Heterotic relationship between INERA, CIMMYT and IITA maize inbred lines under drought and well-watered conditions

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Abstract

The Institute of Environment and Agricultural Research of Burkina Faso has extracted a large number of inbred lines from Open Pollinated Varieties, which are environmentally adapted and adopted by farmers. However, there is a gap in knowledge on heterotic grouping of these lines and their heterotic relationship with exotic lines. Twenty-four CIMMYT and INERA white lines were crossed to two CIMMYT testers and; twenty six IITA and INERA yellow inbred lines were crossed to two IITA testers. Two trials composed of 48 white testcrosses and 52 yellow testcrosses plus three checks were evaluated in well-watered and drought stress conditions in the dry season over two years. Significant general combining ability (GCA) effects due to lines and, testers for many traits including grain yield were observed. However, specific combining ability (SCA) effects for most traits except for plant and ear heights were not significant. Of the 24 CIMMYT and INERA white lines, 15 lines could be classified into heterotic groups based on the SCA effects and testcross mean grain yield in well-watered environment and, 10 lines were classified under drought stress condition. Eighty five percent of the IITA and INERA yellow lines were classified into heterotic groups in both drought and non-drought conditions. Thirteen yellow lines and five white lines maintained their heterotic groups in both well-watered and water-stressed conditions.

Keywords: maize, heterotic patterns, drought

Introduction

Maize is an important source of calories for a significant portion of the population in sub-Saharan African. Maize provides 50% of the calories in diets in southern Africa, 30% in eastern Africa and 15% in West and Central Africa; of the 23 countries in the world with the highest per capita consumption of maize as food, 16 are in sub-Saharan Africa (Bänziger and Diallo, 2001). Maize production in the Economic Community of West African States (ECOWAS) has progressively increased in the last 5 years with an important contribution from Nigeria of about 50%. ECOWAS, representing 17% of the area of the continent, is one of the most populous economic communities in Africa with a regional population of about 300 million in 2008, of which 57% live in rural areas. Burkina Faso is among the top 5 countries in maize production in this region. National statistics show that maize production in Burkina Faso is increasingly important and the local consumption guarantees a domestic and export market. The successful adoption of the commercial hybrid «Bondofa» in the country emphasized the need for development of maize cultivars with high yield potential. Cognizant of this fact, maize breeding program at the Institute of Environment and Agricultural Research, Burkina Faso developed and assembled germplasm from various sources. A large numbers of inbred lines were generated from different adapted and adopted open pollinated varieties (OPVs). Inbred lines have been classified mainly based on their performance per se and source population. Heterotic groups which have important implications in a comprehensive hybrid breeding program have not been developed. Heterotic groups enable the exploitation of heterosis in an efficient and consistent manner through identification of complementary lines. Creation of new heterotic groups for hybrid program development is desirable (Russell, 1991; Cheres et al, 2000). There is little current knowledge of heterotic grouping of lines developed at INERA maize breeding program. In developing countries, judicious application of available crop improvement methods and use of both local and exotic germplasm to improve yields and yield stability are required to meet the increasing demand of improved maize hybrids (Dhliwayo et al, 2009). CIMMYT and IITA are the source of maize breeding materials for a significant portion of Africa. CIMMYT and IITA inbred lines and OPVs are bred to contain considerable diversity and are then taken by National Agriculture Research Programs and selected for further adaptation in their own particular environment(s). Maize germplasm at INERA includes different materials from CIMMYT and IITA but little is known about the heterotic relationships between CIMMYT and INERA and between IITA and INERA inbred lines. To make

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effective use of local and exotic germplams, information about their heterotic relationships and combining ability is desirable. Heterotic groups are not absolute (Hallauer and Miranda, 1988). Studies show that the heterotic patterns of inbred lines and populations can change depending on the test environment under which evaluation is made (Gutiérrez-gaitan et al, 1986; Kim and Ajala, 1996; Vasal et al, 1993; Menkir et al, 2003). Understanding the change in heterotic response of inbred lines under stress and non-stress conditions would be useful for the development of an efficient hybrid breeding strategy. Drought stress is among the major abiotic stresses causing yield reduction in maize grown in the tropics (Edmeades et al, 1995). However, there are few studies on effect of this stress on heterotic patterns of lowland and mid-altitude maize inbred lines.

The objectives of this study were to: i) characterise the heterotic patterns of 24 CIMMYT and INERA white and 26 IITA and INERA yellow inbred lines for grain yield; ii) classify these lines into heterotic groups; iii) evaluate the effect of sources population of the inbreds and drought stress on heterotic grouping of the inbred lines.

Materials and Methods

Genetic materials

Thirteen elite CIMMYT mid-altitude white inbred lines, twelve elite IITA lowland yellow inbred lines, and 25 advanced INERA white and yellow inbred lines were used for this study (Table 1). CIMMYT inbred lines were developed from diverse sources, four lines (VL057903, VL058025, VL057967, and VL058014) were developed from an extra-early population developed through reciprocal recurrent selection from a wide pool of Southern and Eastern Africa adapted inbred lines of N3, Kitale, A and Tuxpeño population backgrounds. Inbred lines VL05615, VL081464, VL081466 were developed from an extra-early population developed through reciprocal recurrent selection from a wide pool of Southern and Eastern Africa adapted inbred lines from SC, Ecuador, B, and ETO population backgrounds. Four lines including VL054794, T02058, VL0511247, and VL05616 were derived from biparental crosses. VL05616 traces 50% of its pedigree to a temperate inbred line (FR812). The remaining two inbred lines (VL058589 and VL0512593) were developed each from different sources. IITA inbred lines were developed from two different sources: the broad-based Striga hermonthica resistant early yellow population, TZE COMP5-Y and the broad-based *Striga hermonthica* resistant and drought tolerant early yellow population, TZE-Y Pop DT STR. The eleven white and thirteen yellow lines from INERA used in the present study were all extracted from the early yellow drought tolerant Open-pollinated variety, FBC6, which has a mixed genetic background. VL0511298 and VL054881, representing heterotic group A and B, respectively, were used as testers for white inbred lines. TZEI 17 and TZEI 10, representing heterotic group A and B, respectively, were used as testers for yellow inbred lines.

Generation and evaluation of testcross hybrids

The testcross hybrids were generated during rainy season in 2011 and 2012 at INERA experimental station in Farako-Bâ. Thirteen CIMMYT and 11 INERA white inbreds were crossed to VL0511298 and VL054881 to generate 48 white testcross hybrids. Twelve IITA and 14 INERA yellow inbred lines were crossed to TZEI17 and TZEI10 to generate 52 testcross hybrids. The 48 white hybrids and 52 yellow hybrids were randomized separately and laid out in different trials but planted at the same time, in the same location and received the same treatments. The white hybrids trial was composed of 48 testcrosses, hybrid between the two inbreds used as testers and two local commercial hybrids. The yellow hybrids trial was of 52 testcrosses, hybrid between the two inbreds used as testers and the same local commercial hybrids. The trials were conducted during the dry season in 2011 and 2012 at field experimental station of INERA in Valley du kou located at 11°22'N Latitude, 4°22'W Longitude; and at 300 m above sea level, characterized by ferruginous and acid soils with silty texture.

The trials were established and managed according to procedures developed by CIMMYT (Bänziger et al, 2000). Adequate irrigation was applied in both water regimes from planting and throughout the vegetative phase, using furrow irrigation system. Drought stress was achieved in water stressed regime by withholding water two weeks before the expected flowering time for 21 days. The white and yellow field trials were laid out in 17 x 3 and 11 x 5 randomized incomplete block design, respectively, with three replications. The experimental unit was one single row of 5 m spaced at 80 cm. Two seeds were planted per hill spaced 25 cm between and thinned to one plant to give a final planting density of 50,000 plants ha^{-1}.

Data collection and statistical analysis

In each plot, days to anthesis and days to silking were recorded as the number of days from planting to when 50% of the plants had shed pollen and emerged silks, respectively. Anthesis-silking interval (ASI) was computed as the interval in days between dates of silking and anthesis. Plant and ear heights were measured in cm as the distance from the base of the plant to the height of the first tassel branch and the node bearing the upper ear, respectively. Ear aspect was scored on a 1 to 5 scale, where 1 = «clean, uniform, large and well-filled ears» and 5 = «rotten, variable, small and partially filled ears». The total number of plants and ears were counted in each plot at the time of harvest. The number of ears per plant was then calculated as the proportion of the total number of ears at harvest divided by the total

Table 1 - Inbred lines evaluated in testcrosses with two inbreds testers in well-watered an water-stressed conditions.

Inbred lines	Origin	Pedigree	Grain color	Maturity
T02058	CIMMYT	[CML389/CML176]-B-29-2-2-B*6-B	white	intermediate
VL0511247	CIMMYT	[INTA-2-1-3/INTA-60-1-2]-X-11-6-3-BBB	white	intermediate
VL0512593	CIMMYT	Syn01E2-64-2-B-2-BB	white	early
VL054794	CIMMYT	[[[K64R/G16SR]-39-1/[K64R/G16SR]-20-2]-5-1-2-B*4/CML390]-B-38-1-B-2-#-1-B-2	white	intermediate
VL05615	CIMMYT	ZEWBc1F2-216-2-2-B-2-B*4-4-2-8-B	white	intermediate
VL057903	CIMMYT	ZEWAc1F2-151-6-1-B-1-BBB-2-2-BB	white	early
VL057967	CIMMYT	ZEWAc1F2-219-4-3-B-1-B*4-1-3-BB	white	intermediate
VL058025	CIMMYT	ZEWAc1F2-164-3-2-B-1-BBB-2-2-BB	white	early
VL058589	CIMMYT	INTA-F2-192-2-1-1-B*7-2-B-3	white	early
VL081464	CIMMYT	ZEWBc2F2-101-2-BB	white	intermediate
VL081466	CIMMYT	ZEWBc2F2-110-1-BBB	white	early
VL05616	CIMMYT	[SC/CML204//FR812]-X-30-2-3-2-1-B*6	white	intermediate
VL058014	CIMMYT	ZEWAc1F2-254-2-1-B-1-BB-1-3	white	early
TZEI124	IITA	TZE-Y Pop DT STR Co S6 Inbred 3-1-3	yellow	early
TZEI146	IITA	TZE-Y Pop DT STR Co S7 Inbred 49-3-3	yellow	early
TZEI148	IITA	TZE-Y Pop DT STR Co S6 Inbred 62-1-3	yellow	early
TZEI149	IITA	TZE-Y Pop DT STR Co S6 Inbred 66-2-2	yellow	early
TZEI151	IITA		yellow	intermediate
TZEI158	IITA	TZE-Y Pop DT STR Co S6 Inbred 102-2-2	yellow	intermediate
TZEI16	IITA	TZE Comp5-YS C6 S6 Inbred 31	yellow	intermediate
TZEI161	IITA	TZE-Y Pop DT STR Co S6 Inbred 103-2-3	yellow	intermediate
TZEI177	IITA	TZE Comp5-Y C6 S6 Inbred 62-1-2	yellow	intermediate
TZEI23	IITA	TZE-Y Pop DT STR Co S6 Inbred 62-2-3	yellow	early
TZEI8	IITA	TZE-Y Pop DT STR Co S6 Inbred 62-3-3	yellow	early
TZI18	IITA	Sete Lag. 7728 x TZSR	yellow	intermediate
ELN41112	INERA	FBC6 x FBMS1	white	intermediate
ELN41114	INERA	FBC6 x FBMS1	white	intermediate
ELN41115	INERA	FBC6 x FBMS1	white	intermediate
ELN41271	INERA	FBC6 x FBMS1	white	intermediate
ELN41272	INERA	FBC6 x FBMS1	white	intermediate
ELN42441	INERA	FBC6 x FBMS1	white	intermediate
ELN42442	INERA	FBC6 x FBMS1	white	intermediate
ELN42444	INERA	FBC6 x FBMS1	white	intermediate
ELN42445	INERA	FBC6 x FBMS1	white	intermediate
ELN48392	INERA	FBC6 x FBMS1	white	intermediate
FBML10	INERA	Derived from Ku1414	yellow	intermediate
ELN39382	INERA	FBC6 x FBMS1	yellow	intermediate
ELN39427	INERA	FBC6 x FBMS1	yellow	intermediate
ELN402213	INERA	FBC6 x FBMS1	yellow	intermediate
ELN40791	INERA	FBC6 x FBMS1	yellow	intermediate
ELN40823	INERA	FBC6 x FBMS1	yellow	intermediate
ELN40941	INERA	FBC6 x FBMS1	yellow	intermediate
ELN431251	INERA	FBC6 x FBMS1	yellow	intermediate
ELN43453	INERA	FBC6 x FBMS1	yellow	intermediate
ELN43574	INERA	FBC6 x FBMS1	yellow	intermediate
ELN45111	INERA	FBC6 x FBMS1	yellow	intermediate
ELN462121	INERA	FBC6 x FBMS1	yellow	intermediate
ELN464171	INERA	FBC6 x FBMS1	yellow	intermediate
ELN47132	INERA	FBC6 x FBMS1	yellow	intermediate
ELN41111	INERA	FBC6 x FBMS1	white	intermediate
Testers				
VL0511298	CIMMYT	MAS[MSR/312]-117-2-2-1-B*4-2-14-BB	white	intermediate
VL054881	CIMMYT	[Ent2:92SEW1-earlySel-22/[DMRESR-W]earlySel-#1-3-2-B/CML390]-B-26-1B-1-#-1-BB-3-1	white	intermediate
TZEI 17	IITA	TZE Comp5-Y C6 S6 Inbred 35	yellow	early
TZEI 10	IITA	TZE-Y Pop DT STR Co S6 Inbred 152	yellow	early

The maturity of CIMMYT and IITA lines indicated in the table was determined based on a screening in a local environment.

number of plants at harvest. Additional data obtained from drought stress plots were the leaf senescence recoded two times at weekly interval commencing two weeks after stress application on a scale of 1 to 10, where 1 = «almost all leaves were green» and 10 = «virtually all leaves were dead». Leaf rolling recorded on a scale of 1 to 5, where 1 = «all leaves are unrolled» and 5 = «all leaves are rolled». Leaf rolling was recorded three time at weekly intervals, commencing a week after stress application; Leaf erectness was recorded based on visual score of 1 (erect leaves) to 5 (lax leaves) two times at a weekly interval commencing a week after stress application. Tassel size was recorded two times at weekly interval commencing 21 days after stress application based on scale of 1 (small tassel size) to 5 (large tassel size); Plant recovery was recorded at 7 and 14 days after stopping drought stress on a scale of 1 to 5, where 1 = «all plants recovered from drought stress» and 5 = «all plants were dead».

Grain yield was calculated according to the procedure described by (Menkir et al, 2003). In well-watered evaluation, all ears harvested from each plot were weighed and representative samples of ears were shelled to determine per cent moisture. Grain yield adjusted to 15% moisture was, thus, computed from ear weight and grain moisture assuming a shelling percentage of 80%, based on the following formula: grain yield (kg ha^{-1}) = ear weight (kg) x 0.8 x (100 - moisture) / 85) x (10 / area m^2) x 1,000.

In water-stressed evaluation, all ears harvested from each plot were shelled to determine per cent moisture. Grain yield adjusted to 15% moisture was computed from the shelled grain based on the following formula : grain yield (kg ha^{-1}) = grain weight (kg) x (100 - moisture) / 85) x (10 /area m^2) x 1,000.

Individual analysis of variance of each tested trait in each year and water regime were conducted with the PROC MIXED procedure from SAS (SAS, 2002) with genotypes being considered as fixed effects, and replications and blocks within replication as random effects. Because the alpha lattice did not provide significant efficiency over randomized complete block design (RCBD), data were then analysis according to RCBD. Combined analysis of variance was conducted by means of PROC GLM in SAS (SAS, 2002) using RANDOM statement with Test option. Means generated from the analysis of variance for each test environment were used for the computation of line x tester analysis as described by Singh and Chaudhary (1985). For combined analysis in well-watered (WW) and water-stressed (WS) conditions, the significance of line GCA , tester GCA and line x tester SCA mean squares were determined using the corresponding interaction with years as error terms. The significance of GCA lines × year, GCA tester x year and SCA × year interactions was determined using the pooled error. Effects of GCA and SCA were calculated for grain yield using the line x tester model.

Classification of inbred lines into heterotic groups

The specific combining ability (SCA) effects and mean grain yields of testcrosses of the lines with the two testers were used to classify the inbred lines into heterotic groups for each of the two growing conditions. Lines that showed positive SCA effects with tester A with testcross mean yields equal to or greater than 10% of the mean yield of hybrid between the two testers but had negative SCA effects with tester B were placed into anti-A or opposite heterotic group of tester A. The designation of «anti-A» (opposite group of tester A) was used instead of «same group of tester B» because lines belonging to the same heterotic group may not have absolutely identical heterotic patterns (Pswarayi and Vivek, 2008), explained by small differences in the alleles they may be carrying (Rawlings and Thompson, 1962). When lines exhibited positive SCA with tester B with testcross mean yield equal to or greater than 10% of the mean yield of the cross between the two testers but had negative SCA with tester A were assigned into anti-B or opposite heterotic group of tester B. Lines that showed positive SCA effects with both testers A and B with testcross mean yields equal to or greater than 10% of the mean yield of hybrid between the two testers were located into anti-A and anti-B groups (or opposite heterotic groups of A and B) whereas lines that exhibited negative SCA effects with both testers A and B or lines that had testcross mean yields less than 10% of the mean of the cross between the two testers were not assigned into either heterotic group.

Results

Means of local and exotic inbred lines evaluated in testcrosses with two inbreds testers in drought and well-watered conditions are presented in Table 2. The differences between testcross means of CIMMYT and INERA inbreds in testcrosses were significant for grain yield in well-watered condition and not significant under drought stress while the difference was not significant between IITA and INERA inbreds in testcrosses for grain yield in well-watered condition but significant under drought stress. When means were averaged over all testcrosses within a water regime, drought stress reduced plant height, ear height, the number of ears per plant, and grain yield, while it increased ear aspect, anthesis-silking interval and extent flowering time. Grain yield reduction was 47% in yellow testcrosses which was higher compared to 36% in white testcrosses. The increase of ASI under drought stress was higher (37%) in yellow testcrosses than white testcrosses (40%). The commercial check, Sanem, was the best check in both water regimes and in white and yellow testcrosses trails. Twelve white hybrids and five yellow hybrids yielded about 10% more than mean grain yield of Sanem in well-watered condition and, means grain

Table 2 - Means (±SE) of traits averaged over two years for white and yellow testcrosses of inbred lines with two testers, evaluated under drought stress and well-watered conditions.

Variable	well-watered condition				water-stressed condition			
	white hybrids		yellow hybrids		white hybrids		yellow hybrids	
	CIMMYT	INERA	IITA	INERA	CIMMYT	INERA	IITA	INERA
AD	74±0.7	78±0.7	75±0.6	77±0.7	76±1	80±0.9	77±1.3	80±1.1
SD	78±0.7	81±0.8	78±0.6	80±0.7	82±1	85±0.7	82±1.3	85±1
ASI	3.5±0.5	3.3±0.6	2.9±0.5	3±0.5	5.9±0.7	5.3±0.6	4.5±0.8	4.8±0.7
PHT	171±5.2	180±5.5	169±5.3	176±5.4	135±5.4	135±5.4	131±7.9	135±6.5
EHT	63±4.1	72±4.2	76±4	82±4.5	57±3.5	62±4	65±4.7	67±4.9
EASP	2.6±0.3	2.9±0.3	2.4±0.2	2.5±0.2	3±0.2	3.1±0.2	2.8±0.2	2.9±0.2
EPP	0.9±0.1	0.9±0.1	0.9±0.1	0.9±0.04	0.8±0.1	0.8±0.1	0.8±0.1	0.9±0.1
GY	2,475±0.3	2,205±0.3	2,487±0.2	2,628±0.3	1,524±0.2	1,499±0.2	1,238±0.2	1,481±0.3
LR					2±0.2	2±0.2	2.5±0.3	2.5±0.3
SEN					4±0.4	4±0.4	4.9±0.5	4.8±0.5
LE					2.7±0.2	2.5±0.2	2.6±0.2	2.5±0.2
TS					2.7±0.2	2.8±0.2	2.8±0.2	2.9±0.2
PR					3±0.4	2.8±0.3	3.1±0.4	2.8±0.4

AD = anthesis-days (50%); SD = silking-days (50%); ASI = anthesis-silking interval; PHT = plant height; EHT = ear height; EASP = ear aspect; EPP = ear per plant; GY = grain yield (kg ha^{-1}); LR = leaves rolling; SEN = leaves senescence; LE = leaves erectness; TS = tassel size; PR = plant recovery.

yield of two white hybrids and three yellow hybrids, in drought stress condition, were higher than that of Sanem by 10%.

Combined analysis of variance for grain yield and other agronomic traits of the white and yellow testcrosses are presented in Table 3 for well-watered condition and Table 4 for water-stressed condition. Significant differences were detected among CIMMYT and INERA lines for anthesis-days (AD), anthesis-silking interval (ASI) and ear height (EHT) under both well-watered and water-stressed conditions, while the difference was significant among IITA and INERA lines only for AD under both water regimes. The variation among white lines (GCA) was significant for grain yield (GY) under drought stress and for ears aspect (EASP) and plant height (PHT) under well-watered condition; and the variation among yellow lines was significant for GY, EPP and PHT under well-watered condition. The two testers within each testcross group differed significantly only for AD under drought stress. The line x tester interactions (SCA) were generally not significant for many traits in both white and yellow testcrosses and under both water regimes. However SCA effects were significant for plant and ear height in well-watered condition for yellow testcrosses. Among the drought adaptive traits including leaf rolling (LR), senescence (SEN) and erectness (LE), tassel size (TS) and plant recovery (PR) measured only under drought stress condition, GCA mean square were significant only for TS and PR in white testcrosses and for LE in white and yellow testcrosses. Mean square of tester GCA was significant only for PR in yellow testcrosses. There were no significant SCA effects for the four adaptive drought traits in either testcrosses group.

Testcross means and estimates of GCA and SCA effects of the white and yellow lines for grain yield are presented in Table 5 and Table 6 respectively. On average, white testcrosses with VL0511298 consistently out-yielded those with VL054881 by 13% under well-watered and 26% under water-stressed condition; but VL054881 x ELN42444 was one of the best hybrids under both water regimes. Hybrids with VL0511298 did better under drought stress. Yellow testcrosses of TZEI10 out-yielded those of TZEI17 by 4% under well-watered condition but under drought stress yellow testcrosses of TZEI17 out-yielded by 11% those of TZEI10.

Mean grain yields of six white testcrosses with VL0511298 tester involving three lines (VL058025, VL057967, and VL058014) with Tuxpeño background, two lines (VL054794 and T02058) developed from biparental crosses, one line (VL05615) with ETO background and three INERA lines (ELN42441, ELN48392, and ELN42445) were higher than that of the hybrid between testers (VL0511298 x VL054881) by at least one standard error in the well-watered environment. Tester VL0511298 produced, in the drought stress environment, five testcrosses with at least one standard error higher than that of VL0511298 x VL054881 with four lines (VL054794, T02058, VL05616, and VL0511247) derived from biparental crosses and one line (VL057967) with Tuxpeño background. Yield increases of these testcrosses over VL051198 x VL054881 varied from 14% to 28% in the well-watered environments and from 20% to 38% in the drought stress environments.

Five hybrids with tester VL054881 crossed with three CIMMYT lines, VL05616, VL0511247 (biparental crosses), and VL058025 (Tuxpeno background) and two INERA lines (ELN42442 and ELN42444) out-yielded the hybrid between testers (VL0511298 x VL054881) by at least one standard error in the well-watered condition with a yield increase over VL0511298 x VL054881 from 11% to 27%. But tester VL054881 produced, in drought stress condition,

Table 3 - Percent of corrected total sum of squares from the combined analysis of variance for the testcross hybrids of 26 IITA and INERA yellow and, 24 CIMMYT and INERA white inbred lines evaluated in well-watered condition at Valley du kou, in Burkina Faso, for two years.

Source	DF	GY	EPP	EASP	AD	ASI	PHT	EHT
				White testcross hybrids				
Year	1	0.05	0.35***	1.18	448.91***	98.61***	179,224.07***	12,201.49***
GCA_{Line}	23	1.61	0.03	1.49**	84.61***	11.82**	1,012.81***	704.69***
GCA_{Tester}	1	7.90	0.03	1.06	227.26*	9.72	418.68	1,434.6
$SCA_{Line\ x\ Tester}$	23	1.01	0.02	0.47	9.55	2.28	302.93	97.02
Year xGCA_{Line}	23	0.81	0.03	0.53	8.70***	3.17	162.08*	92.81
Year x GCA_{Tester}	1	0.53	0.04	0.73	0.46	5.88	25.76	259.24
Year x $SCA_{Line\ xTester}$	23	0.86*	0.01	0.68	5.48*	2.76	114.16	103.89
				Yellow testcross hybrids				
Year	1	10.58***	0.23***	36.72***	12.45	55.46***	20,7001.54***	25,219.08***
GCA_{Line}	25	1.24*	0.030*	0.91	31.97***	3.47	501.66*	276.75
GCA_{Tester}	1	0.28	0.03	1.66	55.13***	7.66	476.80	9.29
$SCA_{Line\ x\ Tester}$	25	0.83	0.03	0.62	5.78	2.04	362.42**	236.77**
Year x GCA_{Line}	25	0.52	0.01	0.85**	5.79*	2.73*	221.08	198.19
Year x GCA_{Tester}	1	0.18	0.14**	0.21	0.00	0.48	1,423.81*	423.28
Year x $SCA_{Line\ xTester}$	25	0.66	0.01	0.37	5.12	1.80	120.61	71.99

AD = anthesis-days (50%); ASI = anthesis-silking interval; PHT = plant height; EHT = ear height; EASP = ear aspect; EPP = ear per plant; GY = grain yield (t ha^{-1}).

only one hybrid with INERA line (ELN42444) that was at least one standard error higher than that of VL0511298 x VL054881 with 15 % of yield increased.

Mean grain yields of 11 yellow testcrosses with each tester, TZEI17 and TZEI10, involving seven INERA lines and 4four IITA lines were higher than that of the hybrid between testers (TZEI17 x TZEI10) by at least one standard error in the well-watered environments. In addition four testcrosses with TZEI17 involving three IITA and one INERA lines, and seven testcrosses with TZEI10 including four IITA and three INERA lines out-yielded the hybrid between testers (TZEI17 x TZEI10) by at least one standard error. Under drought stress, each of the two yellow testers (TZEI17 and TZEI10) produced nine testcrosses, six with INERA and three IITA lines, with at least one standard error higher than that of TZEI17 x TZEI10, and mean grain yields of seven hybrids with TZEI17 involving four INERA and three IITA lines and three hybrids including two IITA and one INERA line were higher than that of TZEI17 x TZEI10 by at least one standard error. Yield increases of these yellow testcrosses over TZEI17 x TZEI10 varied from 11% to 41% in the well-watered environment and from 19% to 56% in the drought stress environment

The number of white lines with positive GCA effects for grain yield was 14 under well-watered condition and 11 under drought stress. Of these, only two lines (ELN42442 and VL058025) under well-watered condition and three lines (T02058, VL054794, and VL057967) under drought stress had significantly positive GCA effects. Eleven and thirteen yellow lines had positive estimates of GCA effects for grain yield under well-watered and water-stressed conditions, respectively. Of these, four lines (ELN431251, ELN43574, ELN45111, and TZI18) under well-watered condition and three lines (ELN39427, ELN43574, and TZEI151) under drought stress had significantly positive GCA effects.

Heterotic grouping of CIMMYT and INERA white lines

Of the 24 lines, 15 were assigned into one heterotic group by either of the two testers under well-watered condition (Table 5). Of these, 10 were classified into anti-VL0511298 heterotic group and five into anti-VL054881 heterotic group. About 42% (10 out of 24) of lines were classified into heterotic group under drought stress with nine lines assigned into anti-VL0511298 heterotic group and one line into anti-VL054881 heterotic group. Four lines (ELN41272, T02058, VL054794, and VL057967) in anti-VL0511298 heterotic group and one line (ELN42444) in the anti-VL054881 group maintained their groups under both water regimes. Anti-VL0511298 heterotic group includes more than 50% of CIMMYT as well as INERA lines compared to anti-VL054881 group under both well-watered and water-stressed conditions.

Heterotic grouping of IITA and INERA yellow lines

Eighty five percent (22 out of 26) of lines were assigned into one heterotic group by either of the two testers in each of the two water regimes (Table 6). Eleven lines were classified into each group under well-watered condition. Twelve lines were assigned into anti-TZEI17 heterotic group and ten into anti-TZEI10 group under drought stress condition.

Seven lines (ELN39382, ELN40791, ELN43574, ELN45111, TZEI146, TZEI151, and TZEI8) in the anti-TZEI17 heterotic group and six lines (ELN39427, TZEI124, TZEI149, TZEI16, TZEI177, and TZEI23) in the TZEI10 group maintained their groups under both water regimes. The distribution of the number of IITA and INERA lines in each of the two groups was fairly equal in well-watered environment. Anti-TZEI17

Table 4 - Percent of corrected total sum of squares from the combined analysis of variance for the testcross hybrids of 26 IITA and INERA yellow and, 24 CIMMYT and INERA white inbred lines evaluated in drought stress condition at Valley du kou, in Burkina Faso, for two years.

Source	DF	GY	EPP	EASP	AD	ASI	PHT	EHT	LR	SEN	LE	TS	PR
White testcross hybrids													
Year		37.05*	1.62***	1.68*	0.88	104.56***	14,501.76***	5,261.49***	29.82***	162***	27.40***	2.26**	341.26***
GCA_{Line}	23	1.12*	0.06	0.20	16.67***	16.672*	333.64	330.04***	0.21	2.44	1.58**	1.07***	2.40***
GCA_{Tester}	1	14.83	0.29	2.92	16.64	16.64	869.47	1,833.47	1.13	0.17	3.52	2.20	5.15
$SCA_{Line\ x\ Tester}$	23	0.40	0.05	0.26	7.79	7.79	322.42	86.81	0.38	1.53	0.48	0.31	1.18
Year $xGCA_{Line}$	23	0.48	0.05	0.33	11.87**	7.039***	304.54	79.37	0.34	1.70	0.43	0.22	0.61
Year x GCA_{Tester}	1	1.97*	0.17*	0.35	26.75*	7.88	33.17	14.67	1.04	1.25	0.98	1.28	0.73
Year x $SCA_{Line\ xTester}$	23	0.38	0.03	0.19	9.43	4.19	306.24	89.15	0.30	1.14	0.41	0.24	0.72
Yellow testcross hybrids													
Year		6.43**	0.84***	1.91*	1,711.68***	7.81	7,548.12***	1,093.67*	56.27***	305.81***	8.48***	3.81***	84.27***
GCA_{Line}	25	0.93	0.04	0.42	35.35**	10.31	540.88	269.98	0.45	2.52	1.45**	0.43	1.72
GCA_{Tester}	1	1.95	0.01	0.01	148.87	9.18	909.96	1,424.87	0.01	0.00	12.69	6.04	5.56*
$SCA_{Line\ x\ Tester}$	25	0.57	0.06	0.33	8.09	6.15	308.90	140.53	0.46	1.78	0.26	0.23	1.56
Year x GCA_{Line}	25	0.76*	0.05	0.77**	12.17	8.29**	520.15	203.10	0.52	2.99	0.46	0.37	1.38
Year x GCA_{Tester}	1	0.37	0.11	0.04	5.15	0.07	308.16	805.95*	2.72	2.10	1.86	1.98	0.01
Year x $SCA_{Line\ xTester}$	25	0.50	0.04	0.35	6.71	3.23	317.68	121.15	0.52	1.80	0.29	0.24	0.93

AD = anthesis-days (50%); ASI = anthesis-silking interval; PHT = plant height; EHT = ear height; EASP = ear aspect; EPP = ear per plant; GY = grain yield (t ha^{-1}); LR = leaves rolling; SEN = leaves senescence; LE = leaves erectness; TS = tassel size; PR = plant recovery.

heterotic group, under drought stress, predominantly contained INERA lines (67%) and anti-TZEI10 group included 60% of IITA lines.

Discussion

The average yield of all the hybrids was 2.4 t ha^{-1} under well-watered condition and 1.4 t ha^{-1} under drought condition. This yield performance was within the range of the yield potential of extra-early and early maturing hybrids reported, under similar condition. Akaogu et al (2012) obtained a mean of 2.8 and 1.7 t ha^{-1} for hybrids created with extra-early inbred lines in Striga free and Striga infested environments, respectively. CIMMYT mid-altitude early maturing hybrids were evaluated under drought, low nitrogen and optimum conditions and the mean yield of the trials was 2.1, 3.2, and 8.3 t ha^{-1} respectively (Pswarayi and Vivek, 2008). Grain yield of some hybrids evaluated in this study across trials were superior compared to the best local commercial check (Sanem). However the actual yield of Sanem in these trials was very low compared to its yield potential estimated at 10.5 t ha^{-1}. This difference could be explained by the dry and cold weather which affected the yield performance of all the hybrids evaluated and also the low plant density. The use of elite inbred lines with known heterotic patterns as testers to classify inbred lines into opposite heterotic groups was suggested (Melchinger and Gumber, 1998; Melchinger, 1999) and used routinely, especially in private sector breeding programs. The four testers, two each from CIMMYT (VL051128 and VL054881) and IITA (TZEI17 and TZEI10) used in this study, correspond to two opposite heterotic groups which have been identified and used in CIMMYT and IITA maize breeding programs. The two white and two yellow testers exhibited contrasting GCA effects in both well-watered and water-stressed environments.

The two CIMMYT testers classified 63% of the 24 CIMMYT and INERA white lines into complementary heterotic groups based on SCA effects and grain yield of the testcrosses in well-watered condition and 42% under drought stress. Of these, means grain yield of 12 hybrids, under well-watered environment, and two hybrids, under drought stress, were higher than that of the best commercial check (Sanem) by 10%. On the other hand, the two IITA testers were able to separate 85% of the IITA and INERA yellow lines into two contrasting heterotic groups in both water regimes based on SCA effects and grain yield of the testcrosses. But only five hybrids, under well-watered condition, and three hybrids, in water-stressed condition, yielded about 10% more than the best commercial check. The outstanding hybrids over the best commercial check could be released for commercial use and or include into three way and double cross hybrids breeding program. The testers were not previously evaluated for local adaptation, however they classified both local and exotic lines. The proportion of local and exotic lines in the two opposite heterotic groups tended to be similar indicating that the grouping of the lines was not based on the origin (breeding program) of the lines but on the heterotic reaction between the testers and lines. This suggests that the testers used in the present study could be used in INERA maize breeding program to evaluate local as well as CIMMYT and IITA lines for combining ability estimates and heterotic patterns. Although the number of local and exotic inbred lines used in this study was rather low, the results show that the CIMMYT lines derived from source population with Tuxpeño background and from biparental crosses tend to be in the opposite heterotic group of the tester, VL0511298 (group A). Two line (VL057967 and VL058025) with Tuxpeño background and two lines (T02058 and VL054794) derived from biparental crosses had consistently positive SCA effect in crosses with tester, VL0511298 (group A) in both well-watered and water-stressed environments and

Table 5 - Mean grain yields, general combining ability (GCA) and specific combining ability (SCA) effects for 13 CIMMYT and 11 INERA white lines in testcrosses with two testers under well-watered and drought stress conditions at Valley du kou, for two years.

	Well-watered condition					Water-stressed condition				
	Grain Yield (t ha-1)					Grain Yield (t ha-1)				
Lines	VL0511298 (A)	VL054881 (B)	GCA effects (t ha-1)	SCA effects with VL0511298	Heterotic group	VL0511298 (A)	VL054881 (B)	GCA effects (t ha-1)	SCA effects with VL0511298	Heterotic group
ELN41111	2.03	2.13	-0.27	-0.22	NA	1.48	1.4	-0.07	-0.19	NA
ELN41112	2.20	1.73	-0.39	0.06	NA	1.35	1.19	-0.24	-0.15	NA
ELN41114	1.54	1.30	-0.92	-0.06	NA	0.74	1.17	-0.56	-0.44	NA
ELN41115	2.03	1.43	-0.62	0.13	NA	1.92	0.89	-0.11	0.28	antiA
ELN41271	2.42	2.2	-0.04	-0.06	NA	2.28	1.44	0.35	0.19	antiA
ELN41272	2.59	2.15	0.02	0.06	antiA	2.07	1.46	0.25	0.07	antiA
ELN42441	2.93	2.36	0.29	0.12	antiA	1.72	1.3	0	-0.02	NA
ELN42442	2.51	3.22	0.52	-0.52	antiB	2.08	1.46	0.26	0.08	antiA
ELN42444	2.16	2.91	0.18	-0.54	antiB	1.63	1.83	0.22	-0.33	antiB
ELN42445	2.74	1.98	0.01	0.21	antiA	1.83	1.45	0.13	-0.04	NA
ELN48392	2.82	0.99	-0.45	0.75	antiA	1.57	0.72	-0.36	0.20	NA
T02058	2.73	2.05	0.04	0.17	antiA	2.27	1.6	0.42	0.10	antiA
VL0511247	2.24	2.91	0.25	-0.53	antiB	1.94	1.47	0.14	0.05	antiA
VL0512593	2.11	1.80	-0.4	-0.01	NA	1.41	1.11	-0.25	-0.08	NA
VL054794	3.00	1.93	0.11	0.37	antiA	2.48	1.58	0.52	0.22	antiA
VL05615	2.92	2.24	0.23	0.18	antiA	1.5	1.09	-0.22	-0.03	NA
VL05616	2.47	2.67	0.22	-0.27	antiB	2.23	1.25	0.23	0.26	antiA
VL057903	2.55	2.62	0.24	-0.2	antiB	1.37	1.11	-0.27	-0.10	NA
VL057967	3.17	2.48	0.47	0.18	antiA	2.49	1.59	0.53	0.22	antiA
VL058014	3.06	2.41	0.38	0.16	antiA	1.48	1.12	-0.21	-0.05	NA
VL058025	3.24	2.64	0.59	0.14	antiA	1.59	0.96	-0.24	0.09	NA
VL058589	2.51	2.00	-0.09	0.09	NA	1.43	0.97	-0.31	0.00	NA
VL081464	2.46	2.07	-0.09	0.02	NA	1.75	1.58	0.15	-0.14	NA
VL081466	1.97	2.05	-0.34	-0.21	NA	1.29	1.13	-0.31	-0.15	NA
VLAxVLB	2.34	2.34					1.55	1.55		
Bondofa	1.39	1.39					1.16	1.16		
Sanem	2.45	2.45					2.17	2.17		
Mean	2.47	2.16	0	0			1.73	1.32	0	0
SE	0.29	0.29	0.26	0.26			0.22	0.22	0.19	0.17

SE = standard error; VLA x VLB = VL0511298 x VL054881; antiA = anti-VL0511298 (or opposite group of VL0511298); antiB = anti-VL054881 (or opposite group of VL054881); NA = not assigned.

the hybrids out-yielded hybrid between testers by 10%. This finding is not in agreement with earlier observations indicating that CIMMYT group A exhibits heterosis similar to N3, Tuxpeño, Kitale and Reid; and group B exhibits heterosis similar to SC, ETO Blanco, Ecuador and Lancaster (Mickelson et al 2001; Pswarayi and Vivek, 2008). Tester, TZEI17 derived from TZE COMP5-Y population, showed consistent positive SCA effects with three IITA lines (TZEI 151, TZEI 146, and TZEI 8) derived from the same population as tester TZEI10, TZE-Y Pop DT STR, in both water regimes. It produced hybrids that yielded between 255 and 1350 kg ha^{-1} better than TZEI17 x TZEI10. In parallel, three lines (TZEI124, TZEI149, and TZEI23) derived from the same population as tester TZEI10 and 2 lines (TZEI16 and TZEI177) derived from the source population as tester TZEI17, exhibited a consistent positive SCA effects in crosses with TZEI10 in both well-watered and water stressed environments and the hybrids out-yielded hybrid between testers by 10%. These results suggest that the two source populations could be regarded as two broad opposite heterotic groups. The white and yellow INERA lines extracted from the same source, FBC6, showed diverse heterotic response with both CIMMYT testers as well as both IITA testers. These inbred lines were classified into different heterotic groups, confirming the mixed genetic background of the source population. This was expected since the composite FBC6 (source population) was developed from the mixture of eight different varieties with different genetic composition and geographical origin. Out of the lines that were separated into heterotic groups, 48% of exotic lines (CIMMYT, IITA) and 65% of local lines (INERA) did not show consistent heterotic classification between well-watered and water-stressed environments. Knowing that the exotic lines were selected for drought resistance contrary to local lines, this result could suggest that the heterotic patterns of the lines are less affected by the effect of the environment when they carry favourable alleles for a stress or have broad adaptation.

More than 50% of the inbred lines had consistent positive or negative GCA effects for grain yield in the two evaluation environments. However, only 2 white lines (VL058025 and ELN42442) and four yellow lines (ELN431251, ELN43574, ELN45111, and TZI18) had significant positive GCA effects for grain yield in the well-watared environment. Inbred line, ELN43574 had significant positive GCA effects for grain yield in well-watered as well as water-stressed conditions. The adapted inbred lines having significant positive GCA effects for grain yield, may be used as a testers in establishing heterotic patterns for the grain yield of local inbred lines.

The results of these experiments indicate that exotic testers with contrasting heterotic response could be used to separate adapted and exotic inbred

Table 6 - Mean grain yields, general combining ability (GCA) and specific combining ability (SCA) effects for 14 IITA and 12 INERA yellow lines in testcrosses with two testers under well-watered and drought stress conditions at Valley du kou, for two years.

Lines	Well-watered condition					Water-stressed condition				
	Grain Yield (t ha^{-1})					Grain Yield (t ha^{-1})				
	TZEI17 (A)	TZEI10 (B)	GCA effects (t ha^{-1})	SCA effects with TZEI17	Heterotic group	TZEI17 (A)	TZEI10 (B)	GCA effects (t ha^{-1})	SCA effects with TZEI17	Heterotic group
ELN39382	2.8	1.80	-0.26	0.53	antiA	1.48	0.87	-0.19	0.23	antiA
ELN39427	1.84	2.84	-0.18	-0.51	antiB	1.68	2.12	0.55	-0.32	antiB
ELN402213	1.78	2.98	-0.13	-0.62	antiB	1.66	1.34	0.12	0.10	antiA
ELN40791	2.73	2.79	0.20	0.00	antiA	1.90	1.59	0.38	0.08	antiA
ELN40823	1.93	2.12	-0.55	-0.05	NA	1.20	1.84	0.12	-0.37	antiB
ELN40941	3.07	2.68	0.31	0.23	antiA	1.65	1.58	0.25	-0.04	antiB
ELN431251	3.36	2.72	0.48	0.36	antiA	1.37	1.28	-0.04	-0.03	antiB
ELN43453	2.04	2.16	-0.47	-0.03	NA	0.86	1.09	-0.38	-0.20	NA
ELN43574	3.2	2.75	0.41	0.25	antiA	2.37	1.80	0.72	0.21	antiA
ELN45111	3.41	2.9	0.60	0.29	antiA	1.84	1.37	0.24	0.16	antiA
ELN462121	2.19	2.34	-0.29	-0.04	NA	0.94	0.95	-0.42	-0.08	NA
ELN464171	2.74	3.00	0.31	-0.10	antiB	1.79	0.95	0.00	0.34	antiA
ELN47132	1.96	2.8	-0.18	-0.38	antiB	1.18	1.03	-0.26	0.0003	antiA
FBML10	2.58	3.60	0.36	-0.31	antiB	1.51	1.16	0.03	0.04	antiA
TZEI124	2.51	3.36	0.38	-0.39	antiB	1.15	1.59	0.02	-0.31	antiB
TZEI146	2.87	2.46	0.10	0.24	antiA	1.83	0.9	0.00	0.39	antiA
TZEI148	2.64	2.07	-0.21	0.31	antiA	1.35	1.39	0.00	-0.09	antiB
TZEI149	2.22	2.56	-0.17	-0.13	antiB	1.25	1.54	0.03	-0.22	antiB
TZEI151	2.79	2.31	-0.06	0.32	antiA	2.41	1.74	0.70	0.26	antiA
TZEI158	2.21	2.21	-0.35	0.04	NA	1.73	0.62	-0.19	0.48	antiA
TZEI16	1.97	2.37	-0.39	-0.17	antiB	0.60	1.27	-0.43	-0.41	antiB
TZEI161	2.79	2.28	-0.03	0.29	antiA	0.93	1.03	-0.39	-0.12	NA
TZEI177	1.97	2.45	-0.35	-0.21	antiB	1.25	1.22	-0.14	-0.06	antiB
TZEI23	2.22	2.66	-0.12	-0.19	antiB	1.35	1.35	-0.02	-0.08	antiB
TZEI8	2.67	2.55	0.05	0.09	antiA	1.31	0.93	-0.25	0.12	antiA
TZI18	3.00	3.31	0.59	-0.13	antiB	0.84	0.85	-0.52	-0.08	NA
TZEI17xTZEI10	2.12	2.12					1.06	1.06		
Bondofa	1.51	1.51					1.08	1.08		
Sanem	2.93	2.93					2.08	2.08		
Mean	2.48	2.57	0	0			1.44	1.3	0	0
SE	0.25	0.25	0.2	0.23			0.25	0.25	0.25	0.20

SE = standard error; antiA = anti-TZEI17 (or opposite group of TZEI17); antiB = anti-TZEI10 (or opposite group of TZEI10).

lines into complementary heterotic groups. The heterotic patterns observed in this study suggests that the adapted inbred lines would produce high yielding hybrids under drought and non-drought conditions when crossed with CIMMYT or IITA inbred lines of the opposite heterotic group. The exotic lines would contribute favourable alleles for yield potential and stress tolerance. The two groups of adapted and exotic inbred lines with opposite heterotic response can be inter-crossed separately to provide two complementary populations (Vasal et al, 1992). The use of such complementary populations would facilitate the development of superior hybrids, as lines extracted from one population would be expected to combine well with the lines from the opposite complementary population (Menkir et al, 2003). Another option would be to select within each heterotic group lines having specific traits of interest that the tester and other lines lack. Each of these lines could, then, be crossed in pair wise combinations to produce source populations and new lines selected for combinations of desirable traits.

Elite inbred lines identified among INERA, CIMMYT and IITA lines, with consistently positive GCA and SCA effects across stress-free and drought conditions could have broad utility in local maize breeding program. The extreme changes in heterotic response of some INERA lines (non drought tolerant) under drought stress and well-watered conditions underscore the need to develop beforehand tolerant lines which would will be more likely to express consistent heterotic response under unpredictable rainfall conditions.

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References

Akaogu C, Badu-Apraku B, Adetimirin OV, Vroh-Bi I, Oyekunle M, and Akinwal RO, 2012. Genetic diversity assessment of extra-early maturing yellow maize inbreds and hybrid performance in Striga-infested and Striga-free environment. Journal of Agricultural Science, 151: 519–537

Bänziger M, Diallo AO, 2001. Stress-tolerant Maize for Farmers in Sub-Saharan Africa, pp. 1-8. In: Maize research highlights 1999-2000. CIMMYT, Mexico

Cheres MT, Miller JF, Crane JM, Knapp, SJ, 2000. Genetic distance as a predictor of heterosis and hybrid performance within and between heterotic groups in sunflower. Theor Appl Genet 100: 889-894

Dhliwayo T, Pixley K, Menkir A, Warburton M, 2009. Combining ability, genetic distances, and heterosis among elite CIMMYT and IITA tropical maize inbred lines. Crop Sci 49: 1201-1210

Gutiérrez-gaitan MA, Cortez-mendoza H, Wathika EN, Gardner CO, Oyervides-garcía M, Hallauer AR, Darrah L, 1986. Testcross evaluation of Mexican maize populations. Crop Sci 26: 99-104

Hallauer AR, Miranda JB, 1988. Quantitative genetics in maize breeding, 2nd edition. Iowa State University Press, Ames

Kim SK, Ajala SO, 1996. Combining ability of tropical maize germplasm in West Africa II. Tropical vs Temperate x Tropical origins. Maydica 41: 135-141

Melchinger AE, 1999. Genetic diversity and heterosis, pp. 99-118. In: The genetics and exploitation of heterosis in crops, Coors JG, Pandey S, eds. CSSA-SP WI, Madison

Melchinger AE, Gumber RK, 1998. Overview of heterosis and heterotic groups in agronomic crops, pp. 29-44. In: Concepts and Breeding of Heterosis in Crop Plants. Lamkey KR, Staub JE, eds. CSSA, Madison

Menkir A, Badu-Apraku B, The C, Adepoju A, 2003. Evaluation of heterotic patterns of IITA's lowland white maize inbred lines. Maydica 48: 161-170

Pswarayi A, Vivek BS, 2008. Combining ability amongst CIMMYT's early maturing maize *Zea mays* L germplasm under stress and non-stress conditions and identification of testers. Euphytica 162: 353–362

Rawlings JO, Thompson DL, 1962. Performance level as criterion for the choice of maize testers. Crop Sci 2: 217-220

Russell WA, 1991. Genetic improvement of maize yields. Advances in Agronomy 46: 245-298

SAS Institute, 2002. SAS/STAT 9 user's guide. SAS Inst, Cary, NC

Singh RK, Chaudhary BD, 1985. Biometrical Methods in Quantitative. Genetics Analysis. Second edition. Kalyani Publishers, New Delhi

Vasal SK, Srinivasan G, Gonzalez F, Becker DL, Crossa J, 1993. Heterosis and combining ability of CIMMYT quality protein maize germplasm. II. Subtropical. Crop Sci 33: 51-57

Vasal SK, Srinivasan G, Pandey S, Cordorva HS, Han GC, Gonzalez FC, 1992. Heterotic patterns of ninety-two white tropical CIMMYT maize lines. Maydica 37: 259-270