot, whereas the test environments were scattered throughout the AMMI biplot (Supplemental Fig. S1a). This indicated that the test environments dominated over genotype and GEI, and that the AMMI biplot is not effective for visual evaluation of the genotypes.

The GGE biplot provided a polygon view for easier visualization of the "which-won-where" patterns (Fig. 2a–2c), by dividing the biplot into different sectors. When different test environments occurred in different sectors, it indicated that they have different high-yielding hybrids for those sectors (Yan and Tinker, 2006), indicating the existence of crossover GEI and suggesting the possibility of dividing the environments used into mega-environments (Yan et al., 2007). Across optimum

environment, the polygon view divided the biplot into two sectors that were represented by HAOP, and GWOP and MPOP (Fig. 2a). Similarly, two sectors represented by BKLN and AMLN were identified for the low N environments (Fig. 2b), whereas a single sector that was represented by CHDS was observed for drought environments (Fig. 2c). Such information is important in dividing environments into various mega-environments for recommending different hybrids for different mega-environments (Gauch and Zobel, 1997; Badu-Apraku et al., 2012; Abakemal et al., 2016). No environment was found in the sector where the ZS261 was the vertex hybrid, indicating that this hybrid was the lowest yielding hybrid under stress and nonstress environments used for the present study. The results of this study provided a preliminary information on mega-environment delineation of the test locations, and multiyear data are required to validate this observation.

As defined by Yan and Kang (2003), an ideal genotype is the highest yielding and the most stable, but this rarely exists. In this this study, most desirable hybrids that had closer proximity to the ideal genotype were identified under each management condition (Fig. 3 and 4). Hybrid H40 was identified as an ideal genotype under optimum management, low N, and across test environments, indicating the inherent potential of this hybrid for higher grain yield and wider adaptation.

According to Yan (2002), the cosine of the angle between the vectors of two test environments determines their relationships. Smaller angles (<90°) indicated similarity in genotype performance between these environments, a right angle (90°) indicated orthogonality and lack of association, and angles >90° indicated a negative relationship of genotype performance between these environments. The vector view of the GGE biplot (Fig. 5a–5c) clearly showed that some environments had positive correlations, whereas others had negative correlations. Positive correlations indicated similarity in genotype performance among the environments, whereas negative or low correlations exhibit that the environments that are quite different and heavily influenced by GEI (Makumbi et al., 2015; Sserumaga et al., 2016). When strong negative correlations are observed between test environments, such environments should be treated independently for genotype evaluation to increase the efficiency of selection for high grain yield. In METs, environments with strong positive correlations are considered redundant because they may not provide additional information on varietal performance but simply increase trial evaluation expenses (Yan and Kang, 2003).

Environments with long vectors and small angles with the AEC abscissa are useful for evaluating cultivars (Yan et al., 2007). In this study, MPOP, BKLN, and CHDS were identified as highly discriminating environments for the QPM hybrids tested in their respective group of environments, so these test environments were considered as "ideal environments" for selecting superior hybrids and for the provision of information that is important for the identification of desirable varieties (Tukamuhabwa et al., 2012). Early-generation testing in such environments will minimize germplasm development expenses by decreasing the number of varieties to be tested in METs, and inherently minimizing the number of test environments (Gasura et al., 2015).

CONCLUSIONS

The present study identified the most promising QPM hybrids under stress and nonstress environments. These included H40, H41, H56, and H58 under optimum management; H2, H9, H40, and H87 under low N; H3, H10, H11, and H94 under drought; and H9, H10, H40, H56, and H94 across test environments. Moreover, several hybrids that showed higher grain yield across contrasting management conditions were identified. The AMMI and GGE biplots were more efficient than the linear regression stability model and ASV in selecting outstanding hybrids in terms of grain yield and stability. Based on AMMI and GGE biplots, the most desirable hybrids in this study were H40, H41, and H58 under optimum management, H40 and H87 under low N, and H11 under drought. In addition, H10 and H40 were identified as the most desirable hybrids across the test environments. The GWOP, BKLN, and CHDS environments were ideal for their discriminating power and representativeness. The desirable QPM hybrids identified in this study should be extensively tested on-farm and commercially produced to improve food, income, and nutritional security of smallholder farmers and consumers in SSA.

Supplemental Material Available

Supplemental material is available online for this article.

Conflict of Interest

The authors declare that there is no conflict of interest.

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