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G × E interaction studies in relation to heterosis and stability of grain yield in maize (*Zea mays* L.)

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Abstract

Interaction of homozygous inbreds and heterozygous single, three way and double crosses with environment had shown a differential response in achieving yield stability. Seven diverse maize inbreds, their 21 single crosses and 105 each of three way and double crosses obtained through diallel were evaluated for twelve characters across three diverse locations to estimate comparative stability of homozygous and heterozygous genotypes for grain yield. Contrasts in heterobeltiosis, combining ability and stability parameters in three environments and interaction effects were observed. Gain in heterobeltiosis (%) for grain yield was observed with decreased environmental quality in different hybrid classes suggesting that heterozygous hybrids are more stable due to individual buffering in single crosses and both individual and population buffering in case of three way and double crosses. Significant increase in SCA effects was observed in moderate environment at Hyderabad rather than at high yielding environment Palem. Significant G × E and Environment (linear) in all the crosses was observed for grain yield suggesting the effect of environment and its pre dominant effect on grain yield. Stability of hybrids was attributed to their superior performance over the parents in low yielding environment. Thus the potential use of selected heterozygous hybrids would allow under diverse environments is suggested to mitigate losses arising out of climate change.

Key words: Maize, heterosis × environment, stability, genotype × environment, interaction, heterobeltiosis.

Introduction

Genotype × Environment (G × E) interaction and its influence on performance of maize cultivars can help maize breeders to improve stability of performance of cultivars across environments. Significant G × E component results in reducing the correlation between phenotypic and genotypic values and affects breeding of quantitative traits in crop improvement (Parra, 1985). G × E interaction is usually present in all the varieties whether those are purelines, single cross, three way cross or double cross hybrids, top crosses or any other material that are handled by the breeder. Genotypes with low G × E interaction are considered desirable for breeding because of their wider adaptability and stability (Sprague and Federer 1951; Pixley and Bjarnason 2002). Effect of environments on yield stability of genotypes also depend on their homozygous or heterozygous nature due to differences in individual buffering capacities (Shrestha 2013; Chaudhary et al. 2019). Theoretically, heterozygous genotypes are adapted to diverse environments through allelic variation by producing complex enzymes leading to individual buffering or results in biochemical versatility that allows divergent biochemical pathways under diverse environmental conditions (Haldane 1954; Lewis 1954). This clearly indicates that heterosis is also influenced by environment when tested in different locations. Single crosses can have excellent performance or otherwise depending upon the specific combination and are more sensitive to environmental conditions than three-way crosses or double crosses (Sprague and Federer 1951; Eberhart and Russell 1969). Therefore, adequate knowledge on causes of G × E interaction is necessary to identify the best testing conditions and areas of optimal cultivar adaptation. In assessing the varietal adaptability, estimates of phenotypic stability had proven to be a valuable tool. More stable genotypes can adjust their

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phenotypic responses to achieve uniformity despite environmental fluctuations. This information can be obtained from the description of performance of individual genotype in various environments as it identifies genotypic traits involved in G × E interaction. Since, the aim of a plant breeder is to develop stable genotypes with maximum economic yield/unit area and consistent performance for productivity across environments, it becomes imperative to study the level of impact of G × E interaction over different types of genotypes to identify the best genotypes with high yield potential across all the environments. Insights on buffering capacity of homozygotes and heterozygotes would serve as a proxy for selection of varieties or hybrids for targeted environments. Hence, this research was undertaken to know the impact of G × E over yield stability of homozygotes and heterozygotes by means of agronomic stability (Eberhart and Russell 1966), heterosis and gene effects. The magnitude of heterotic performance of heterozygotes (Crosses) over homozygotes (Inbreds) as compared to mean performance of both in different environments show the comparative yield stability of crosses and inbreds whereas the agronomic stability model is useful in predicting the performance of genotype in response to the environments. This information help us in improving the stability of performance in maize breeding programmes by understanding productivity path and its contribution to yield stability.

Materials and methods

To represent contrasting levels of zygotic diversity, two populations i.e., homozygotes and heterozygotes were used. Inbreds are homozygotes whereas single, three-way and double crosses are heterozygotes. This was done to detect environmental effect on different zygosity levels for yield stability. The stability of crosses was visualized by plotting heterobeltiosis against environmental mean of hybrids in the studied environments. Heterosis is directly proportional to the genetic distance between the parents involved in the cross. More diverse the parents more will be the magnitude of desirable heterosis and *vice versa* (Moll et al.1995). Hence, to obtain high heterosis, inbred lines belonging to different ancestry were deliberately selected. Diverse parents were selected in terms of earliness, plant height, ear characters, late wilt tolerance etc. The experimental material consisted of seven inbreds *viz*., BML 51, BML 32, BML 14, BML 13, BML 10, BML 7 and BML 6. Crosses were made in diallel fashion (Griffing 1956 Method I Model II) and obtained twenty one crosses during *kharif* 2014. In *rabi* 2014, 21 F_1's were involved in crosses with inbreds such that no parent appears twice in the same cross and generated 105 three-way crosses. Similarly, single crosses were utilized in diallel set with restriction that only unrelated crosses were involved in crossing programme and obtained 105 double crosses in *rabi* 2014. The coding of crosses is illustrated and given in Table 1. In *kharif* 2015, field evaluation of 7 parents, 21 single crosses and 105 each of three-way and double crosses and 18 public/private checks was conducted at three contrasting environments *viz*., RARS, Palem (E1) (16°35'N latitude, 78°1'E longitude), MRC, ARI, Rajendranagar (E2) (17°18'N latitude, 78°23'E longi-tude) and ARS, Karimnagar (E3) (18°30'N latitude, 79°15'E longitude) in the state of Telangana. All these 256 entries were laid out in a balanced lattice (16 × 16) in two replications at each location and each genotype was sown in two-row plots of 3 m length with a spacing of 60 cm between rows and 20 cm within rows. Traits measured on plot basis were days to 50% pollen shed, days to 50% silk emergence, days to 75% dry husk, shelling percentage (%),100-kernel weight (g), grain yield (kg ha^{-1}) and fodder yield (kg plot^{-1}) whereas for plant height (cm), ear height (cm), ear length (cm), ear diameter (cm), number of kernel rows ear^{-1}and number of kernels row^{-1}, ten randomly selected plants were selected.

Table 1. Code numbers of crosses given in figures

Code No.	Genotype
1	BML 51
2	BML 32
3	BML 14
4	BML 13
5	BML 10
6	BML 7
7	BML 6
12	BML 51 x BML 32
13	BML 51 x BML 14 and so on…
(12)3	(BML 51 x BML 32) x BML-14
(12)4	(BML 51 x BML 32) x BML-13 and so on…
(12)(34)	(BML 51 x BML 32) x (BML 14 x BML 13)
(12)(35)	(BML 51 x BML 32) x (BML 14 x BML 10) and so on…

Statistical analysis

The data was analyzed following standard statistical procedures. However, due to higher intra block variation over block differences, the efficiency of the design couldn't be carried out. Hence, the data was analyzed as per randomized block design (Eberhart et al. 1964). Plot means were used for statistical analysis. The Bartlett's test for homogeneity of variances was computed to test the homogeneity of error variance among the three locations for single, three-way and double crosses for all the characters. The data was subjected to analysis of variance (ANOVA) for pooled as well as for individual environments to study the combining ability and heterotic effects both at individual and pooled locations (Patil et al. 2017). To test the normal probability distribution of the data, Shapiro-Wilk test (1965) was done using RStudio. Heterosis was computed over better parent so that difference in heterobeltiosis for the same cross across the environments could indicate us about the yield stability of hybrid in relation to its parents in different environments. Gene effects of single crosses were calculated as per Griffing (1956) whereas three-way and double crosses were calculated as per Rawlings and Cockerham (1962 a and b). The Eberhart and Rusell (1966) model for stability analysis was used to detect the stability parameters (x = mean, bi = regression coefficient, S^2di = deviation from regression) of the genotypes.

The cause of superiority of potential genotypes in each class of hybrid was derived by comparing their performances with the mean of all genotypes in that class and expressed as deviation from this group mean. These per cent deviation values help in identifying the important yield contributing traits responsible for high productivity seen in the group as well as in superior genotypes.

The per cent deviation was calculated by using the following formula (Ranganatha and Patil, 2015).

$$\text{Percent deviation} = \frac{\text{Genotypic mean–Group mean}}{\text{Group mean}} \times 100$$

In the present study, top five potential crosses as well as bottom five crosses in each class of hybrids i.e., single, three way and double were taken to calculate the per cent deviation of genotypes from group mean. With the help of this it will be possible to identify the role of different traits contributing to the superiority and inferiority of genotypes in each class.

Results and discussion

The Bartlett's test for homogeneity of variances revealed homogeneous error variances for majority of the yield contributing characters in all the three classes of hybrids i.e., single, three-way and double. As the error variances were found to be homogeneous for grain yield in all the three classes of hybrids, pooled analysis was carried out. Shapiro-Wilk test of normality indicated that all the characters followed normal distribution.

Heterosis × environment interaction

Perusal of data in Table 2 indicated that significant improvement in yield stability might have resulted from the ability of each heterozygous genotype to obtain promising yield in low yielding environment. The range of values for heterobeltiosis of single, three-way and double cross hybrids were higher in low yielding environment at Hyderabad (E2) or Karimnagar (E3) than high yielding environment at Palem (E1) and the values were high in single crosses followed by three-way and double crosses. This could be due to decreased performance of homozygous inbreds or heterozygous single cross hybrids in low yielding environment which in turn showed increased stability of hybrids in low yielding environment. Single crosses were better parents in calculating heterobeltiosis of three-way and double crosses rather than inbreds. In single crosses, heterobeltiosis was positive and significant and range was high in low yielding environment E3, moderate in E2 and low in high yielding environment i.e., E1. Contrary to this, significant negative heterobeltiosis was also observed in three way and double crosses, where high range of heterobeltiosis was observed in Karimnagar and Hyderabad and low range in Palem. Heterobeltiosis for top performing single, three-way and double cross hybrids across environments showed a decline in heterosis as mean yield of parents increased in favourable environments in case of single crosses whereas, varied response was shown by three-way and double crosses (Fig. 1). This could be due to differential performance of all crosses i.e. single, three-way and double crosses in favourable or unfavourable environments. There was a strong association between heterosis and environment mean and the effect each had on stability. This suggested us the effectiveness of heterozygotes in obtaining stable yields. It is clear that heterobeltiosis increased as environmental yields decreased which indicate the more yield stability of heterozygotes in low yielding environments than

Table 2. High and low performance of single, three-way, double crosses and parents for grain yield (kg ha^{-1}) across environments

Single crosses				
			SCA (Crosses)	
Hybrid performance for grain yield (kg ha^{-1})	Pooled	E1 (Palem)	E2 (Hyderabad)	E3 (Karimnagar)
Maximum	2026.58**	2323.49**	2855.17**	2407.88**
Mean	7160	7740	7312	6427
			GCA (Parents)	
Better parent value	Pooled	E1	E2	E3
Maximum	490.25**	501.11*	447.41*	522.22**
Mean	3279	4684	2475	2678
			Heterobeltiosis (%)	
Heterobeltiosis (%)	Pooled	E1	E2	E3
Maximum	141.65**	104.57**	230.60**	213.50**
GCA/SCA	0.04	0.08	0.07	0.03
Three way crosses				
			2 line specific effect of first kind (dij)	
Hybrid performance for grain yield (kg ha^{-1})	Pooled	E1 (Palem)	E2 (Hyderabad)	E3(Karimnagar)
Maximum	543.40**	653.10**	812.90**	549.70**
			2 line specific effect of second kind (sij)	
Maximum	659.40**	677.70**	987.60**	805.80**
			3 line specific effects (tijk)	
Maximum	1175.10**	1343.70**	1480.10**	1338.40**
Mean	7017	7844	6601	6605
			GCA (Parents) – hi (as grand parent)	
Better parent value	Pooled	E1	E2	E3
Maximum	303.90**	242.70**	298.90**	370.00**
			gi (as parent)	
Maximum	442.80**	518.10**	455.70**	537.20**
Mean	3279	4684	2475	2678
			Heterobeltiosis (%)	
Heterobeltiosis (%)	Pooled	E1	E2	E3
Maximum	28.69**	49.14**	53.33**	67.93**
Double crosses				
			2 line specific effect (ij) (- -) i.e. tij	
Hybrid performance for grain yield (kg ha^{-1})	Pooled	E1 (Palem)	E2 (Hyderabad)	E3(Karimnagar)
Maximum	316.68	335.67	585.17	336.48
			2 line specific effect (i-) (j-), i.e. ti.j.	
Maximum	223.72	225.37	272.38	173.4
			2 line specific effect Sij	
Maximum	72.54	108.35	111.00	107.34
			3 line specific effects (ij) (k-), i.e. tij.k.	
Maximum	418.69	746.32	865.02	582.88
			3 line specific effects Sijk	
Maximum	125.24	199.74	236.22	155.21
			4 line specific effects (ij) (kl), i.e. tij.kl.	
Maximum	496.39	899.26	1142.27*	606.28
			4 line specific effects Sijkl	
Maximum	315.27	466.82	475.09	326.19
Mean	7197	7892	6884	6813
			1 line general effects- Parents	
Better parent value	Pooled	E1	E2	E3
Maximum	65.77	70.01	153.94	194.63
			Heterobeltiosis (%)	
Heterobeltiosis (%)	Pooled	E1	E2	E3
Maximum	23.79**	26.88*	33.02**	44.66**

*, ** Significant at 5% and 1% level, respectively.

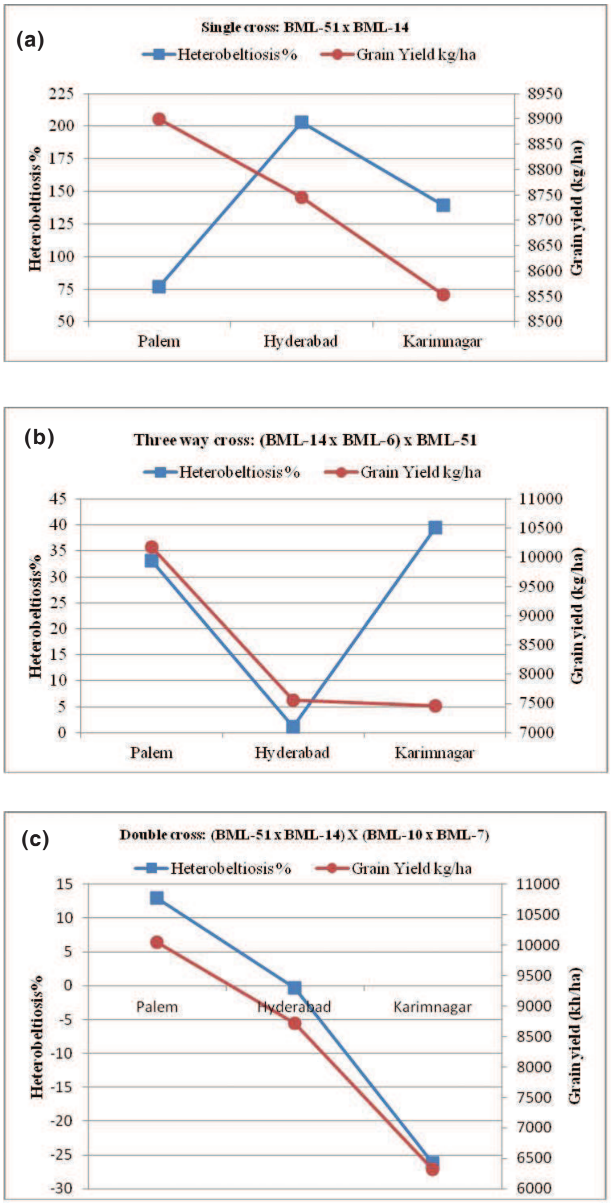

Fig. 1. Relation of heterobeltiosis and mean grain yield (kg ha^{-1}) in high yielding single, three way and double crosses

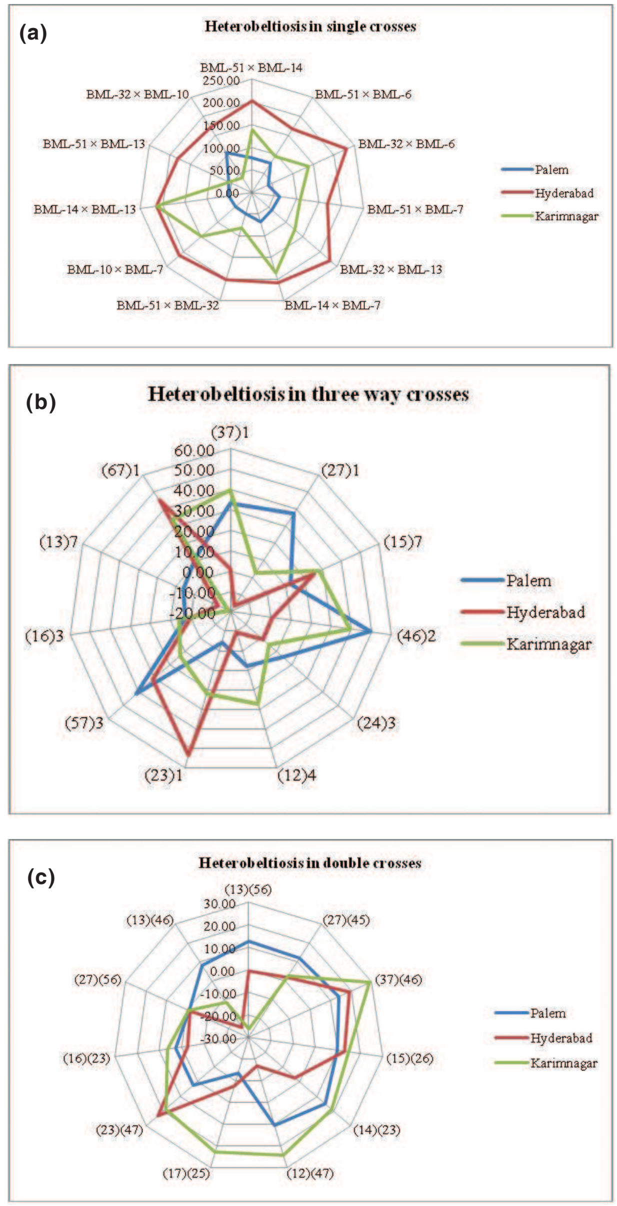

Fig. 2. Radar showing trend of heterobeltiosis (%) of high yielding 11 hybrids each in single, three-way and double crosses over the environments at three locations

homozygotes. 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. The trend of heterobeltiosis over environments for grain yield (kg ha^{-1}) is graphically represented in Fig. 2.

Gene effects × environment interaction

The pooled analysis of variance was done cross wise *i.e* for single crosses, three-way crosses and double crosses separately over three locations (data not shown). The mean squares for genotypes x environments, environments and pooled deviations were found to be significant in all the three types of crosses which indicated that environments were much diverse to influence the yield of homozygotes as well as heterozygotes (Shrestha 2013). Heterosis is not entirely the result of genetic stimuli rather it is the result of interaction between genetic and environmental stimuli and implicated that the environment was a significant factor in the manifestation of heterosis (Griffing and Zsiros 1971). Data in Table 2 revealed that for single crosses, SCA for grain yield (kg ha^{-1}) was high and significant at E2 followed by E3 and E1, while GCA of parents was high and significant at E3 followed by E2 and E1.Similarly, 2 line and 3 line specific effects were high and significant at E2 and 1 line general effects either as grandparent (hi) or immediate parent (gi) were high and significant at E3.Same trend was noticed for double crosses, but the effects were non significant. This clearly indicated impact of environment on gene effects.

In single crosses, genetic Ratio (GCA: SCA ratio) for grain yield at all locations was less than one indicating that non-additive effects were more important than additive effects in contributing to yield stability (Table 2). These non additive effects had resulted from increased performance of heterozygotes over homozygotes which was evident from the increased heterobeltiosis as a consequence of decrease in environmental quality. The GCA effects were higher at Karimnagar and Palem than Hyderabad indicating predominance of additive effects for yield environmental quality increased which was evident from lower heterobeltiosis at Palem than Karimnagar and Hyderabad (Table 2).

Relation of heterosis and gene effects

Positive association was observed between heterobeltiosis and non additive gene effects in most of the single crosses but not in all the crosses. Highly heterotic crosses showed very high SCA effects in all the environments for grain yield (kg ha^{-1}) indicating strong association between heterosis and SCA (Table 3a). Number of kernels row^{-1} was the most important yield contributing trait that had positive association of heterobeltiosis and SCA in moderate yielding environment indicating predominance of non additive effects over additive effects. The presence of non additive gene effects and its desirable interaction with low or moderate yielding environment suggests that heterosis breeding would be rewarding as heterobeltiosis possess desirable interaction with low yielding environment in order to achieve stable yield performance. Thus increased heterobeltiosis can be attributed to non additive effects and genotype × environmental interaction (Griffing and Zsiros 1971).

Studies on productivity path leading to yield stability

Per cent mean deviation of the top five and bottom five crosses for grain yield and yield contributing characters in all the three classes of hybrids from corresponding group mean are shown in Tables 4a and 4b and differences were observed for per cent contribution by the component traits.

Grain yield components were observed to determine yield productivity path and contribution each had towards yield stability. Top yielding five each of single, three way and double crosses had positive values for grain yield and its contributing characters except number of kernel rows ear^{-1}. However, the same set of double crosses showed negative percent deviation for flowering and maturity traits which is highly desirable. High yielding single, three way and double crosses exhibited positive percent deviation for ear length, number of kernels row^{-1}, shelling percentage and 100 kernel weight. The superior stability of heterozygotes was attributed to an increased yield production in low yielding environments resulting from an increase in number of kernels row^{-1} in single and double crosses and 100 kernel weight in three way crosses (Tables 3a, 3b and 3c). Different yield components contributed to change in per cent heterosis and SCA in low to high yielding environments in different hybrids. For example, single cross BML 51 × BML 14 exhibited high heterobeltiosis and high SCA for number of kernels row^{-1} which can be attributed to the contribution from increase in ear length, 100 kernel weight and shelling percentage (data not shown). Clear cut differences were observed regarding the path of productivity among the genotypes in all the three classes of hybrids and various traits contributing to yield stability in all the environments. In future by knowing the exact magnitude of the environment × trait interaction, rapid progress in the maize breeding programme could be possible by giving thrust on the most important productivity path for assured yield improvement. Hence selection based on number of kernels row^{-1}, ear length, 100 kernel weight and shelling percentage in all three classes of hybrids and ear diameter in single and three way crosses across the tested environments could be helpful for development of stable hybrids across the locations.

Agronomic stability across environments

Crosses also showed differences in stability measured with regression model and through heterosis, indicating

Table 3a. Heterobeltiosis (BPH) and specific combining ability (SCA) for number of kernels row^{-1} and SCA for grain yield in top five single crosses across environments

Cross	Palem (E_1)		Hyderabad (E_2)		Karimnagar (E_3)		Stability parameters			SCA forgrain yield (kg ha^{-1})		
	BPH (%)	SCA	BPH(%)	SCA	BPH(%)	SCA	Xi	bi	s^2di	(E1)	(E2)	(E3)
BML-51 × BML-14	32.12*	3.47	54.61**	3.68**	29.57**	2.51	31.75	0.95	-2.93	1516.10**	2166.67**	2396.99**
BML-51 × BML-6	39.69**	6.09*	57.58**	4.97**	44.76**	2.39	37.25	1.51	12.05*	1982.49**	1377.00**	1076.15
BML-32 × BML-6	36.08**	4.10	64.62**	4.67**	69.04**	4.36**	38.33	1.10	-2.13	312.76	2018.56**	2407.88**
BML-51 × BML-7	31.52*	1.02	67.08**	4.10**	39.63**	3.31*	33.35	-0.09	-2.67	829.60	1358.67**	1507.43*
BML-32 × BML-13	53.83**	3.22	75.51**	6.45**	76.39**	6.58**	37.93	-1.19	6.95	724.15	1754.61**	2090.71**

Table 3b. Heterobeltiosis (BPH) and 3-line effects for 100 kernel weight and 3-line effects for grain yield in top five three way crosses across environments

Cross	Palem (E_1)		Hyderabad (E_2)		Karimnagar (E_3)		Stability parameters			3-line effect for grain yield (kg ha^{-1})		
	BPH (%)	3-line effect	BPH (%)	3-line effect	BPH (%)	3-line effect	Xi	bi	s^2di	(E1)	(E2)	(E3)
(37)1	16.86	0.10	9.61	-1.14	8.86	1.29	37.39	0.51	4.46	750.4*	-175.9	910.3**
(27)1	10.34	1.41	10.15	-1.57	-2.85	-0.32	35.45	0.91	2.80	980.4**	-15.5	54.5
(15)7	-3.75	2.94	-2.08	2.50	7.51	-0.50	36.07	0.59*	-7.38	534.5	-528.1	236.8
(46)2	-5.71	-2.12	8.77	0.34	0.93	0.82	34.37	0.95	10.07	657.2*	-107.9	-274.5
(24)3	17.59	1.50	14.63	-1.71	32.35*	2.09	40.93	0.63	-7.15	503.8	126.3	618.6*

Table 3c. Heterobeltiosis (BPH) and 4-line effects for number of kernels row^{-1} and 4-line effects for grain yield in top five double crosses across environments

Cross	Palem (E_1)		Hyderabad (E_2)		Karimnagar (E_3)		Stability parameters			3-line effect for grain 4-line effect yield (kg ha^{-1})		
	BPH (%)	4-line effect	BPH (%)	4-line effect	BPH (%)	4-line effect	Xi	bi	s^2di	(E1)	(E2)	(E3)
(1356)	7.95	-0.22	-1.16	0.52	3.48	-0.05	34.52	1.23	-3.58	598.90	365.85	424.58
(2745)	-8.71	-0.92	-0.67	0.89	-6.19	0.42	36.32	-0.84	-2.74	899.26	48.53	367.29
(3746)	-0.46	-1.27	0.42	0.19	12.42	0.53	34.42	-3.12	-3.01	40.08	205.62	462.17
(1526)	6.00	0.48	1.12	0.06	-0.14	0.78	36.62	2.80	0.54	377.27	158.76	458.53
(1423)	-0.57	-1.25	-4.95	-0.63	-5.77	-0.19	33.52	2.61	-2.22	-249.32	-46.11	-74.28

*,** significant at 5% and 1% level, respectively

heterosis cannot explain all the variation observed in the yield stability of the hybrids (Tables 3a,3b and 3c). Hence, the agronomic stability of all the three categories of hybrids was measured by using regression model of Eberhart and Russell (1966). Diversity with respect to environments was important to produce sufficient variability to measure stability. Environment (linear) was significant for all the characters 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. The genotype × environment (linear) interaction was significant for flowering and maturity traits, ear diameter, shelling percentage and fodder yield in single crosses, number of kernels row^{-1} in three way crosses and ear diameter in double crosses suggesting that there are genetic differences among the genotypes taking into account their responses to environmental variation (data not shown). Pooled deviation mean squares in single, three way and double crosses were highly significant for grain yield indicating that the major components for differences in stability were due to deviation from linear function. Therefore, it may be concluded that the relatively unpredictable components of interaction may be more important than the predictable components.

Three parents and seven single crosses were found to be stable for grain yield with high mean than parental mean and hybrid mean respectively with non significant deviation from regression (Fig. 3). Similarly

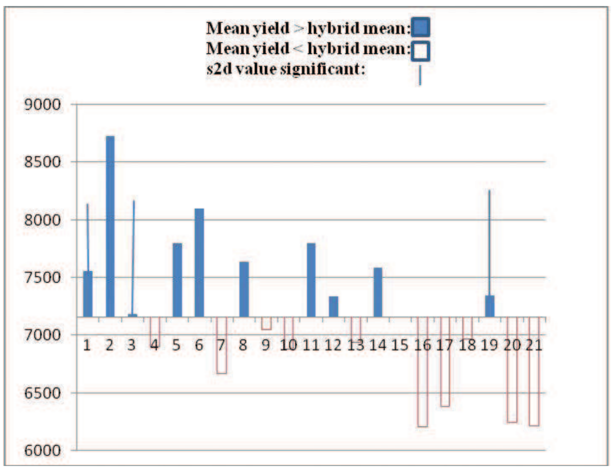

Fig. 3. Stability parameters of single crosses (mean and s^2d) for grain yield (kg ha^{-1})

of the 105 each of three-way and double crosses, fifty five and forty crosses were stable with high mean than hybrid mean with non-significant deviation from regression. Of all these single, three-way and double stable crosses, some crosses were more stable approaching the regression coefficient nearer to unity but showed relatively low mean than the other stable crosses. Seven single crosses were found to be stable and of these five had average response and cross BML 51 × BML 6 (8096 kg ha^{-1}) had specific adaptation to favourable environments with high mean greater than 8 q, non significant s^2d and significant regression coefficient greater than one (b=1.88*). About fifty, three-way and forty double crosses were found to be stable and almost all had average response i.e. suitable to all environments and out of which eight, three-way and ten double crosses had grain yield greater than or nearer to 8 q. Three way cross (BML 14 × BML 6) × BML 51 (x=8096 kg, b=2.15*) and double cross (BML 51 × BML 13) × (BML 32 × BML 7)

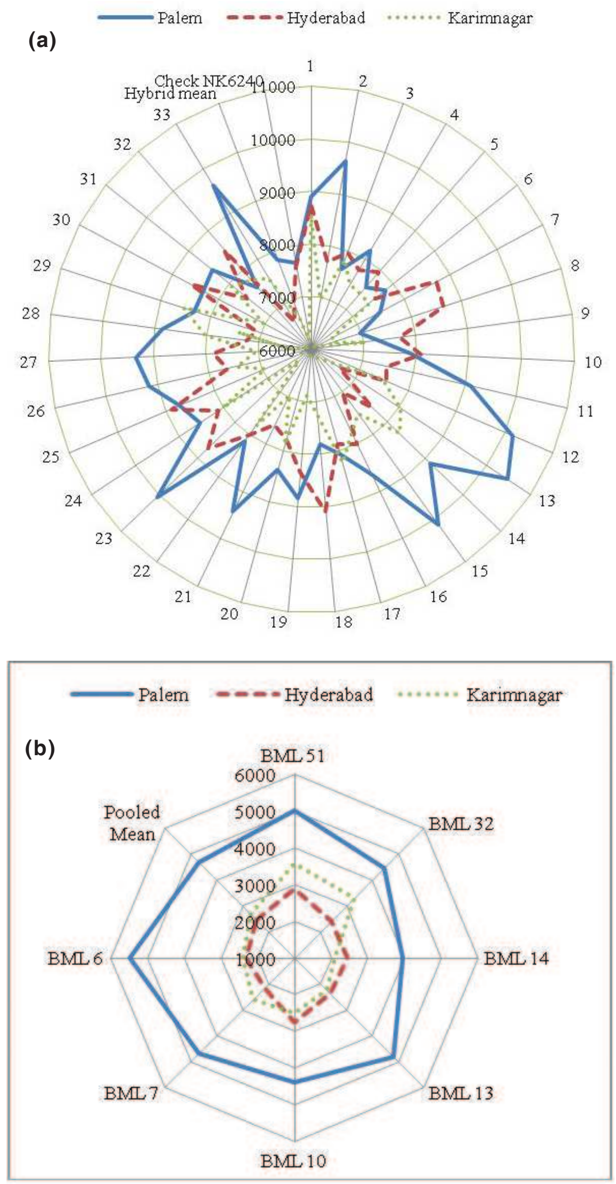

Fig. 4. (a) Radar showing mean performance of crosses for grain yield (kg ha^{-1}) over the environments; (b) Radar showing mean performance of parents for grain yield (kg ha^{-1}) over the environments

(x=7874 kg, b=2.97*) were highly responsive to the favourable environments and improved environmental quality as evident from their significant regression coefficient value (b>1*). Mean of three way and double crosses was higher than the mean of single crosses at E3 and E1 indicating their feasibility both in low and high yielding environments, while reverse trend was observed in E2. Across the environments, highest better parent heterosis was found in single cross BML 14 × BML 7 (141.65%) followed by BML 14 × BML 13

Table 4a. Percent deviation of top five single, three way and double crosses from overall mean of single, three way and double crosses, respectively for grain yield and yield components

Particulars	GY	DT	DS	DM	PLHT	EHT	EL	ED	NKRE	NKRR	SH	100 KW	FY
Single cross													
BML-51×BML-14	8733	54.00	56.83	92.00	201.20	103.33	18.95	4.27	12.73	31.75	82.53	41.83	4.12
BML-51×BML-6	8096	54.17	57.00	91.17	210.50	113.83	19.65	4.55	13.73	37.25	83.15	35.26	3.18
BML-32×BML-6	7801	57.67	60.00	93.83	192.80	99.00	19.15	4.72	14.98	38.33	83.43	31.38	2.64
BML-51×BML-7	7798	55.67	57.17	89.67	200.30	105.83	18.67	4.44	13.00	33.35	82.05	36.69	3.24
BML-32×BML-13	7637	56.67	59.00	91.67	171.00	86.17	20.83	4.38	13.23	37.93	85.62	32.29	2.60
Top 5 mean	8013	55.63	58.00	91.67	195.16	101.63	19.45	4.47	13.54	35.72	83.36	35.49	3.16
Group mean	7160	55.20	57.70	91.60	182.40	93.40	18.80	4.40	13.60	33.70	82.00	33.70	2.90
% Deviation#	11.91	0.79	0.52	0.07	7.00	8.82	3.46	1.61	-0.47	6.00	1.65	5.31	8.86
Three way cross													
(37)1	8395	54.33	56.17	91.67	207.70	107.33	19.43	4.40	13.20	34.88	81.60	37.39	4.48
(27)1	8378	55.83	57.50	93.50	214.50	113.33	20.60	4.43	13.33	36.02	83.42	35.45	3.90
(15)7	8349	55.33	58.17	93.50	201.00	111.33	18.60	4.61	14.30	34.58	82.12	36.07	3.64
(46)2	8214	58.00	60.50	93.00	195.00	95.17	20.48	4.55	13.62	37.57	84.03	34.37	3.28
(24)3	8137	55.50	57.17	93.50	187.50	90.67	19.63	4.43	13.07	32.25	80.95	40.93	4.05
Top 5 mean	8295	55.80	57.90	93.03	201.14	103.57	19.75	4.48	13.50	35.06	82.42	36.84	3.87
Group mean	7017	55.50	57.93	92.17	188.20	97.11	18.93	4.40	13.82	33.74	81.57	33.54	2.97
% Deviation#	18.21	0.55	-0.06	0.94	6.88	6.65	4.33	1.98	-2.26	3.92	1.05	9.84	30.09
Double cross													
(1356)	8362	54.00	56.33	93.17	197.20	106.83	19.77	4.48	13.67	34.52	78.93	36.58	3.74
(2745)	8223	54.33	56.67	91.00	184.30	97.00	18.73	4.29	13.80	36.32	83.65	31.14	3.34
(3746)	8190	53.33	55.17	90.00	184.50	98.33	19.35	4.37	13.60	34.42	83.02	34.51	3.39
(1526)	8086	56.00	59.17	91.17	206.20	108.00	19.97	4.50	13.70	36.62	84.33	34.08	3.28
(1423)	8081	54.83	57.00	92.00	193.70	94.50	19.78	4.30	13.10	33.52	83.38	36.36	3.18
Top 5 mean	8188	54.50	56.87	91.47	193.18	100.93	19.52	4.39	13.57	35.08	82.66	34.53	3.39
Group mean	7197	55.34	57.78	92.06	189.50	98.30	19.02	4.38	13.68	34.05	81.94	34.33	3.07
% Deviation#	13.78	-1.51	-1.58	-0.65	1.94	2.67	2.64	0.02	-0.75	3.03	0.88	0.58	10.12

#Per cent deviation of top 5 cross mean from group mean

(134.18%), in three way crosses (BML 13 × BML 7) × BML 32 (28.69%) followed by (BML 7 × BML 6) × BML 51 (28.51%) and in double crosses (BML 13 × BML 7) × (BML 10 × BML 6) (23.79%) followed by (BML 51 × BML 10) × (BML 32 × BML 7) (17.14%). The above mentioned crosses also exhibited increased heterobeltiosis with decreased environmental quality supporting the fact that stability of these crosses proved through regression model is partly attributed to the increased heterobeltiosis resulted from the increased yield of these crosses than parents due to decreased environmental quality. Zhi et al. (2018) studied g x e interaction on F_1 performance in maize across the diverse environment and reported that heterosis is influenced by the environment. They also found that variance across the environments was not significantly different among the traits in inbreds and hybrids. The results on g x e interactions for identifying baby corn hybrids of maize were supportive to the higher proportion of the variation is attributable to environment (Choudhary et al. 2019). Among the parents BML 51 (x=3829 kg, bi=1.21), BML 32 (x=3385 kg, bi=1.02) and BML 6 (x=3406 kg, bi=2.31) were found to be stable and suitable for all environments with regression coefficient non significantly deviating from unity. With regards to grain

Table 4b. Percent deviation of bottom five single, three way and double crosses from overall mean of single, three way and double crosses, respectively for grain yield and yield components

Particulars	GY	DT	DS	DM	PLHT	EHT	EL	ED	NKRE	NKRR	SH	100 KW	FY
Single cross													
BML-32×BML-14	6666	58.50	60.33	95.33	182.50	83.50	19.83	4.33	12.83	34.83	82.60	34.66	2.70
BML-13×BML-7	6383	54.83	57.00	89.67	155.70	80.17	18.45	4.29	13.02	33.02	81.82	33.88	2.54
BML-10×BML-6	6241	55.83	59.00	91.83	169.20	91.50	16.28	4.33	15.23	32.62	79.15	27.57	2.72
BML-7×BML-6	6215	57.50	60.50	92.17	194.20	103.83	17.50	4.46	14.43	34.45	79.87	27.23	2.57
BML-13×BML-10	6208	50.17	52.67	89.83	148.80	79.67	17.30	4.19	13.52	30.87	81.78	30.79	2.74
Bottom 5 mean	6343	55.37	57.90	91.77	170.08	87.73	17.87	4.32	13.81	33.16	81.04	30.82	2.65
Group mean	7160	55.20	57.70	91.60	182.40	93.40	18.80	4.40	13.60	33.70	82.00	33.70	2.90
% Deviation#	-11.41	0.30	0.35	0.18	-6.75	-6.07	-4.93	-1.83	1.52	-1.61	-1.17	-8.53	-8.58
Three way cross	GY	DT	DS	DM	PLHT	EHT	EL	ED	NKRE	NKRR	SH	100 KW	FY
(27)5	5824	54.00	57.17	92.17	175.80	88.83	18.03	4.39	14.13	30.95	78.00	29.15	2.52
(12)6	5734	60.00	61.17	94.67	187.30	90.83	17.40	4.25	13.35	32.18	78.73	28.40	2.56
(45)6	5686	57.00	60.00	92.83	173.80	89.83	17.63	4.37	13.95	29.15	79.55	30.58	2.62
(67)4	5675	53.83	56.83	90.67	168.30	80.33	18.30	3.93	15.25	34.55	80.88	24.39	2.46
(36)7	5387	57.67	60.67	92.00	173.50	88.67	16.48	4.37	14.07	30.27	78.27	27.82	2.49
Bottom 5 mean	5661	56.50	59.17	92.47	175.74	87.70	17.57	4.26	14.15	31.42	79.09	28.07	2.53
Group mean	7017	55.50	57.93	92.17	188.20	97.11	18.93	4.40	13.82	33.74	81.57	33.54	2.97
% Deviation#	-19.32	1.81	2.13	0.32	-6.62	-9.69	-7.18	-3.12	2.42	-6.86	-3.04	-16.32	-14.97
Double cross	GY	DT	DS	DM	PLHT	EHT	EL	ED	NKRE	NKRR	SH	100 KW	FY
(2367)	6221	55.17	58.50	91.83	192.30	96.50	19.85	4.34	14.13	36.03	81.65	28.89	3.17
(1256)	6137	56.83	59.33	93.67	196.20	99.83	17.97	4.15	13.13	32.65	81.12	31.93	2.88
(2456)	6002	56.17	59.00	93.50	183.00	96.33	19.08	4.02	13.92	34.22	82.77	32.01	2.86
(2357)	5962	59.33	62.17	94.67	174.50	85.17	18.68	4.34	13.70	33.28	81.68	31.00	2.47
(1726)	5867	59.50	61.17	91.50	198.20	97.00	18.25	4.31	13.43	32.87	82.50	30.35	2.82
Bottom 5 mean	6038	57.40	60.03	93.03	188.84	94.97	18.77	4.23	13.66	33.81	81.94	30.83	2.84
Group mean	7197	55.34	57.78	92.06	189.50	98.30	19.02	4.38	13.68	34.05	81.94	34.33	3.07
% Deviation#	-16.11	3.73	3.90	1.06	-0.35	-3.40	-1.32	-3.48	-0.09	-0.69	0.00	-10.19	-7.67

GY = Grain yield (kg ha^{-1}), DT = Days to 50% tasseling, DS = Days to 50% silking, DM = Days to maturity, PLHT = Plant height (cm), EHT = Ear height (cm), EL = Ear length (cm), ED = Ear diameter (cm), NKRE = Number of kernel rows ear^{-1}, NKRR = Number of kernels row^{-1}, SH = Shelling percentage (%), 100 KW = 100-kernel weight (g) and FY = Fodder yield (kg $plot^{-1}$)

#Per cent deviation of bottom 5 cross mean from group mean

yield, the mean values of parents are much lower than the top performing hybrids indicating that with the same environment and agronomic practices, these parents had low grain yields than hybrids across the environments (Figs. 4a and b). High SCA and high heterobeltiosis in low or medium yielding environment could have resulted because a faster growing hybrid population could take full advantage of favourable environmental conditions early in the season and better tolerate unfavourable conditions occurring later in the season. This could result in increased grain yields and stability relative to the inbreds which in turn shows desirable heterosis in heterozygotes over its homozygous parents. Reverse to this would occur under favourable environmental conditions where any advantage associated with increased rate of growth would be negated by inbred genotypes exploiting a full season of favourable conditions (Went, 1953). Therefore these single, three way and double crosses could be regarded as stable and feasible for the tested environments than parents for achieving higher yields. High heterobeltiosis and high SCA across environments indicated the substantial genetic diversity among the parents (Moll et al. 1965) and supported the selection of these inbreds for development of single and multiple crosses. Therefore these results highlighted the importance of these potential parents for future maize breeding programme in the tested environments to achieve yield stability. Stable performance of high yielding crosses was partly attributed to the stability of the yield contributing traits, desirable interaction of non additive effects with environment and their individual buffering capabilities. Hence these crosses could be used as stable combinations across the environments taking into account of their *per se* performance, heterosis and combining ability performances across the environments.

Authors' contribution

Conceptualization of research (KS, TP); Designing of the experiments (KS, TP); Contribution of experimental materials (TP); Execution of field/lab experiments and data collection (KS, DS); Analysis of data and interpretation (KS, TP); Preparation of manuscript (KS, TP, DS).

Declaration

The authors declare no conflict of interest.

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