AMMI Analysis of Genotype x Environment Interaction for Grain Yield in Drought-Tolerant Maize (*Zea mays* L.)

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Abstract: Eight drought tolerant maize lines and their 28 crosses with two local hybrids were evaluated separately in 12 environments to estimate the magnitude of genotype x environment interaction (GEI) and relationships between parents and progenies in stability. An additive main effects and multiplicative interaction (AMMI) model was used to analyze the grain yield data. The first two IPCAs of the AMMI 2 analysis accounted for 56 % of the GEI sum squares in trials of the hybrids. High yielding hybrids like O, P, S, Z, U, G and one of the checks (BH140) showed minimum GEI, indicating wide adaptation of these varieties over environments. In contrast, high yielding hybrids such as A, D and J adapted to unfavorable environments and K and T to favorable environments. Most of the crosses from drought tolerant parents were better than the check (BH540) in mean grain yield and stability. Although no considerable association in stability was observed between crosses and their parents, increased stability occurred in most of the crosses due to increased stress tolerance.

Keywords: Drought Tolerance; Genotype x Environment Interaction; Yield Stability

1. Introduction

In sub-Saharan Africa, crop yield variability under rainfed conditions is likely to be of greater socio-economic importance than in any other part of the world (Heisey and Edmeades, 1999). This is mainly due to drought and low nitrogen (N) stresses, which are most frequently limiting maize production in the tropics (Betran *et al.*, 2003). In addition, the typical practice of low input farming systems should be considered due to increased population pressure and poverty in the region. All these phenomena are common in Ethiopia, where environmental conditions vary considerably, and means of modifying the environment are far from adequate. Under these conditions, genotypes that provide high average yields with minimum genotype by environment interaction (GEI) have been gaining importance over increased yields (Ceccarelli, 1989; Gauch and Zobel, 1997; Kang, 1998).

The relative magnitude of GEI provides information concerning the likely area of adaptation of a given genotype. It is also useful in determining efficient methods of using time and resource in a breeding program (Ceccarelli, 1989; Kang, 1998). Various biotic and abiotic stresses have been implicated as causes of GEI, which is considered as an inheritable trait. Consequently, improving genotype resistance/tolerance to different stresses to which they would likely be exposed might minimize GEI (Kang, 1998). Selection under managed drought stress at flowering is suggested as an effective means of increasing tolerance to a number of stresses occurring near flowering. Thus mid-season, drought tolerant genotypes that perform well under variable moisture regimes (Chapman *et al.*, 1997) and N levels (Bänziger *et al.*, 1999) are expected to give a better yield with increased stability across variable growing conditions compared to conventionally developed genotypes. However, there is limited information about their GEI across different environments, and relationships between lines and their crosses with regard to this trait.

On the other hand, it has to be taken into consideration that data from multilocation trials are imprecise, complex and noisy (Kang, 1998). The conventional method of partitioning total variation into components due to genotype, environment, and GEI conveys little information on the individual patterns of response (Zobel *et al.*, 1988). To increase accuracy, additive main effects and multiplicative interaction (AMMI) is the first model of choice when main effects and interaction are both important. Thus, the objectives of this study were to estimate the magnitude of GEI among the hybrids developed from drought tolerant lines compared to conventional (local) hybrids as well as relationships between the crosses and parental lines based on AMMI stability values.

2. Material and Methods

A diallel cross without reciprocals was made among eight drought-tolerant maize lines (CML440, CML442, CML202, Mex101 (DTPWC8F31-1-1-1-B), Mex102 (DTPWC8F266-1-1-1-B), Mex103 (DTPWC8F347-1-3-1-B) CML443 and CML445) from CIMMYT during 2001/2002 at the Grain Crops Institute at Potchefstroom, Republic of South Africa. In Ethiopia, these lines and their 28 crosses with two local hybrids (BH540 and BH140) were evaluated separately in two trials planted

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side by side in 12 environments (Table 1). The off-season trials (well-watered normal density (WN), drought stressed normal density (DN), well-watered high density (WH), and drought-stressed high density (DH)) were conducted only at Melkasa, where a furrow irrigation system was used to apply about 40 mm of water (estimated by partial flume) every seven days. However, for DN and DH, watering was suspended from 15 days prior to anthesis until 25 days after anthesis when one additional irrigation was applied. A randomised complete block design with four replications was used for each trial. Each plot consisted of four 4.2 m rows with a spacing of 75 cm between rows. Intra row spacing was 15 and 30 cm between hills for high plant density and normal density respectively. Two seeds hill^{-1} were planted, and plots were later thinned to obtain the required plant density. Fertilizer was applied as recommended for each location, and trials were kept free of weeds.

In the text, the names of the hybrids are replaced by alphabetical codes (Table 3). Observations were recorded on grain yield plot^{-1}, which was reported in ton hectare^{-1} (t ha^{-1}) at 15% moisture content. An analysis of variance (ANOVAs) was performed for the grain yield of each trial (data not shown). The AMMI analysis of the log-transformed yield data (based on Bartlett's test) was performed separately for each type of genotype (lines and hybrids) using AGROBASE (1998) software. However, the hybrid trials results were mainly discussed, while results from the lines trials used only to estimate association with their crosses. The AMMI model first arranges additive effects for the main factors; that is, genotypes and environments, using the additive analysis of variance procedure. Subsequently it arranges multiplicative effects for genotype by environment interaction (GEI) by principal component analysis (PCA) (Zobel *et al*., 1988). The statistical significance of analysis of variance, and the optimum number of interaction principal component axes (IPCA) to be retained in the model were determined using the F-test as given by the analytical software mentioned above. AMMI's stability value (ASV) was calculated in order to rank genotypes in terms of yield stability using the formula suggested by Purchase *et al.* (2000) as shown below.

AMMI stability value (ASV) =

$$\sqrt{\left[\frac{SSIPCA1}{SSIPCA2}\left(IPCA1score\right)\right]^2+\left[IPCAscore2\right]^2}$$

Where: SS = Sum of squares; IPCA1 = Interaction Principal Component Analysis axis 1

IPCA2 = Interaction Principal Component Analysis axis 2

In general, an absolute AMMI stability value (ASV) was determined using a procedure that combines IPCA1 and IPCA2. By using Pearson correlation coefficient (r) between inbred lines and crosses, the association in stability was estimated by regressing F_1 hybrid ASV on mid-parent values. In addition, the AMMI- adjusted mean grain yield (t ha^{-1}) for each cross was estimated from original data to demonstrate mean performances.

Table 1. The 12 environments used for evaluation of parental lines and 30 hybrids independently.

Environment No.	Code	Location	Year	Season	Moisture source/status	Plant density
1.	WN [a]	Melkasa	2002	Off-season	Irrigation, well-watered	Normal
2.	DN [a]	Melkasa	2002	Off-season	Irrigation, stressed during flowering	Normal
3.	WH [a]	Melkasa	2002	Off-season	Irrigation, well-watered	High
4.	DH [a]	Melkasa	2002	Off-season	Irrigation, stressed during flowering	High
5.	NB2 [b]	Bako	2002	Main season	Rain fall, adequate	Normal
6.	NM2 [b]	Melkasa	2002	Main season	Rain fall, adequate	Normal
7.	NB3 [c]	Bako	2003	Main season	Rain fall, adequate	Normal
8.	NM3 [c]	Melkasa	2003	Main season	Rain fall, adequate	Normal
9.	HB2 [b]	Bako	2002	Main season	Rain fall, adequate	High
10.	HM2 [b]	Melkasa	2002	Main season	Rain fall, adequate	High
11.	HB3 [c]	Bako	2003	Main season	Rain fall, adequate	High
12.	HM3 [c]	Melkasa.	2003	Main season	Rain fall, adequate	High

[a] *Environments of 2002 off-season trials at Melkasa, WN= well-watered normal plant density; DN= drought-stressed normal density; WH= well-watered high density; DH= drought-stressed high density*

[b] *Environments of 2002 main season trials, NB2= Normal plant density at Bako; NM2=Normal density at Melkasa; HB2= high density at Bako; NM2= Normal density at Melkasa*

[c] *Environments of 2003 main season trials, NB3= Normal density at Bako; NM3=Normal density at Melkasa; HB3=High density at Bako; HM3=High density at Melkasa*

3. Results and Discussion

The AMMI analysis for grain yield showed that environments, genotypes, and GEI were highly significant ($P<0.001$) and accounted for 79.96, 3.03 and 17.01% of the treatment combination sum of squares (E+G+GEI SS) respectively (Table 2). The results indicated that specific and wide adaptations were equally important as suggested by Gauch and Zobel (1997). Although the GEI sum of square was about five times larger than that for genotypes, environmental effects dominated the analysis. As indicated by the F-test, the first three interaction PCA axes were highly significant. The IPCA1, IPCA2 and IPCA3 declared 33, 23 and 14 % of the observed hybrids by environment variation sum of squares respectively. Although IPCA3 was significant it was discarded due the difficulty of obtaining reliable information from its relatively small contribution to the interaction. Thus, since the first two IPCAs accounted for 56 % of the GEI sum of squares, the AMMI 2 model was the best fit for the hybrid trials. The residual 44 % that included IPCA3 was discarded.

High variability among environments, both in the main and interaction effects were demonstrated with a distinct pattern as indicated in Fig. 1 (biplot). All high potential environments were evenly distributed in the second (WN, NM2, HM2, HM3, WH, HB2) and third quadrants (NB2, NM3), while low yielding environments were sparsely scattered in the fourth (DH, and top soil eroded fields HB3 and NB3) and first quadrants (DN). As expected, the severely stressed environment (DH) showed the lowest yield and also the highest interaction with genotypes.

Table 2. AMMI analysis for grain yield of 30 hybrids evaluated in 12 environments.

Source	df	Sum squares	Mean squares
Total	1439	47.057	
Treatment combinations	359	34.76	0.097
Environments (E)	11	27.793	2.527**
Replicates within E	36	2.379	0.066
Genotype (G)	29	1.053	0.036**
Genotype x E	319	5.914	0.019***
IPCA1	39	1.938	0.05***
IPCA2	37	1.372	0.037***
IPCA3	35	0.802	0.023***
IPCA Residual	208	1.803	0.009
Error	1044	9.918	0.01
C.V (%) = 2.63;	R^2 = 78.92;	Log (mean yield) = 3.709	

*, ***, significant at P = 0.01 and P = 0.001, respectively*

Considerably less variation in mean yield was exhibited among hybrids compared to the environments used for evaluation (Figure 1). Based on mean performance (main effects), four groups of hybrids were evident from the biplot. Group 1 consisted of hybrids W, C_1, X, K, V, Q, H_2, I, F, H, Y, U, L, Z, E and B, which had mean yields closer to the grand mean but varied in interaction (IPCA1) scores. Hybrids W, C_1, X, K, V, E and B exhibited greater interaction with environments, of which W, C_1, X, K and V showed positive interaction with drought-stressed (DN) and most high yielding environments but negative interaction with DH and most environments at Bako. The reverse held true in the case of E and B hybrids. When IPCA1 was plotted against IPCA2 (Figure 2), their interaction scores remained as high as in Figure 1, and ranked above nineteenth in ASV values (Table 3), reflecting an unstable yield over environments. Others like H_2, F, H, I, Y and U were close to zero, while Q and Z showed medium interaction. Similarly, when IPCA1 was plotted against IPCA2, most of them appeared close to zero. However, H, I, Q, F and L ranked second to fifteenth in ASV values, indicating good yield stability across environments but were found to be unacceptable in most areas due to their poor mean yields. Thus, in Group 1, only H_2, U and Z were superior both in mean yield and stability. Hybrids O, S, C_2, P, H_1, A, J, T, R and M were included in Group 2, which relatively better than Group 1 in mean yield, of which O, S, C_2, P, and H_1 had IPCA1 scores close to zero. However, when the IPCA1 scores were plotted against the IPCA2 scores (Figure 2), only O, P, C_2 and H_1 remained close to zero. Thus, considering both mean yield and ASV values O, P, S, C_2 and H_1 were superior in both terms over environments. A top cross hybrid BH140 (C_2) was one of them, mainly due to an improvement made by CIMMYT for reduced plant height in one of its parents (Tuxpeño Sequia C_{18}). Consistent with the current study, Fischer *et al.* (1983) has indicated short maize plants as being more tolerant to drought at flowering than taller plants.

Group 3 consisted of the highest yielding (> 6.0 tha^{-1}) hybrids G and D, which showed the same pattern when IPCA1 was plotted against IPCA2. Accordingly, G and D were the best crosses in drought-stressed environments

DN and DH respectively. Contrary to stability, it was also suggested that emphasis should be given to specific adaptation to extreme drought stress in semi arid climates (Haussmann *et al.*, 2000). Thus, hybrids G and D are preferable in areas facing recurrent drought stress, since a reliable minimum grain yield is more important to subsistence farmers than high yields in rarely favorable seasons. In Group 4, low yielding hybrids C and N are included, as these hybrids revealed diverse reaction. The cross N showed the lowest mean yield, stability and growth period of the tested hybrids.

Based on a combination of both mean grain yield and ASV values, hybrids O, P, C_2, S, H_1, H_2, Z, U and G were relatively superior in descending order, due to a combination of both mean yield and ASV values. Based on two sorghum populations, Zavala-Garcia *et al.* (1992) suggested that a combined index using a stability index and genotype means increased selection efficiency. Hybrids Y, I, Q, F and H were superior only in their ASV (stability) and may not be recommended for direct use in production due to their poor mean yield. However, these five crosses can be used for breeding purposes in areas with erratic rainfall patterns. In line with the observations in this study, Kang (1998) and Tollenaar and Lee (2002) pointed out that reduced GEI (increased stability) occurred due to increased stress tolerance. They also suggested that increased stability occurred due to the selection of genotypes under both stress and non-stress conditions. High yielding hybrids such as A, D, G and J, were specifically adapted to unfavorable environments that included drought stress and eroded topsoil. These hybrids were relatively poor in high yielding environments but top yielding in the unfavorable environments as emphasized in another study (Haussmann *et al.*, 2000). In contrast, the other high yielding hybrids K and T were narrowly adapted to well-managed conditions but not suitable for resource-constrained farmers, particularly in areas with unpredictable rainfall patterns and eroded topsoil. Of the 30 hybrids, X, W, N, B and C_1 were the most unstable over environments, while N and B were also the poorest in mean yield. BH540 (C_1) was improved for high rainfall areas at Bako but proved to be one of the most inferior in the present study, both in mean yield and stability. This study agreed with Betran *et al.* (2003) who suggested that good performance across stress levels can be achieved in tropical maize hybrids, especially when developed from drought tolerant lines.

The estimated relationship between crosses and mid parents based on their ASV values showed that there was no significant association ($r_{F1ASV.MPASV}$ = -0.004). This indicated that the magnitude of GEI (ASV) of the crosses was not dependent on the parental lines *per se.* Considering ASV values, CML445, CML440, CML442 and Mex103 appeared to be superior lines over various environments (data not shown). However, the performances of the crosses developed from stable lines (CML442 x CML445 and Mex103 x CML440) were not stable (Table 3). On the other hand, all the lines except Mex102 were involved in the nine superior crosses (O, P, C_2, S, H_1, H_2, Z, U and G) but lines with poor stability were more involved in these crosses than the stable lines. This also confirmed the suggestion made above because GEI expression controlled non-additive gene effects (Kang, 1998). However, good yield stability in lines may be important for F_1 seed production if it is practiced under erratic rainfall conditions.

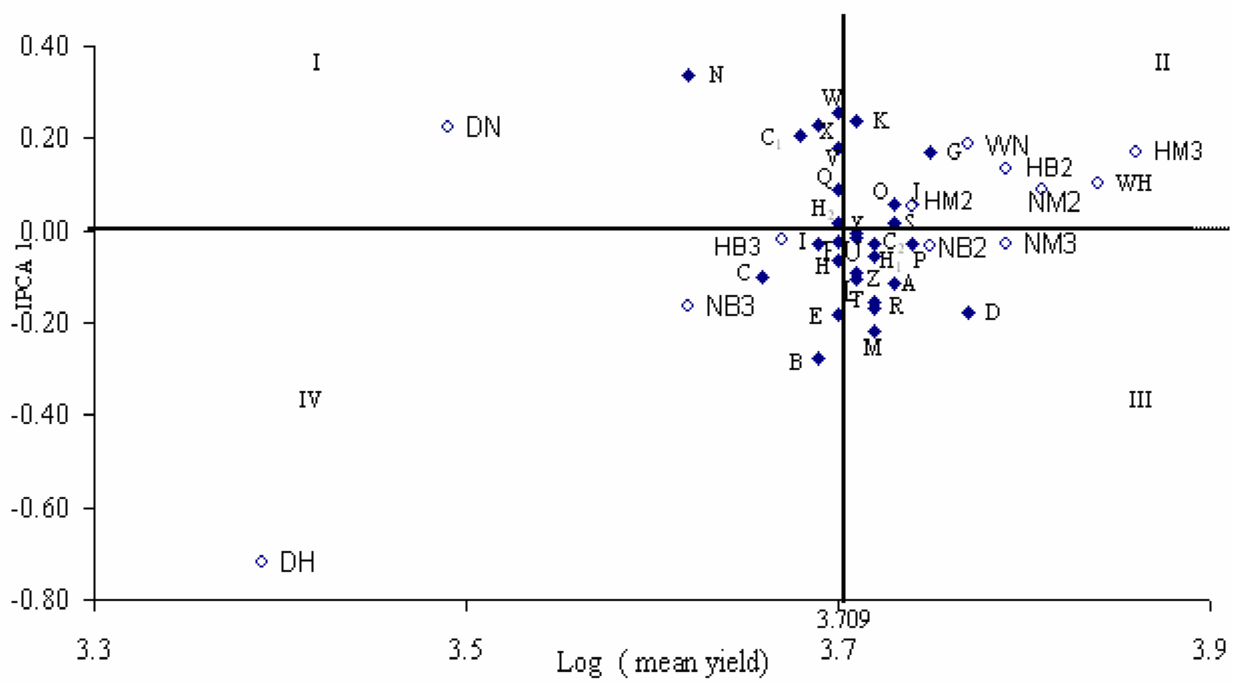

Figure 1. AMMI model 2 biplot of the 30 hybrids (◆) evaluated in 12 environments (o).

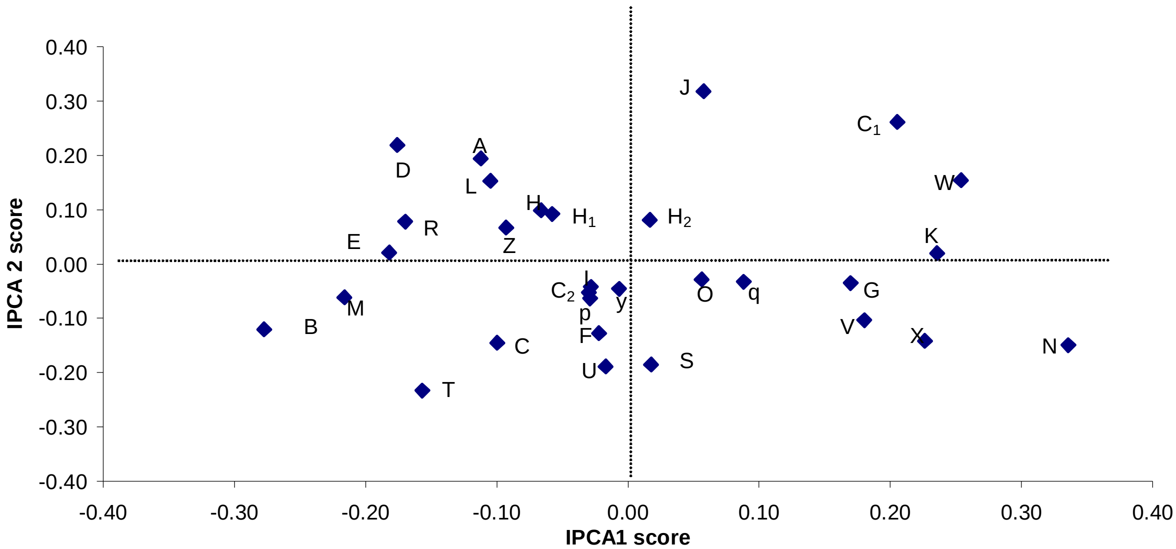

Figure 2. IPCA1 and IPCA2 scores of maize hybrids plotted against one another.

Table 3. AMMI adjusted mean grain yield (t ha^{-1}) based on raw data, and ASV and ranking orders of the 30 hybrids evaluated across 12 environments.

		Mean		ASV				Mean		ASV	
Hybrid Name	Code	t ha^{-1}	rk*	Value	rk	Hybrid Name	Code	t ha^{-1}	rk*	Value	rk
Mex101xMex102	A	5.79	4	0.251	17	Mex103xCML202	P	5.79	5	0.076	4
Mex101xMex103	B	5.14	27	0.410	29	Mex103x CML443	Q	5.40	21	0.129	8
Mex101xCML440	C	4.88	29	0.203	14	Mex103xCML445	R	5.53	13	0.252	18
Mex101xCML442	D	6.30	1	0.331	24	CML440xCML442	S	5.77	7	0.187	12
Mex101xCML 202	E	5.29	24	0.258	19	CML440xCML202	T	5.68	8	0.321	22
Mex101xCML443	F	5.28	25	0.131	9	CML440x CML443	U	5.52	14	0.191	13
Mex101xCML445	G	6.06	2	0.242	16	CML440xCML445	V	5.38	22	0.275	20
Mex102xMex103	H	5.23	26	0.136	10	CML442xCML 202	W	5.50	16	0.390	27
Mex102xCML440	I	5.09	28	0.058	2	CML442x CML443	X	5.50	17	0.350	26
Mex102xCML442	J	5.88	3	0.328	23	CML442xCML445	Y	5.44	20	0.047	1
Mex102xCML202	K	5.78	6	0.333	25	CML202x CML443	Z	5.54	12	0.147	11
Mex102x CML443	L	5.44	18	0.213	15	CML202xCML445	H_1	5.63	10	0.123	7
Mex102xCML445	M	5.44	19	0.311	21	CML443x CML 445	H_2	5.52	15	0.084	5
Mex103xCML440	N	4.69	30	0.497	30	BH540 (Check 1)	C_1	5.31	23	0.390	28
Mex103x CML442	O	5.66	9	0.084	6	BH140 (Check 2)	C_2	5.61	11	0.068	3
						LSD (0.05)		0.347			

* *rk = rank*

4. Conclusions

Most crosses from drought tolerant parents were better than the conventional hybrid (BH540) in mean grain yield and stability. Selection for drought tolerance through simultaneous evaluation of parental lines under both stress and non-stress conditions can be considered as the main cause for reduced GEI. However, some hybrids like K and T were narrowly adapted to well-managed conditions, which is not affordable for resource-constrained farmers. In this study, considerable relationships were not observed between lines and their crosses in stability, indicating independence between them for this trait.

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