Comparative performance and genotype by environment interaction effects on grain yield of single and multiple crosses of maize (*Zea mays* L.)

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Abstract

A set of 256 entries involving seven parents and their single, three-way and double crosses derived through half diallel were evaluated along with private/public hybrids for grain yield in a balanced lattice design at three environments during *kharif* 2015. ANOVA revealed that TWC × Parents, DC × TWC, DC × SC, DC × Parents, SC × Parents interaction were significant at all the locations. Mean squares for singles, double and three-way crosses were similar at Hyderabad, Karimnagar locations and at Palem location with high mean squares for three-way crosses. Data were also obtained on the variety × environment interaction patterns for the three types of crosses. Significant interaction deviate was higher for double crosses followed by three-way crosses and single crosses. Average yield of double crosses was 37 kg ha^{-1} greater than that for single crosses, and the average for single crosses was 143 kg ha^{-1} greater than for three-way crosses. The range of single crosses was 483 kg ha^{-1} less than that for three-way crosses and 30 kg ha^{-1} greater than that for double crosses. Stability analysis for grain yield showed significant genotype × environment interaction in all the three classes of hybrids and the crosses (BML-51 × BML-10) × (BML-6), (BML-51 × BML-32) × (BML-13 × BML-6) and (BML-13 × BML-7) × (BML-10 × BML-6) were found to be stable, had average response to all environments, hence these are need to be exploited to combat biotic and abiotic stresses arising through climate change.

KeyWords *Maize, hybrids, interaction deviate, genotype environment interaction, grain yield*

Introduction

In India during 2016, maize was cultivated in an area of 10.2 million hectares with a production of 26.26 million metric tonnes and productivity of 2.57 tonnes ha^{-1} (FAOSTAT, 2016).Seed production of single cross hybrids in maize is not economically feasible due to high cost of cultivation. In 1918, Jones suggested the use of Double crosses (DC) to overcome the seed production problems of single crosses. Hence, in the initial phase of maize crop improvement, hybrid seed corn industry developed majorly on the use of double crosses. Later with the advent of modern seed production technologies and identification of promising inbreds with good general combining abilities (Jones, 1958), the cost of single cross seed was reduced (Eberhart, 1969) and single crosses became commercially available to the farming community. This was clearly evident with the increase in the use of single crosses at the expense of double crosses in the united states corn belt area (Weatherspoon, 1970) and later spread to the remaining world. Previous research indicated that single crosses outperform double crosses and three-way crosses (Eberhart, 1969; Eberhart and Russel, 1969; Weatherspoon, 1970). In India, since 1990's single cross hybrids became popular and it occupies nearly 100 % maize cultivated area. In the newly formed state of Telangana, entire maize grown area is occupied with single cross hybrids.

Average yield of hybrid is not only the criterion to estimate its performance. Moreover, the consistence superiority across the years and locations is much more important to benefit the seed producers with the constant supply of corn every year. Allard and Bradshaw (1964) discussed two ways of achieving stability. If a hybrid or population is composed of a number of different genotypes such as for three-way and double crosses, it could possess population buffering; if a hybrid such as single cross is composed of members all alike, but each member is adapted to a wide range of environments, it possess individual buffering. Population buffering is the most effective method to attain stability (Weatherspoon, 1970), Eberhart and Russell (1969). However, Allard (1961) and Eberhart and Russell (1969) have pointed out the importance of individual buffering and suggest that it is an inherited characteristic in certain genotypes.

Eberhart and Russell (1969) presented data for yield and stability for a 10-line diallel of single cross and double cross hybrids grown at 12 locations over a 2-year period in a total of 21 environments. Yield levels varied from 30 to 97.8 q/ha. Their measures for stability were the regression of individual hybrid yields at each environment on the mean of all hybrids, and the mean square of deviations from the regression line for each hybrid. In general, they found single crosses to be less stable than double crosses but they emphasized that some single crosses were just as stable as the best double crosses. Eberhart et al (1964) compared single and three-way crosses in the same experiment and reported crosses × year interactions were significantly greater for single crosses than for three- way crosses.

Detailed summaries and comparisons of the statistics involved in calculating stability by means of regression and deviations from regression are presented elsewhere (Finlay and Wilkinson, 1963; Eberhart and Russell, 1966; Bucio Alanis, 1966; Baker, 1969; Fripp and Caten, 1971; Hardwick and Wood, 1972). Hence, the statistical methods will not be dealt with in detail here. Mather (1949) proposed a method that was later adapted by Bucio Alanis (1966) and Bucio Alanis and Hill (1966) to evaluate inbred lines of *Nicotiana rustica* and their offspring. This method involved partitioning the quantitative data according to genetic and environmental effects and the interaction of these.

Finlay and Wilkinson (1963) used regression analysis to measure the stability of a group of barley introductions over years and locations. They computed the regression, across all locations, of each entry on the mean yield of all entries at that location. From this a range of regression coefficients (b) was established for the entries. They concentrated on the identification of cultivars adapted to high-yielding environments (high b-values) or those adapted to low-yielding environments (small b-values). This technique was subsequently used by Eberhart and Russell (1966) in evaluation of several series of corn hybrids. Their definition of a stable cultivar included a small deviation from regression as well as a high mean yield and unit regression coefficient.

The present study was undertaken (1) to determine the relative yields of single, three-way, and double crosses, and (2) to investigate the cross × environment interaction pattern for the three types of crosses. Stability of performance is defined by three parameters: mean yield, regression of mean yield on location averages, and the standard error of this regression.

Materials and Methods

Site description

The present investigation was carried out at three main research centres of Professor Jayashankar Telangana State Agricultural Univeristy, Telangana, India during kharif season of 2015. Agricultural Research Station, Karimnagar is located in Northern Telangana agro climatic zone of Telangana state. Geographically, it lies at 18°30'N latitude, 79°15'E longitude with an altitude of 259.15 meters above Mean Sea Level (MSL).The average rainfall of the Research Station is 994 mm. The soils are red sandy loam type with pH of 6.64. Source of irrigation water is from Sri Ram Sagar Project (SRSP) and open wells.

Maize Research Centre, Agricultural Research Institute, Rajendranagar, Hyderabad is located in Southern Telangana agro climatic zone of Telangana state. Geographically, it lies at 17°18'N latitude, 78°23'E longitude with an altitude of 542 meters above Mean Sea Level (MSL).The average rainfall of the Research Station is 831 mm. The soils are medium black type with pH of 7.2. Main source of irrigation water is from open well/ bore wells.

Regional Agricultural Research Station, Palem is located in Southern Telangana agro climatic zone of Telangana state. Geographically, it lies at 16°35'N latitude, 78°1'E longitude with an altitude of 662 meters above Mean Sea Level (MSL).The average rainfall of the Research Station is 772 mm. The soils are red sandy loams type with pH of 6 to 7. Source of irrigation water is from bore wells and farm pond.

Genetic material and breeding activities

To study the *per se* and stability of single, three-way and double crosses, seven promising inbred lines of maize *viz.*, BML-51, BML-32, BML-14, BML-13, BML-10, BML-7 and BML-6 developed from Maize Research Centre, Rajendranagar, Hyderabad (Table 1) were crossed in half diallel fashion and obtained twenty one crosses during *kharif*, 2014. Later these F1's were involved in crosses with inbreds such that no parent appears twice in the same cross and obtained 105 three-way crosses. Similarly, single crosses were involved in diallel set with restriction that only unrelated crosses were involved in crossing programme and obtained 105 double crosses. Single crosses were obtained during *kharif* 2014 while three-way crosses and double crosses were obtained during rabi 2014-15 at ARS, Karimnagar.

Experimental layout

During *kharif*, 2015, the experimental material comprised of seven parents, twenty one single crosses and 105 each three-way and double crosses and eighteen public /private checks were evaluated at three diverse agro climatic locations viz. MRC, ARI, Rajendranagar, ARS, Karimnagar and RARS, Palem, the main research

Table 1 Origin and descriptions of the maize inbred lines used in the study

Sl. No.	Inbred line	Pedigree	Days to 50% silking (days)	Maturity group.	Grain type	color
1	BML-51	JCY 2-7-1-2	62.5	Late	Semi-flint	Orange with cap
2	BML-32	SRRL 68-B46-1-1-2- # -1-2-1-Ä-1-1-Äb-Äb	61.5	Late	Semi-flint	Yellow with cap
3	BML-14	CO1B 96k-1-#-1-2-×b-1-2-×b-×b-2	64.2	Late	Flint	Dark orange
4	BML-13	[×2Y Pool × MMH 9607]-B 98k-2-1-3-1-Ä-Ä-Äb-Äb-Äb-Äb	57.5	Medium	Semi-dent	Yellow with cap
5	BML-10	[×2Y Pool × Suman 1 (T)]-B 98k-1-2-1-1-2-3-Ä-2-Ä-1-Äb-Äb-Äb	54.7	Medium	Flint	Pinkish orange
6	BML-7	[×2Y Pool × CML 226]-B 98 R-1-1-1-Äb-Äb-Äb-Äb-Äb-Äb	63.3	Late	Flint	Orange
7	BML-6	SRRL 65-B96-1-1-2- # -2-2-1-Ä-1-1-Äb-Äb	62.7	Late	Semi-flint	Yellow

centres of Professor Jayashankar Telangana State Agricultural University (PJTSAU). All these 256 entries were laid out in balanced lattice (16 × 16) in two replications at each location and each entry was sown in two rows of 3 m length with 75 cm row to row spacing and 20 cm plant to plant spacing. All the intercultural operations were carried out in accordance with the recommended schedule (Vyavasaya panchangam, 2015).

Data collection and analysis

Grain yield was recorded plot-wise (kg plot^{-1}) and was corrected for stand variation using the methodology of covariance, as suggested by Mendes (2015), correction was for expected stand (Se=30) for individual plots using the formula Yc= Yo+ b (Se – So), where Yc is the corrected yield, Yo is the observed yield, b is the linear regression coefficient of Yo over the variation of the observed stand (So). Further, this hand harvested shelled corn of each entry was adjusted to 15.5 moisture in kg ha^{-1} similar to grain yield in bushels per acre at 15.5 moisture as suggested by Joe Lauer (2002).

The gain in efficiency for lattice design was small over a randomized block design (Eberhart et al, 1966). Hence, in the present study also 16 × 16 balanced lattice was analyzed as Randomized Block Design to avoid confounding of the mean square expectations for the analysis of variance. Of the eighteen private/public checks tested, only five widely adapted/newly released checks viz. NK 6240, 900MGold, Ekka 2288, DHM-117 and KNMH-4010131 *i.e.*, former three private checks and the later two public checks were used in computing statistical analysis. Statistical analysis was done for 243 entries *i.e.*, seven parents, twenty one single crosses, 105 each three-way and double crosses and five high yielding checks.

Analysis of variance was conducted on the means of the hybrid types in each location. For each hybrid of particular group, the mean yield was regressed against the mean yield of all hybrids in that particular group. This will give a b-value of 1.00 and a standard deviation of the b-value of 0.0 for the average of all hybrids in each hybrid group across all locations. Standard errors of each b-value were calculated.

The cross × environment interaction pattern for the three types of hybrids was investigated by calculating interaction deviates for each entry of each type of hybrid separately. The calculation of the deviates was as follows: Interaction Dev. = Cross Environment Mean – (Environment Mean + Cross Deviation from General Mean) or Dev. = Xij – Xi. –X.j + X.. for the i th environment and jth cross. The standard deviation for the deviates was estimated as $\sqrt{\sigma^2}$ Xij + σ^2 X. j. σ^2 X i. and σ^2 X.. were very small and for this reason were not included in the estimate of error for the deviates. Stability analysis was done separately for diallel, triallel and quadriallel crosses as per Eberhart and Russell (1966) using INDOSTAT software

Table 2 Analysis of variance for yield at individual locations

Source	d.f.	Hyderabad	Karimnagar	Palem
Replicates	1	643391.94	227176.05	9186.77
Varieties	242	2904540.00**	2249385.25**	2164733.00**
Double	104	1969411.00**	1001953.13**	1411618.63**
Triple	104	1725177.25**	1603902.63**	1901749.00**
Single	20	1689208.75**	1847245.75**	1473535.88**
Parent	6	132622.83	596309.94	478154.56
Cross	4	1830027.88**	1753354.88**	2299516.25**
Double Vs Triple	1	8411043.00**	4544592.00**	242832.86
Double Vs Single	1	6398606.50**	5226961.50**	813562.13
Double Vs Parent	1	255195680.00**	224424016.00**	135077648.00**
Double Vs Cross	1	4880915.00**	92675.08	3774.67
Triple Vs Single	1	17673332.00**	1113989.13	381268.84
Triple Vs Parent	1	223486848.00**	20240985.00**	131058232.00**
Triple Vs Cross	1	1781803.63	114472.30	7593.49
Single Vs Parent	1	245668816.00**	147549392.00**	98034952.00**
Single Vs Cross	1	10545583.00**	669533.63	141963.61
Parent Vs Cross	1	79616784.00**	95047128.00**	59292548.00**
Error	242	510617.78	489322.78	498574.25

Table 3 Yields and interaction deviates for 21 single-crosses

Entry	Interaction deviates and kg ha^{-1} at each environment			Cross means and dev. from mean kg ha^{-1}
	Hyderabad	Karimnagar	Palem	
BML-51 × BML-32	8710(999*)	6466(-360)	7500(-639)	7559
BML-51 × BML-14	8746(-140)	8553(553)	8900(-414)	8733
BML-51 × BML-13	8085(751)	5562(-887)	7899(136)	7182
BML-51 × BML-10	6090(-966*)	6489(318)	8132(648)	6903
BML-51 × BML-7	7763(-187)	7444(379)	8187(-191)	7798
BML-51 × BML-6	7687(-562)	6961(-402)	9641(964)	8096
BML-32 × BML-14	5928(-890)	5941(7)	8130(883)	6666
BML-32 × BML-13	7938(149)	7397(493)	7576(-641)	7637
BML-32 × BML-10	7475(274)	4561(-1754*)	9109(1480*)	7048
BML-32× BML-7	6761(-275)	5551(-600)	8340(875)	6884
BML-32 × BML-6	7968(14)	7815(746)	7622(-760)	7801
BML-14 × BML-13	7689(198)	7046(441)	7280(-639)	7338
BML-14 × BML-10	6798(-293)	6717(512)	7301(-218)	6938
BML-14 × BML-7	7551(-186)	7400(548)	7804(-361)	7585
BML-14 × BML-6	7467(495)	5348(-740)	7645(245)	6820
BML-13 × BML-10	6393(32)	6076(600)	6156(-633)	6208
BML-13 × BML-7	6971(435)	5391(-260)	6789(-175)	6383
BML-13 × BML-6	6990(-133)	5901(-337)	8021(470)	6971
BML-10 × BML-7	8642(1142*)	6434(-181)	6967(-961)	7347
BML-10 × BML-6	6381(-13)	6090(581)	6253(-568)	6241
BML-7 × BML-6	5525(-843)	5826(343)	7296(500)	6215
Mean	7312	6427	7740	7160
SD for yield	904	955	919	216
SD for deviation	922	1035	985	

*significant at 0.05 level

Results

In the analysis of variance all mean squares are highly significant for all the three types of hybrids *i.e.* ., single, three-way and double crosses at all the three locations (Table 2). TWC × Parents, DC × TWC, DC × SC, DC × Parents, SC × Parents interaction were significant at all the environments and where as TWC × SC interaction was significant at Hyderabad location. This indicates there are clear cut differences in the yield performance among single, three-way and double crosses. The mean squares for singles, doubles and three-way crosses were almost similar at Hyderabad location where as at Karimnagar single crosses and at Palem location three-way crosses had high mean square values.

Yields at each environment, mean yields and interaction deviates for the 21 single crosses are given in Table 3. Corresponding tables were prepared for the 105 each three-way and double crosses (data not shown). Single crosses had 5 significant deviates (8%), three-ways had 71 significant deviates (23%), and doubles had 99 significant deviates (31%). Performance of top ten high yielding single/three-way/double crosses at each location was presented in Table 4. At Karimnagar location of the 243 entries tested, none of the entry was found significantly superior for grain yield against the high yielding checks KNMH-4010131 (7324 kg ha^{-1}) and Ekka-2288 (7866 kg ha^{-1}). However over DHM-117 (6722 kg ha^{-1}), one double cross and four three-way crosses gave significantly superior and one each single (8553 kg ha^{-1}) and double cross hybrids (8549 kg ha^{-1}) gave highly significant superior grain yields. At Hyderabad location, three-way cross hybrid (BML-32 × BML-14) × BML-51 yielded 9090 kg ha^{-1} and was found to be significantly superior in grain yield over the highest yielding check NK-6240 (7597 kg ha^{-1}). Over popular public check DHM-117 (6604 kg ha^{-1}), one three-way cross, three single crosses and eight double crosses recorded significantly superior grain yields. At Palem location, none of the hybrid gave significantly superior grain yield over the highest yielding check KNMH-4010131 (9502 kg ha^{-1}) and Ekka-2288 (8134 kg ha^{-1}), a widely grown private hybrid in Mahaboobnagar district. But one single cross, three double crosses and five three-way crosses yielded numerically superior grain yields over check KNMH-4010131 and significantly superior grain yields over check Ekka-2288.

Yield data pooled over the locations indicated that, the average yield of double crosses was 37 kg ha^{-1} greater than that for single crosses and the average yield for single crosses was 143 kg ha^{-1} in excess of three-way crosses (Table 5). The best single cross was 338 kg ha^{-1} above the best three-way cross and 371 kg ha^{-1} above the best double cross based on the yield data across the locations. The poorest single cross was 821 kg ha^{-1} in excess over the poorest three-way cross and 341 kg ha^{-1} in excess over the poorest double cross. The range of single crosses was 483 kg ha^{-1} less than that for three-ways and 30 kg ha^{-1} greater than that for double crosses.

The average maximum hybrid × environment interaction deviate for singles was 239 kg ha^{-1} greater than that for three-ways and 341 kg ha^{-1} greater than that for doubles (Table 5).

For each hybrid of particular hybrid type, the mean yield of hybrid was regressed against the mean yield of all hybrids in that hybrid group. This will give a b-value of

Table 4 Top ten high yielding single, three-way and double crosses at Hyderabad, Karimnagar and Palem locations

		Single crosses			
Hyderabad		Karimnagar		Palem	
Entry	kg ha^{-1}	Entry	kg ha^{-1}	Entry	kg ha^{-1}
BML-51 × BML-14	8746	BML-51 × BML-14	8553	BML-51 × BML-6	9641
BML-51 × BML-32	8710	BML-32 × BML-6	7815	BML-32 × BML-10	9109
BML-10 × BML-7	8642	BML-51 × BML-7	7444	BML-51 × BML-14	8900
BML-51 × BML-13	8085	BML-14 × BML-7	7400	BML-32 × BML-7	8340
BML-32 × BML-6	7968	BML-32 × BML-13	7397	BML-51 × BML-7	8187
BML-32 × BML-13	7938	BML-14 × BML-13	7046	BML-51 × BML-10	8132
BML-51 × BML-7	7763	BML-51 × BML-6	6961	BML-32 × BML-14	8130
BML-14 × BML-13	7689	BML-14 × BML-10	6717	BML-13 × BML-6	8021
BML-51 × BML-6	7687	BML-51 × BML-10	6489	BML-51 × BML-13	7899
BML-14 × BML-7	7551	BML-51 × BML-32	6466	BML-14 × BML-7	7804
		Three-way crosses			
Hyderabad		Karimnagar		Palem	
(BML-32 × BML-14) × BML-51	9090*	(BML-51 × BML-10) × BML-6	8313	(BML-32 × BML-6) × BML-51	10463
(BML-10 × BML-6) × BML-14	8331	(BML-32 × BML-6) × BML-14	8284	(BML-14 × BML-6) × BML-51	10172
(BML-32 × BML-14) × BML-13	8280	(BML-51 × BML-32) × BML-13	8240	(BML-13 × BML-7) × BML-32	10125
(BML-51 × BML-13) × BML-6	8035	(BML-14 × BML-7) × BML-32	8222	(BML-51 × BML-14) × BML-32	9938
(BML-7 × BML-6) × BML-51	8010	(BML-32 × BML-6) × BML-51	8028	(BML-51×BML-14) × BML-7	9541
(BML-13 × BML-10) × BML-6	8001	(BML-51×BML-7) × BML-6	7942	(BML-51 × BML-14) × BML-6	9428
(BML-51 × BML-7) × BML-6	8000	(BML-51 × BML-7) × BML-14	7870	(BML-14 × BML-13) × BML-7	9250
(BML-7 × BML-6) × BML-32	7997	(BML-7×BML-6) × BML-51	7791	(BML-51 × BML-10) × BML-6	9129
(BML-32 × BML-13) × BML-14	7992	(BML-51 × BML-7) × BML-32	7788	(BML-51 × BML-7) × BML-13	9003
(BML-51 × BML-32) × BML-13	7881	(BML-14 × BML-10) × BML-6	7769	(BML-14 × BML-10) × BML-6	8965
		Double crosses			
Hyderabad		Karimnagar		Palem	
(BML-14 × BML-6) × (BML-13 × BML-7)	8891	(BML-51 × BML-6) × (BML-32 × BML-10)	8549	(BML-51 × BML-14) × (BML-10 × BML-7)	10054
(BML-14 × BML-13) × (BML-10 × BML-7)	8852	(BML-51 × BML-14) × (BML-13 × BML-6)	8157	(BML-51 × BML-13) × (BML-32 × BML-7)	9938
(BML-51 × BML-14) × (BML-10 × BML-7)	8715	(BML-51 × BML-13) × (BML-32 × BML-10)	8046	(BML-51 × BML-14) × (BML-13 × BML-7)	9627
(BML-32 × BML-14) × (BML-13 × BML-6)	8607	(BML-51 × BML-32) × (BML-13 × BML-6)	8040	(BML-51 × BML-13) × (BML-32 × BML-14)	9345
(BML-32 × BML-10) × (BML-13 × BML-7)	8547	(BML-32 × BML-6) × (BML-13 × BML-10)	8019	(BML-51 × BML-10) × (BML-32 × BML-7)	9170
(BML-51 × BML-14) × (BML-13 × BML-10)	8541	(BML-51 × BML-7) × (BML-32 × BML-14)	7925	(BML-32 × BML-7) × (BML-14 × BML-13)	9154
(BML-32 × BML-6) × (BML-14 × BML-7)	8515	(BML-13 × BML-7) × (BML-10 × BML-6)	7851	(BML-32 × BML-10) × (BML-7 × BML-6)	9093
(BML-32 × BML-6) × (BML-10 × BML-7)	8501	(BML-51 × BML-10) × (BML-7 × BML-6)	7780	(BML-32 × BML-14) × (BML-13 × BML-7)	9082
(BML-32 × BML-10) × (BML-13 × BML-6)	8384	(BML-32 × BML-6) × (BML-10 × BML-7)	7747	(BML-51 × BML-6) × (BML-32 × BML-14)	8919
(BML-51 × BML-7) × (BML-13 × BML-10)	8205	(BML-51 × BML-6) × (BML-14 × BML-10)	7699	(BML-32 × BML-10) × (BML-14 × BML-7)	8884
		Checks			
DHM-117	6604	DHM-117	6722	DHM-117	6576
KNMH-4010131	5175	KNMH-4010131	7324	KNMH-4010131	9502
Ekka 2288	5551	Ekka 2288	7866	Ekka 2288	8134
NK 6240	7597	NK 6240	6184	NK 6240	7671
900 M Gold	5921	900 M Gold	5478	900 M Gold	7481
Mean	6657	Mean	6569	Mean	7766
C.V. (%)	10.7	C.V. (%)	10.6	C.V. (%)	9.1
C.D. (0.05)	1408	C.D. (0.05)	1378	C.D. (0.05)	1391
C.D. (0.01)	1855	C.D. (0.01)	1816	C.D. (0.01)	1833

*significant at 0.05 level

Table 5 Comparison of single, three-way and double crosses tested at three locations

Type of cross	No.	Yield (kg ha-1)					Regression coefficient (b-values)		Standard error of b (Sb)	Correlations		
		Mean	Highest	Lowest	Range	Avg max deviate	Mean	Range		b and Sb	b and yield	Sb and yield
Single	21	7160	8733	6208	2525	980	1	-0.171 to 2.901	0.02 to 1.56	0.23	-0.18	-0.18
Three-way	105	7017	8395	5387	3008	741	1	-1.361 to 2.959	0.004 to 2.18	-0.11	-0.02	-0.03
Double	105	7197	8362	5867	2495	639	1	-1.576 to 3.373	0.01 to 2.72	0.07	0.01	-0.11
Mean		7112								0.02	-0.02	-0.05

1.00 and a standard deviation of the b-value of 0.0 for the average of all hybrids across all locations. From this a range of regression coefficients (b) was established for the entries (Table 5). Standard errors of each b-value were calculated. Using the parameter of standard error of b to evaluate the stability as suggested by Eberhart and Russell (1969) among three types of crosses, no difference in the average stability of the single and three-way crosses over locations was observed. Range was also similar for single and three-way crosses.

Table 6. Analysis of variance for grain yield in stability analysis of single, three-way and double cross hybrids of maize

Source of variation	d.f	Grain yield (kg ha^{-1})
Single crosses		
Genotypes	32	8558884.00**
Envi.+ (Geno.× Envi.)	66	1254797.75
Environments	2	17896010.00**
Geno.× Envi.	64	734759.81**
Environments (Linear.)	1	35792020.00**
Geno.× Envi.(Linear.)	32	675186.56
Pooled Deviation	33	770262.44*
Pooled Error	96	428735.13
Total	98	3639805.50
Three-way crosses		
Genotypes	104	1358717.88**
Envi.+ (Geno.× Envi.)	210	1135790.88**
Environments	2	53909824.00**
Geno.× Envi.	208	628348.31**
Environments (Linear.)	1	107819648.00**
Geno.× Envi.(Linear.)	104	779189.44
Pooled Deviation	105	472959.44**
Pooled Error	312	250820.23
Total	314	1209626.63
Double crosses		
Genotypes	104	925147.81
Envi.+ (Geno.× Envi.)	210	991465.69*
Environments	2	38254028.00**
Geno.× Envi.	208	633171.81**
Environments (Linear.)	1	76508056.00**
Geno.× Envi.(Linear.)	104	585930.31
Pooled Deviation	105	673933.25**
Pooled Error	312	181526.61
Total	314	969500.50

The pooled analysis of variance was done cross wise i.e for single crosses, three-way crosses and double crosses separately for grain yield over three locations viz. Hyderabad, Karimnagar and Palem. Highly significant differences among single, three-way and double crosses were observed except grain yield of double crosses and environments were also significant for all the three types of crosses. It indicated significant genetic variability for grain yield, as well as the presence of variability among hybrids and environments (Table 6). The presence of significant G × E interaction showed the inconsistent performance of maize hybrids across the environments. Further, environment (linear) and pooled deviation were significant among all the three types of crosses i.e. single, three-way and double crosses.

In the present study single crosses exceeded three-way crosses and double crosses for all the variance components such as error, genotype × environment and genotypes. In case of genotype × environment, the component for single crosses was greater than that of three-way and double crosses, suggesting double and three-way crosses were more stable than single crosses.

Single, three-way and double crosses that had shown high mean than general mean, non significant deviation from regression (s^2d) and non significant regression coefficient (b) indicating stable and wide adaptation to all environments (Table 7). Out of 21 single crosses, fourteen crosses including one check namely NK6240 expressed high mean than grand mean, non significant deviation from regression and non significant regression coefficient indicating hybrids are stable for this trait. Crosses BML-51 × BML-14 (Mean:8733 kg, b= 0.226), BML-32 × BML-6 (Mean:7801 kg, b= -0.171), BML-51 × BML-7 (Mean:7798 kg, b= 0.501) and BML-32 × BML-13 (Mean:7637 kg, b= 0.041) were found to be stable with grain yield greater than 7500 kg ha^{-1} with non

Table 7 Stable single, three-way and double crosses of maize adapted to all the environments

Crosses	Mean grain yield (kg ha^{-1})	bi	s^2di
Single crosses			
BML-51 × BML-14	8733	0.226	-465381.621
BML-32 × BML-6	7801	-0.171	-441764.002
BML-51 × BML-7	7798	0.501	-464729.618
BML-32 × BML-13	7637	0.041	-319833.478
BML-14 × BML-13	7338	0.064	-263074.919
NK 6240	7151	0.869	114702.754
BML-32 × BML-10	7048	2.901	1012477.37
BML-13 × BML-6	6971	1.399	-345835.852
BML-14 × BML-10	6938	0.423	-464179.649
BML-51 × BML-10	6903	1.299	42494.194
BML-32 × BML-7	6884	1.879	-387531.721
BML-14 × BML-6	6820	1.354	808361.818
BML-32 × BML-14	6666	1.641	-177455.093
BML-13 × BML-7	6383	0.774	374857.22
Average	6300		
Mean of bi		1.0	
SE of bi		0.8	
Three-way crosses			
(BML-32 × BML-6) × BML-51	8378	2.522	695436.359
(BML-51 × BML-10) × BML-6	8349	0.944	-804.005
(BML-13 × BML-7) × BML-32	8214	2.31	-135369.627
(BML-32 × BML-13) × BML-14	8137	0.625	-222176.447
(BML-51 × BML-32) × BML-13	8066	0.015	-183989.816
(BML-51 × BML-7) × BML-14	8011	0.444	-245033.267
(BML-51 × BML-14) × BML-6	7996	1.729	-43166.185
(BML-7 × BML-6) × BML-51	7987	0.209	-224546.953
(BML-14 × BML-10) × BML-6	7851	1.348	196938.024
(BML-51 × BML-14) × BML-7	7770	2.141	-167591.476
(BML-32 × BML-14) × BML-13	7755	0.213	507615.569
(BML-7 × BML-6) × BML-32	7718	0.452	188704.157
(BML-51 × BML-13) × BML-6	7660	0.361	304085.58
(BML-51 × BML-6) × BML-32	7603	0.881	199064.384
(BML-32 × BML-7) × BML-51	7601	1.578	540301.736
(BML-13 × BML-10) × BML-32	7597	0.782	293178.791
(BML-32 × BML-13) × BML-51	7553	1.294	-229934.525
(BML-7 × BML-6) × BML-10	7539	0.805	-243835.448
(BML-10 × BML-7) × BML-14	7533	0.344	-221026.728
(BML-32 × BML-13) × BML-7	7482	1.05	-83028.19
(BML-51 × BML-10) × BML-14	7470	1.01	288805.931
(BML-13 × BML-7) × BML-14	7464	1.221	380218.236
(BML-51 × BML-32) × BML-14	7436	0.784	-159941.562
(BML-51 × BML-10) × BML-13	7320	1.84	131507.403
(BML-14 × BML-10) × BML-32	7308	0.08	-226790.657
(BML-32 × BML-10) × BML-14	7298	1.811	676595.491
(BML-51 × BML-6) × BML-13	7288	1.537	105687.994

*significant at 0.05 level

Table 7 - *Continue*

(BML-13 × BML-7) × BML-6	7269	0.126	-148895.411
(BML-51 × BML-32) × BML-6	7258	0.182	-215483.168
(BML-14 × BML-13) × BML-32	7235	1.707	72301.734
(BML-51 × BML-6) × BML-14	7229	0.656	132953.493
(BML-51 × BML-6) × BML-10	7169	0.885	160189.446
(BML-10 × BML-7) × BML-51	7144	0.646	132547.783
(BML-13 × BML-7) × BML-51	7127	1.107	630365.704
(BML-32 × BML-10) × BML-51	7113	0.358	711442.355
(BML-32 × BML-14) × BML-7	7093	0.553	106795.489
(BML-51 × BML-10) × BML-32	7091	1.536	-243763.035
(BML-51 × BML-32) × BML-10	7077	0.996	13663.998
(BML-14 × BML-13) × BML-7	7075	2.629	-225403.922
(BML-32 × BML-7) × BML-10	7075	2.253	78303.855
(BML-32 × BML-13) × BML-10	7069	1.149	292527.059
(BML-51 × BML-13) × BML-32	7049	2.004	-240776.944
(BML-32 × BML-14) × BML-6	7040	0.694	542573.882
(BML-51 × BML-13) × BML-7	7038	1.455	-238991.254
Average	7017		
Mean of bi		1.0	
SE of bi		0.7	
Double crosses			
(BML-32 × BML-6) × (BML-13 × BML-10)	8223	0.448	-178466.884
(BML-51 × BML-10) × (BML-32 × BML-7)	8086	1.561	-178483.696
(BML-51 × BML-13) × (BML-32 × BML-14)	8081	1.849	49493.665
(BML-51 × BML-32) × (BML-13 × BML-6)	8044	1.132	216926.299
(BML-51 × BML-7) × (BML-32 × BML-14)	7966	0.627	-95196.413
(BML-32 × BML-6) × (BML-10 × BML-7)	7934	-0.506	132113.088
(BML-51 × BML-14) × (BML-13 × BML-7)	7934	2.377	482143.754
(BML-32 × BML-10) × (BML-13 × BML-6)	7910	-0.121	177280.657
(BML-51 × BML-7) × (BML-14 × BML-13)	7908	0.39	-79406.146
(BML-13 × BML-7) × (BML-10 × BML-6)	7902	0.989	50634.34
(BML-51 × BML-7) × (BML-13 × BML-10)	7844	0.359	239826.761
(BML-51 × BML-32) × (BML-14 × BML-10)	7828	0.167	3989.646
(BML-51 × BML-6) × (BML-32 × BML-14)	7805	1.63	-6949.638
(BML-51 × BML-13) × (BML-10 × BML-6)	7775	1.378	-149382.003
(BML-32 × BML-10) × (BML-14 × BML-7)	7694	1.675	70021.188
(BML-32 × BML-14) × (BML-13 × BML-7)	7663	2.051	-150077.467
(BML-51 × BML-32) × (BML-13 × BML-7)	7639	1.295	-56847.363
(BML-51 × BML-7) × (BML-13 × BML-6)	7584	0.074	-176056.409
(BML-51 × BML-13) × (BML-14 × BML-10)	7572	0.235	-175864.758
(BML-51 × BML-14) × (BML-10 × BML-6)	7560	1.192	268412.18
(BML-51 × BML-32) × (BML-14 × BML-13)	7555	0.512	-67948.633
(BML-51 × BML-13) × (BML-14 × BML-6)	7538	1.724	-125735.673
(BML-51 × BML-14) × (BML-32 × BML-6)	7491	1.294	-177058.164
(BML-32 × BML-6) × (BML-14 × BML-10)	7443	0.86	-180507.343
(BML-51 × BML-10) × (BML-32 × BML-6)	7421	0.824	301396.697
(BML-51 × BML-32) × (BML-13 × BML-10)	7387	0.484	-178304.013
(BML-32 × BML-10) × (BML-14 × BML-13)	7380	0.497	310528.762

Table 7 - *Continue*

(BML-32 × BML-10) × (BML-14 × BML-13)	7380	0.497	310528.762
(BML-51 × BML-13) × (BML-7 × BML-6)	7352	0.847	-129009.474
(BML-51 × BML-10) × (BML-14 × BML-7)	7351	0.419	-173948.821
(BML-32 × BML-7) × (BML-14 × BML-13)	7337	2.651	142598.561
(BML-32 × BML-7) × (BML-14 × BML-10)	7327	1.877	-165427.424
(BML-51 × BML-32) × (BML-10 × BML-6)	7305	1.316	-27361.425
(BML-51 × BML-6) × (BML-13 × BML-10)	7275	-0.531	-83811.127
(BML-14 × BML-10) × (BML-13 × BML-7)	7225	0.889	-119946.857
(BML-32 × BML-13) × (BML-14 × BML-7)	7222	1.757	269927.903
(BML-51 × BML-6) × (BML-14 × BML-7)	7214	1.941	-51048.07
(BML-51 × BML-10) × (BML-14 × BML-6)	7212	0.281	-128476.895
Average	7197		
Mean of bi		1.0	
SE of bi		1.0	

*significant at 0.05 level

significant regression coefficient and non significant deviation from regression. Cross BML-51 × BML-6 (8096 kg) had specific adaptation to favourable environments with high mean, non significant s^2d and significant regression coefficient greater than one (b=1.881*). Two hybrids *viz*., BML-14 × BML-7 (Mean:7585 kg, b= 0.276*) and DHM-117 (Mean:6634 kg, b= -0.089*) were specifically adapted to unfavourable environments with high mean, significant regression coefficient of less than one and non significant deviation from regression. Five crosses namely BML-51 × BML-32 (Mean:7559 kg, b= 0.386), BML-10 × BML-7 (Mean:7347 kg, b= 0.018), KNMH 4010131 (Mean:7334 kg, b= 2.001), Ekka2288 (Mean:7183 kg, b=0.6) and BML-51 × BML-13 (Mean:7182 kg, b= 1.314) had high mean, non significant regression coefficient suggesting suitability to all environments but, performance is unpredictable due to significant deviation from regression (s^2d).

Among the 105 three-way crosses, about fifty crosses had shown high mean values than grand mean for grain yield and non significant deviation from regression indicating hybrids are stable. Of these eight crosses viz. (BML-51 × BML-10) × BML-6 (8349 kg), (BML-51 × BML-6) × BML-32 (7603 kg), (BML-32 × BML-13) × BML-7 (7482 kg), (BML-51 × BML-10) × BML-14 (7470 kg), (BML-51 × BML-6) × BML-10 (7169 kg), (BML-13 × BML-7) × BML-51 (7127 kg), (BML-51 × BML-32) × BML-10 (7077 kg) and (BML-32 × BML-13) × BML-10 (7069 kg) were well adapted to all the environments with regression coefficient nearer to unity and non significant deviation from regression. Two crosses namely (BML-14 × BML-6) × BML-51 (Mean: 8395 kg, b=2.147*) and (BML-10 × BML-7) × BML-6 (Mean: 7036 kg, b=2.061*) had significant regression coefficient values greater than one indicating specific adaptation to favourable environments while, three crosses namely (BML-13 × BML-10) × BML-14 (Mean: 7789 kg, b=0.333*), (BML-32 × BML-10) × BML-7 (Mean: 7785 kg, b=0.418*) and (BML-51 × BML-7) × BML-6 (Mean: 7408 kg, b= -1.361**) had shown specific adaptation to unfavourable environments with significant regression coefficient value less than one and the performance is predicted with non significant s^2d values. Eight crosses had high mean, non significant regression coefficient suggesting adaptation to all environments but unpredicted performance due to significant deviation from regression.

Discussion

The mean squares for singles, doubles and three-way crosses were almost similar at Hyderabad location where as at Karimnagar single crosses and at Palem location three-way crosses had high mean square values (Table 2). In a study by Weatherspoon (1970), mean square for singles was twice as great as that for three-ways and three-ways was almost three times as great as that for doubles.

At all the three locations either three-way or double crosses were equally competitive to single crosses in performance and in particular at Palem location, three-way crosses and double crosses excelled in yield performance against single crosses (Table 4). It is due to population buffering of multiple crosses *i.e.*, three-way and double crosses tolerance to major abiotic stresses like drought.

The average maximum hybrid × environment interaction deviate for singles was 239 kg ha^{-1} greater than that for three-ways and 341 kg ha^{-1} greater than that for doubles (Table 5). Similarly, Weatherspoon (1970) reported that the average maximum hybrid × environment interaction deviate for singles was 1.4

q ha^{-1} greater than that for three-ways and 2.9 q ha^{-1} greater than that for doubles.

The pooled analysis of variance for stability in single, three-way and double crosses separately for grain yield over three locations *viz.*, Hyderabad, Karimnagar and Palem indicated significant differences among single and three-way crosses for grain yield and environments revealing significant genetic variability for grain yield, as well as the presence of variability among hybrids and environments (Table 6). Significant differences among the genotypes for yield stability were reported by Gomes et al. (2000). Significant mean squares for genotype × environment (G × E) interactions were observed in all the three categories of hybrids *i.e.*, single, three-way and double crosses. Several researchers (Kamutando, 2013; Abuali et al, 2014; Tripathi and Shreshtha, 2016) reported significant differences among genotypes, environments and G × E interaction for grain yield and other traits. The presence of significant G × E interaction showed the inconsistent performance of maize hybrids across the environments. Further, environment (linear) was significant among all the three types of crosses *i.e.*, single, three-way and double crosses which indicated considerable differences among the environments and their pre-dominant effects on the traits. This could be due to the variations in weather and soil conditions over different locations. Pooled deviations were significant in all the three types of crosses and this suggested that the deviation from linear regression also contributed substantially towards the differences in stability of hybrids thereby indicating difficulty in predicting the performance of hybrids over environments. Gargi and Saikia (2000) and Khalil (2013) observed significant G × E interaction, genotype × environment (linear) interaction and pooled deviations for grain yield.

In case of genotype × environment, the component for single crosses was greater than that of three-way and double crosses, suggesting double and three-way crosses were more stable than single crosses. This could be due to heterogeneous populations (three-way and double cross hybrids) that tended to have better yield stability (less GE interactions) than homogeneous (single cross hybrids) populations. Similar results of higher stability of double crosses than single crosses was reported by Sprague and Federer (1951), while Pixley and Bjarnason (2002) reported open pollinated varieties were more stable than double crosses followed by three-way crosses and single crosses.

High yielding hybrids were found to be highly stable and widely adapted to favourable environments or specific environments (Table 7) (Owusu, 2016; Tripathi and Shreshtha, 2016). There was no correlation between a hybrid's average ability to yield and its ability to exploit a high yielding environment or its lack of performance in a poor environment, *i.e.*, the regression coefficient of a variety is no indication of its mean yield (Table 5). This agrees with the work of Kaltsikes and Larter (1970) on wheat (*Triticum durum* Desf.) and Lynch et al. (1973) on maize.

Results envisaged that the average yield of double crosses and single crosses is almost similar. Moreover, single crosses can perform very poorly or very well depending upon the specific combination and are more sensitive to environmental conditions than three-way crosses or double crosses (Sprague and Federer, 1951; Rojas and Sprague, 1952; Eberhart et al, 1964; Eberhart and Russell, 1969). However, high yielding single crosses which are relatively stable can be isolated. BML-51 × BML-14 with grain yield 8733 kg ha^{-1} is one of such combination with no significant interaction deviate and adapted to all environments. At individual locations, three-way or double crosses gave higher grain yields than single crosses. Three-way cross (BML-51 × BML-10) × (BML-6) and double crosses (BML-51 × BML-32) × (BML-13 × BML-6) and (BML-13 × BML-7) × (BML-10 × BML-6) that had unit regression coefficient and grain yield greater or equal to 8000 kg ha^{-1} indicating average response to all environments and need to be exploited to minimize the expenses incurred by farmers in purchase of seed for cultivation and to combat biotic and abiotic stresses arising through climate change.

Conclusion

From our study, it was concluded that three-way crosses and double crosses were found to be more variable than single crosses for grain yield and are more advantageous when crop is grown under adverse climatic conditions. Hence, replacement of double or three-way crosses with single crosses resulted in loss of genetic homeostatis and it could invite disastrous epidemics of new strains of disease to which all plants of a single cross become susceptible. Moreover, single crosses possess individual buffering and lack population buffering unlike three-way and double crosses which have both population as well as individual buffering. This enables three-way and double crosses to perform better under adverse climatic conditions with stable and consistent performance than single crosses. Further, the cost of seed production of three-way and double cross hybrids is low with the use of single cross as seed parent and becomes easy to make available seed at low cost to farmers. Hence, the three-way and double cross hybrids with good *per se*, stable performance and wide adaptation to all environments may be tested in multilocations to obtain climate resilient hybrids

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