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Yield potential and yield stability of maize hybrids selected for drought tolerance

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Abstract

Objective: Drought and low soil nitrogen (low N) are the most important environmental constraints contributing to yield instability of maize (*Zea mays* L.). Evaluation of maize genotypes under different stresses would be useful for identifying genotypes that combine stability with high yield potential for stress-prone areas. This study was conducted to (i) estimate stability of yield in maize hybrids developed from inbred lines with differential reactions to drought stress; and (ii) identify hybrids that combine stability with high yield potential across stress and non-stress environments.
Methodology and results: Six hybrids, each formed by crossing drought tolerant x tolerant (T x T), susceptible x susceptible (S x S), T x S and S x T inbred lines and 4 checks were selected from 100 hybrids tested for two years under severe drought, mild drought, low N and high N; and for four years under optimal conditions, making a total of 12 environments in Nigeria. Combined analysis of variance showed that environments, genotypes and genotype-by-environment (GE) interaction effects were highly significant, suggesting that the hybrids responded differently relative to each other to a change in environment. Genotype and genotype-by-environment (GGE) biplot analysis explained 90% of the yield variation due to GGE. Most hybrids of T x T, T x S crosses were stable, while most S x T and S x S crosses were unstable across environments.
Conclusion and application of findings: The study depicted severe drought stress as a representative test environment, indicating that selection of maize hybrids under drought stress would lead to yield improvement in low N as well as optimal growing environments. This study has identified four hybrids, (4058 x Fun.47-3), (161 x KU1409), (KU1409 x 4008) and (1824 x 9432), that are stable and have high yield potential, however, they need to be tested further in multiple environments to confirm consistency of their stability.

Key words: Drought stress, genotype, genotype by environment interaction, low nitrogen, maize hybrid, yield stability

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Introduction

Drought and low N are the most important environmental constraints to yield stability (Gorman *et al*., 1989; Biarness-Dumoulin *et al*., 1996). Yield stability is influenced by the capacity of a genotype to react to environmental conditions, which is determined by the genetic composition of the genotype (Borojevic, 1990). Yield improvement and stability in maize genotypes has been ascribed to increased tolerance to drought and low N (Duvick, 1992 & 1997; Tollenaar & Lee, 2002). Extensive testing of maize hybrids improved for drought conditions under low N, severe drought and mild drought stress as well as in optimal growing environments would be useful for identifying hybrids that combine high yield and stability.

Several studies (Finlay & Wilkinson, 1963; Eberhart & Russell, 1966; Russell & Eberhart, 1968; Yan & Kang, 2003) have shown that genotypes differ significantly in their ability to interact with environments. Therefore, extensive testing of maize hybrids in different environments would be required to identify hybrids with the least interaction with environments. Heterozygosity has been reported to be a prerequisite for efficient yield stability in maize improvement (Becker & Leon, 1988). Eberhart and Russell (1969) demonstrated that heterogeneous maize populations have better yield stability than homozygous populations, and further observed that two single cross hybrids were not only as stable as any of double crosses but also higher yielding. Evaluating yield stability of maize hybrids from parental lines with different levels of tolerance to drought across stress and non-stress environments could give good information on the combinations that provide wider adaptation.

Regression analysis has been commonly used for estimating yield stability in plant breeding programs (Finlay & Wilkinson, 1963; Eberhart & Russell, 1966; Perkins & Jinks, 1968). This approach partitions the genotype-by-environment interactions (GEIs) into GE and residual across varying environments in order to provide a meaningful biological explanation of GEIs (Eberhart & Russell, 1966; Avis *et al*., 1980). Although regression approaches have been used by many breeders to select stable genotypes, new statistical tools such as genotype and genotype-by-environment (GGE) biplot analysis can provide comprehensive visual information and are better, faster and easier to interpret than the results obtained from regression analysis (Yan & Kang, 2003). The GGE biplot integrates the genotypes main effect (G) and GEI using principal component analysis (PCA). The GGE biplot analysis removes the large environmental effect (E), which is irrelevant to genotype evaluation, and keeps only G and GE that are relevant for making meaningful genotype evaluation and selection decisions (Yan *et al*., 2000 & 2001; Yan & Kang, 2003). This study was, thus, conducted to (i) estimate stability of yield in maize hybrids formed from inbred lines with differential reactions to drought stress; and (ii) identify hybrids that combined stability with high yield potential across stress and non-stress environments.

Materials and Methods

Materials: The genetic materials consisted of 24 maize hybrids and 4 hybrid checks selected from 100 hybrids using a base index for both drought and low N test environments according to Baker (1986) and Lin (1978). The index summarized the worth of a hybrid by making use of information from different traits recorded. To add together traits measured in different units, the phenotypic values, Pi, were standardized as: $P_i = (X_{ij} – m_i)/s_j$; where m_i and s_j are the mean and standard deviation of trait '*i*' in the hybrids, and x_{ij} is the value of the trait measured on inbred '*j*'.

The base index I in its simplest form can be written as: $I = b_iP_i + b_jP_j….b_nP_n$

where Pi is the observed standardized value of the trait and bi is the weight assigned to that trait in the base index. Weights were chosen based on the relative economic value and the relative value of each trait as an indicator of drought or low N tolerance.

The weights were assigned in a way that sought to maintain grain yield under optimal growing (irrigated and high N) conditions, increase in grain yield and number of ears per plant, decrease anthesis-silking interval (ASI) and rate of leaf senescence under both low N and severe drought stress. This index combined grain yield under drought or low N with ASI, plant and ear aspect, leaf death scores and number of ears per plant. Since each parameter was standardized with mean zero and standard deviation of 1 to minimize the effects of different scales, a positive value was an indicator of good performance of hybrids under drought stress or low N, while a negative value was an indicator of poor performance under similar conditions. The selected hybrids were 6 crosses each of drought tolerant x tolerant (T x T), susceptible x susceptible (S x S), T x S and S x T inbred lines, resulting in four hybrid groups. Each of the group comprised of three best and three worst hybrids. However, among the hybrid checks we found three best and only one worst hybrid (Table 1).

Table 1: Selected maize hybrids and four checks tested under severe drought stress, mild drought stress, well-watered, low and high Nitrogen conditions in Nigeria between 2002 and 2005.

		Number of hybrids	
Hybrid designation	Hybrid group†	Best	Worst
01 - 06	T x T	3	3
07 - 12	T x S	3	3
13 - 18	S x T	3	3
19 - 24	S x S	3	3
25 - 28	Checks	3	1

† T = Tolerant and S = susceptible to drought stress

Experiments: The hybrids and hybrid checks were tested in trials for two years under severe drought stress (SS), mild drought stress (MS), low N (LN) and high N (HN); and for four years under well-watered (WW) conditions, making up a total of 12 environments. Experimental design was a 10 x 10 triple lattice design. The trials were conducted under WW, SS and MS conditions at Ikenne (6° 53′ N; 3° 42′ E, and 60 metres above sea level) between 2002 and 2005 as well as under LN and HN at Mokwa (9° 18′ N; 5° 04′ E, and 457 [masl]) in 2002 and 2003 in Nigeria. Apart from targeted stress (drought or low N), experiments in the same location were planted in adjacent blocks of the same field on the same date to ensure that other environmental factors were similar among trials.

At Ikenne, the trials were conducted during the dry season in well-watered (block 1) and drought stress (block 2) blocks. Normally, maize crop planted during this period depend on irrigation water. A sprinkler irrigation system was used to supply sufficient water every week to all treatments in both blocks during the first 35 days following germination. Block 1 continued to receive irrigation until the crop attained physiological maturity. In block 2, drought was imposed by withdrawing irrigation at 15 to 21 days before 50% pollen shed to ensure drought stress at flowering and grain filling stages. No irrigation was applied during the remainder of the growing period, thus allowing the crop to mature on stored soil water. However, there were unexpected rains in 2003 (69.4 mm) and 2004 (71.8 mm) that coincided with the flowering period. Throughout the text, block 2 in 2002 and 2005 will be referred to as SS and in 2003 and 2004 as MS. On the other hand, the trials at Mokwa were conducted in low and high N blocks that received different N treatments. The low N block had been depleted of soil nitrogen by growing high population density of maize without additional N fertilizer. This block received 20 kg N ha^{-1}, while high N block received 90 kg N ha^{-1} applied as urea.

In all trials, each entry was planted in a single-row of 3 m long, 0.75 m apart with 0.25 m spacing between hills within each row. Two seeds were planted in a hill and thinned to one plant two weeks after emergence to attain plant density of 53,333 plants ha^{-1}. All trials received standard cultural practices to control weeds.

Data collection and analysis: In experiments with low N and drought stress, the plants nearest to the alley showed more vigour and bigger ears than plants within the row and were removed during harvest. Only competitive plants within a row were harvested. Various traits were measured, however, only grain yield data is reported in this paper. Yield data of selected 24 hybrids and 4 checks from the test environments were used to estimate their yield stability and yield potential in stress and optimal growing environments.

For each growing condition, an analysis of variance (ANOVA) was carried out for grain yields using a mixed model in SAS (SAS Institute, 1999) with genotypes being considered as fixed effects, replications and year random effects. ANOVA was performed with PROC GLM in SAS using a RANDOM statement with the TEST option. A combined ANOVA was carried out across the test environments to determine genotypic main effects, environmental effects and genotype-by-environment interactions. A GGE biplot analysis of grain yield was performed to measure the response of genotypes to SS, MS, WW, LN and HN using the procedure developed by Yan and Kang (2003).

Results

General analysis of variance: The combined analysis of variance for grain yield revealed highly significant mean squares for environment and genotypes. The mean square due to genotype x environment interaction was also significant, indicating variation in yield performance of different genotypes in different environments. A large proportion of sum of squares was accounted for by environment (Table 2). Genotype x Environment interaction effects accounted for 12% and genotype effects for only 14% of the total variation in grain yield. Results from GGE biplot also showed that genotype x environment interaction effects accounted for 11%, while genotypes main effect accounted for 25% of the total variation in grain yield.

***Per se* performance of hybrids across environments:** Comparison of mean grain yields of genotypes under stress and non-stress environments indicated that seven hybrids, 07 (4058 x Fun.47-3), 01 (161 x KU1409), 09 (KU1409 x 4008), 08 (1824 x 9432), 02 (TZMI501xKU1414x501 x KU1409), 25 (Oba Super1) and 26 (Oba Super 2) were consistently high yielders, both under stress and non-stress conditions, while 22 [(KU1403x1368 x KU1403x1368)BC2] was consistently a low yielding hybrid across stress and non-stress environments (Table 3). Hybrid 10 (9450 x 4008), 11 (9613 x 9071), 23 [(KU1403x1368)BC2 x GH 24] and 28 (MM9916-12) were consistently low yielders under stress but had grain yields above average yield under non-stress conditions.

GGE biplot genotype-focused scaling: The biplot explained 90% of the yield variation due to GGE (Fig.1). To determine mean grain yield and stability of the genotypes across stress and non-stress environments, an average environment coordinate (AEC) was drawn on the genotype – focused biplot. Coefficient of determination between the projection of mean yield of the genotypes and environment was 0.998. On the average, hybrid 01 (161 x KU1409) was the most stable with high grain yield, followed by 07 (4058 x Fun.47-3), 09 (KU1409 x 4008), 08 (1824 x 9432), 13 (9432 x TZMI501xKU1414x501) and 14 (4008 x 9006), whereas hybrid 22 [KU1403x1368 x (KU1403x1368)BC2] was the lowest yielding and unstable across environments (Fig. 1). Most hybrids of T x T, T x S and S x T had grain yield above average, while hybrids of S x S crosses performed below average. With regards to the discriminating ability of the test environments, the GGE biplot showed SS as a representative test environment (Fig. 1).

Results from symmetrical scaling of environment-centered yield data showed three mega-environments (SS and HN; LN; WW and MS) (Fig. 2). The two best hybrids, 01 (161 x KU1409) and 07 (4058 x Fun.47-3) under both SS and HN produced the highest mean grain yields and were stable across environments. On the other hand, hybrid 09 (KU1409 x 4008) had high yield but less stable compared with 01 and 07. The best hybrid under MS and WW was 03 (9006 x 1824), while 13 (9432 x TZMI501xKU1414x501) and 14 (4008 x 9006) produced grains above the average yield under SS, MS and WW conditions. Under LN, 25 (Oba Super1) was the best hybrid followed by 08 (1824 x 9432) (Fig. 2).

Ranking of the hybrids based on both average yield performance and stability across test environments showed that 07 and 01 were near-ideal hybrids followed by 09, 08, 02, 13 and 14. Hybrid 22 had the lowest average yield and was the least stable (Fig. 3).

Table 2: Mean squares and sum of squares of the effects of environments on grain yield of selected maize hybrids tested under stress and non-stress conditions between 2002 and 2005.

Source	D.F.	ANOVA mean square	GGE biplot analysis sum of squares (%)
Environment	11	185.03***	54.84
Rep (Environment)	24	3.20***	2.07
Genotype	27	19.49***	14.18
Genotype x environment	297	1.54***	12.36
Residual	648	0.95	

*** Significantly different at 0.001 probability level.

Discussion

The analysis of variance showed that the differences among hybrids, environments and their interactions were significant for grain yield, suggesting differences in their relative ranking in the test environments (Eberhart & Ressell, 1966). However, the magnitude of the contributions of these effects to the total sum of squares was highest for the environmental effects and lowest for hybrid main effects. This reveals not only the amount of variability that existed among environments but also the presence of genetic variability and phenotypic stability among the hybrids.

Eberhart and Russell (1966) observed that the stability of performance of maize hybrids appear to be partly a property of the parental lines. In this study, the most stable hybrids had at least one drought tolerant inbred parent (T x T and T x S). These hybrid groups also were found to be high yielders under both drought and LN conditions. The GGE biplot analysis showed that four hybrids, 07 (4058 x Fun.47-3), 01 (161 x KU1409), 09 (KU1409 x 4008) and 08 (1824 x 9432) combined high grain yield with stable performance, consistent with Kang and Pham's (1991) proposal that emphasizes the need for integrating stability of yield performance with mean yield to select high-yielding and stable genotypes.

Table 3: Means of grain yield of selected maize hybrids and checks tested under severe drought (SS), mild drought (MS), well-watered (WW), low nitrogen (LN) and high nitrogen (HN) between 2002 and 2005.

Hybrid	Hybrid designation[†]	SS	MS	WW	LN	HN
1	T x T	2.51	4.08	6.04	2.16	3.97
2	T x T	2.45	3.96	5.32	1.89	4.16
3	T x T	2.45	4.18	6.82	1.71	3.46
4	T x T	1.67	2.20	4.82	1.28	1.96
5	T x T	1.75	2.54	5.04	1.28	2.90
6	T x T	2.08	2.77	5.73	1.09	3.08
7	T x S	2.63	4.54	5.60	2.15	3.87
8	T x S	2.33	3.92	5.46	2.18	4.92
9	T x S	2.41	4.02	5.64	2.19	4.27
10	T x S	1.50	1.10	3.38	0.90	1.81
11	T x S	1.30	1.51	4.59	1.19	2.69
12	T x S	1.57	2.38	4.50	1.28	2.72
13	S x T	2.43	4.14	6.36	1.72	4.02
14	S x T	2.48	4.72	5.82	1.65	3.74
15	S x T	2.31	3.64	5.21	1.63	4.15
16	S x T	1.47	2.69	5.61	1.02	2.55
17	S x T	1.63	2.62	4.37	1.18	2.67
18	S x T	0.99	1.94	4.12	1.69	3.90
19	S x S	2.12	4.09	5.00	1.57	3.66
20	S x S	2.17	2.82	4.37	1.81	3.51
21	S x S	1.76	2.10	5.69	1.88	3.67
22	S x S	0.74	0.40	1.26	1.09	0.71
23	S x S	1.27	1.70	3.87	1.05	1.88
24	S x S	1.39	2.10	3.06	1.27	2.64
25 Check1	Oba Super1	2.58	3.33	4.47	2.23	4.66
26 Check2	Oba Super2	1.96	3.33	4.91	1.88	3.53
27 Check3	MM9916-11	1.63	3.58	4.99	1.84	3.44
28 Check4	MM9916-12	1.08	3.58	4.49	1.26	2.11
Mean		1.88	3.00	4.88	1.58	3.24
SE±		0.10	0.21	0.21	0.08	0.18

[†] T = tolerant and S = susceptible to drought

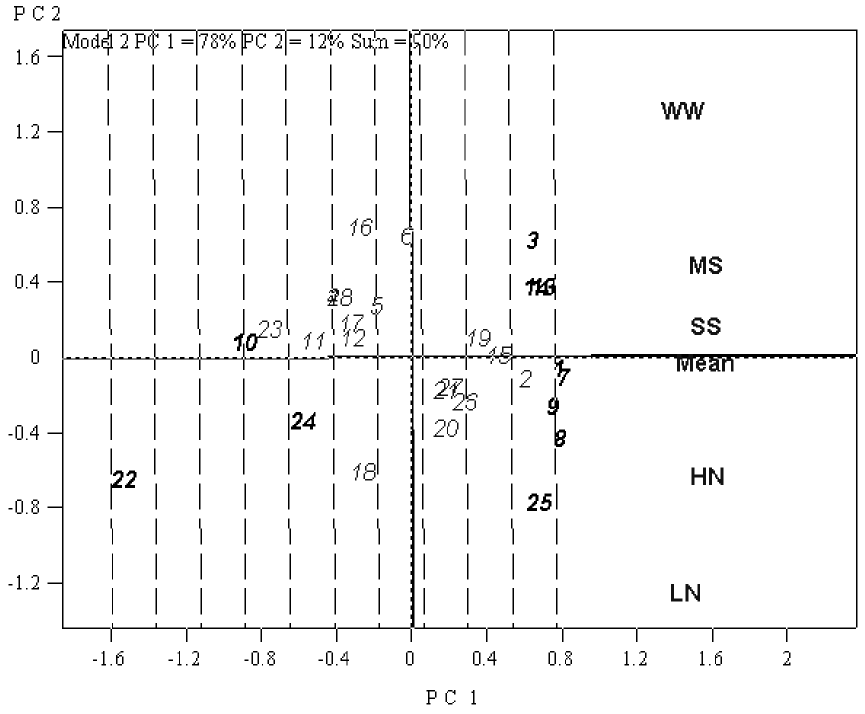

Figure 1: The average environment coordinate (AEC) view of the GGE biplot based on the genotype-focused scaling, showing the mean yield and stability of genotypes.

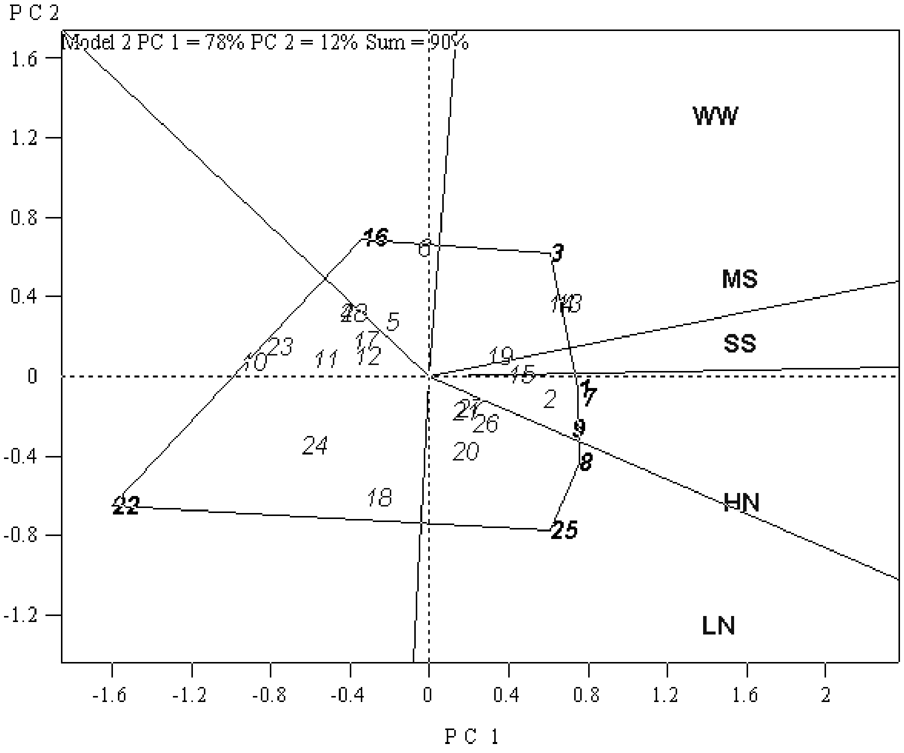

Figure 2: The winning genotype in each mega-environment (group of environments).

Hybrids that performed well under SS, MS and LN tended to perform well under HN and WW conditions, indicating that hybrids selected under stress maintained their superiority under non-stress conditions. In this study, GGE biplot depicted SS as a representative test environment, suggesting that selection of drought tolerant maize hybrids under severe drought stress would lead to yield improvement in low N as well as optimal growing environments. This set of data seems to suggest that selection under drought stress may confer stability of hybrids to low N as well as optimum growing conditions. Thus, genotypes developed under drought stress have high probability of producing high grain yields under low N or a lower probability of giving yields below average under optimal conditions (Ceccarelli & Grando, 1991).

Our study demonstrated that breeding gains made under drought stress apparently translate to gains in low N and optimal growing environments. Although four stable hybrids, (4058 x Fun.47-3), (161 x KU1409), (KU1409 x 4008) and (1824 x 9432) with high yield potential were identified, they need to be tested further in multiple environments to confirm consistency of their stability.

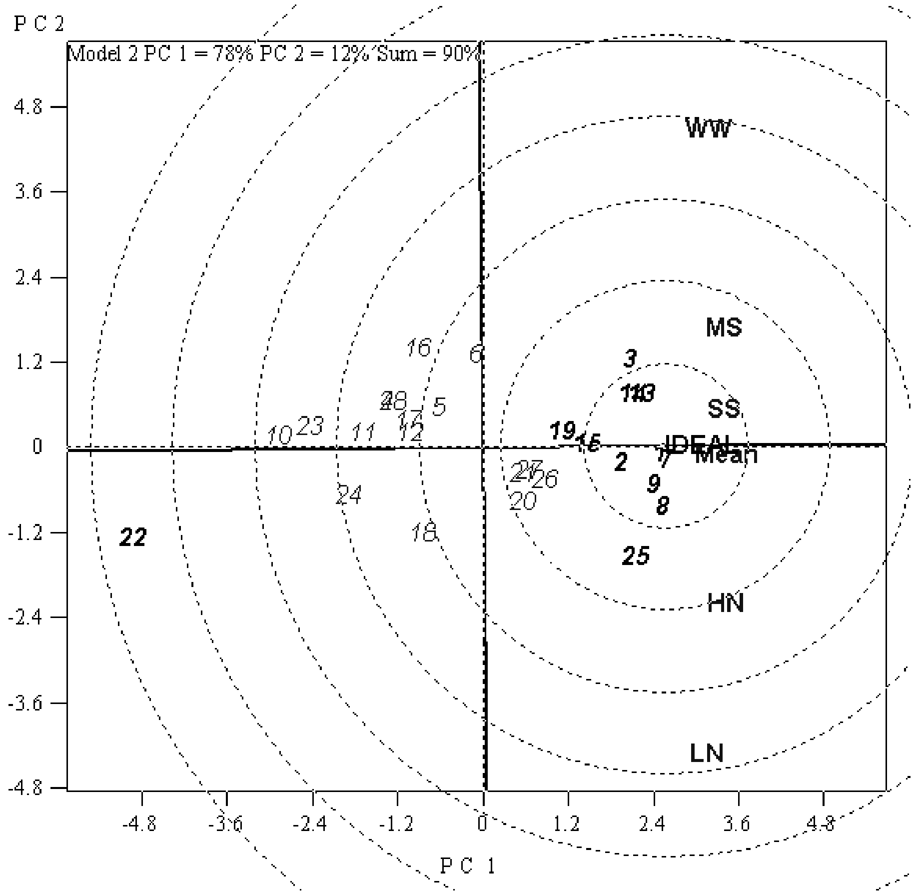

Figure 3: Ranking of genotypes based on both average yield and stability.

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