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PREDICTION OF DOUBLE CROSS PERFORMANCE BASED ON SINGLE AND THREE-WAY CROSSES IN MAIZE (*Zea mays*)

K. SUMALINI[*1], T. PRADEEP[2] and D. SRAVANI[1]

[1,3]Agricultural Research Station, Professor Jayashankar Telangana State Agricultural University (PJTSAU), Karimnagar - 505001, Telangana, India
[2]Seed Research and Technology Centre, Professor JayashankarTelangana State Agricultural University (PJTSAU), Rajendranagar, Hyderabad - 500030, Telangana, India
*Corresponding author's email: sumalinikatragadda@gmail.com
Email addresses of co-authors: tekalepradeep@yahoo.co.in, dsravanireddy@gmail.com

SUMMARY

A new set of seven promising maize inbred lines were involved in half-diallel mating design to get 21 single crosses. These were further utilized to produce all possible 105 each three-way and double crosses. The single, three-way and double crosses along with their seven inbred parents and 18 checks were evaluated during the rainy season 2015 at three locations *viz*., Hyderabad, Karimnagar and Palem Research Centers of Professor Jayashankar Telangana State Agricultural University (PJTSAU), Hyderabad, India. Performance of double cross hybrids was predicted based on the performance of single and three-way crosses. Actual grain yields of the double cross hybrids were found to be higher than the predicted yields in majority of the hybrids tested at Karimnagar and Palem locations and in the pooled analysis. However, a reverse trend was observed at Hyderabad location. The double cross hybrids *viz*., (BML-51 × BML-14) × (BML-10 × BML-7) and (BML-32 × BML-6) × (BML-13×BML-10) with grain yields of 8362 and 8223 kg ha^{-1}, respectively were the best hybrids in pooled analysis, and needs further testing to assess their suitability for commercial exploitation. (BML-32×BML-6) × (BML-10×BML-7) had shown good performance both at Hyderabad and Karimnagar locations and locations combined. The correlation analysis revealed a positive association between the actual and the predicted performance of the double cross hybrids based on average performance of single crosses at Karimnagar and locations combined. Actual and the predicted performance of the double cross hybrids based on average performance of three-way crosses were positively correlated at Karimnagar location only. Actual mean performance of double crosses was higher than the predicted mean performance of double crosses based on single crosses and three-way crosses. It could be due to broader adaptation to environment and more protection against pests and diseases with population buffering.

Key words: Maize, double cross, non-parental single cross, three-way cross, yield prediction

Key findings: The present study indicated that highest yielding double cross combination could be predicted based on single cross data.

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INTRODUCTION

Initially, double crosses were commercially used because more seed of a desirable size and shape could be produced on a single cross parent than on the inbred lines as a parent. Now-a-days, single crosses are exploited commercially due to more uniformity and high yielding capacity. However, in recent years, an increasing trend towards susceptibility of the inbred lines to biotic and abiotic stresses has been observed, and this has become a limiting factor in the production of single crosses for commercial production. Sprague and Federer (1951) reported that double crosses interact with environments less than single crosses and double crosses are superior to single crosses for stability of performance. The hypothesis advanced was that, since each double cross is a mixture of genotypes, whereas each single cross is theoretically a single genotype, the double cross would vary less in its performance over a series of environments. Allard and Bradshaw (1964) suggested that heterozygous and heterogeneous populations offer the best opportunity to produce varieties which show small genotype-environment interactions, greater stability of production, broader adaptation to environment, and greater protection against disease with population buffering.

In the development of a double cross, it is necessary to ascertain how the four inbred lines can be combined to obtain the best double cross. The number of possible double crosses also becomes unmanageable, if number of inbreds is more than six. The number of possible double crosses obtained involving 'n' number of inbreds is n (n-1) (n-2)/2. Methods of prediction of double cross hybrid performance was devised and tested soon after the recognition of commercial potential of double cross maize hybrids. Jenkins (1934) suggested four methods and obtained significant correlations between predicted and observed double cross means. Anderson (1938) and Hayes *et al*. (1946) reported good agreement of predicted and observed means when they used non-parental single cross means for the prediction of double cross performance (Jenkins method B). As the double cross involves single crosses as parents, new inbred lines are to be tested for specific combining ability with a seed parent after identification as a good general combiner. Prediction of double cross performance based on three-way cross means was also used by previous breeders. Here, instead of predicting the performance of all possible double crosses, the average of two appropriate three way crosses is used to predict only the double crosses with the selected single crosses as seed parent.

MATERIALS AND METHODS

Seven promising inbred lines of maize were crossed in a diallel fashion excluding reciprocals to obtain twenty one crosses during rainy season of 2014 and were further utilized to obtain all possible three-way and double cross hybrids during post rainy season, 2014 at Agricultural Research Station, Karimnagar, India. All the 21 single crosses and 105 each of three-way and double crosses along with seven parents and eighteen public /private checks were evaluated during rainy season of 2015 at three locations i.e. Maize Research Centre, Agricultural Research Institute, Rajendranagar, Hyderabad; Agricultural Research Station, Karimnagar and Regional Agricultural Research Station, Palem, India. All these 256 entries were laid out in balanced lattice (16 × 16) in two replications at each location. As gain in efficiency for lattice design is small over a randomized block design (Eberhart *et al*., 1964). Balanced lattice (16 × 16) was analyzed as randomized block design. Of the 18 private/public checks tested, only five widely adapted/newly released checks were used in statistical analysis. Each entry was sown in two rows of 3 m length spaced at 75 × 20 cm^2. All the recommended agronomic practices and plant protection measures were provided to raise a healthy crop. The grain yield obtained was corrected for stand variation using the methodology of covariance, as suggested by Mendes *et al*. (2015) (Vencovsky and Barriga, 1992); grain yield correction was done 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 Lauer (2002). Simple phenotypic correlations between actual and predicted performances of double cross hybrids were computed and their significance was determined using the t-test for individual locations and pooled data.

Five methods are available for the prediction of double cross performance based on the means of single crosses and three-way crosses when only additive and dominance effects were considered. S_{ij} will be used to denote the single cross (line i × line j), $T_{ij.k}$ will be used for the three-way cross (S_{ij} × line k), and $D_{ij.kl}$ denotes the double cross ($S_{ij} \times S_{kl}$). The five prediction formulas are presented below.

$$D^{\wedge sa}_{ij.kl} = 1/6\ (S_{ij+} S_{ik} + S_{il} + S_{jk} + S_{jl}+S_{kl})$$
$$D^{\wedge sb}_{ij.kl} = 1/4\ (S_{ik} + S_{il} + S_{jk} + S_{jl})$$
$$D^{\wedge tij}_{ij.kl}= 1/2\ (\ T_{ij.k} + T_{ij.l})$$
$$D^{\wedge tkl}_{ij.kl}= 1/2\ (\ T_{kl.i} + T_{kl.j})$$
$$D^{\wedge t}_{ij.kl}= 1/2\ (\ D^{tij}_{ij.kl\ +}\ D^{tkl}_{ij.kl})$$
$$D^{\wedge t\text{-}s}_{ij.kl}= 2\ D^{\wedge t}_{ij.kl}\text{-}\ D^{\wedge s}_{ij.kl}$$

The first two formulae based on performance of single crosses were proposed by Jenkins (1934) as methods A and B. The second formula $D^{\wedge sb}_{ij.kl}$based on performance of non-parental single crosses has been used extensively. The last formula, based on three-way cross performance, $D^{\wedge t}_{ij.kl}$ has been used less than $D^{\wedge sb}_{ij.kl}$ to predict all possible double crosses from a set of lines, because more three-way crosses than single crosses are needed. However, $D^{\wedge tij}_{ij.kl}$ is commonly used when a desirable single cross S_{ij} is available, and new lines k and 1 are to be selected to form the double cross $D_{ij.kl.}$

All the five prediction formulae are unbiased by additive effects and dominance effects except $D^{\wedge sa}_{ij.kl}$ by dominance effects. If epistasis is negligible, $D^{\wedge sb}_{ij.kl}$, $D^{\wedge tij}_{ij.kl,}$ $D^{\wedge tkl}_{ij.kl}$ or $D^{\wedge t}_{ij.kl}$ adequately predict the double cross provided the genotype × environmental interactions and the experimental errors are not of unreasonable magnitude. Although all prediction formulae are biased by epistasis, $D^{\wedge t}_{ij.kl}$ contains less bias than $D^{\wedge sb}_{ij.kl.}$ Because of the linear relation of the epistatic effects in $D^{\wedge sb}_{ij.kl}$ and $D^{\wedge t}_{ij.kl}$, a linear function of these formulae will predict the genetic effects that occur in the double cross except for part of the dominance × dominance epistasis. This linear function will be designated by $D^{\wedge t\text{-}s}_{ij.kl}$, where $D^{\wedge t\text{-}s}_{ij.kl}= 2D^{\wedge t}_{ij.kl} – D^{\wedge sb}_{ij.kl.}$

RESULTS AND DISCUSSION

Analysis of variance for grain yield at individual locations revealed significant differences among the genotypes tested. In quadriallel analysis of double crosses, significant effect of locations is the result of variations among locations. Significant effects of double crosses were shown at all the three locations indicating that double crosses differed in performance at each location. However, the differences among double crosses were found to be non-significant for the combined locations implying that the performance of each double cross was similar at all the three locations and the variances were quite homogeneous. It is clearly evident from the test of homogeneity that error variances were found to be homogeneous for grain yield (Table 1). Therefore, results from the combined analysis appeared to be relevant.

Table 1. Test of homogeneity of error variances from the ANOVA on performance of double cross maize hybrids between locations.

Locations	Error	F calculated
Hyderabad	245721.500	
Karimnagar	406888.760	9.53 (p 0.009)
Palem	436549.362	

Average yield superiority of the double cross hybrids over the check hybrids was indicated with an excellent performance of (BML-51 × BML-14) × (BML-10 × BML-7) and (BML-32 × BML-6) × (BML-13 × BML-10) with grain yields of 8362 and 8223 kg ha^{-1}, respectively at locations combined. (BML-51 × BML-14) × (BML-10 × BML-7) was found to be promising with grain yields of 10054 kg ha^{-1} at Palem and 8715 kg ha^{-1} at Hyderabad, whereas (BML-32 × BML-6) × (BML-13 × BML-10) was found to be promising with grain yield of 8019 kg ha^{-1} at Karimnagar (Table 2). These could be exploited for commercial production. Eberhart and Russell (1969) found that single crosses were less stable than double crosses, but they emphasized that some single crosses were just as stable as the best double crosses. Weatherspoon (1970) also opined that stability of the genotypes is influenced by heterogeneity of the genotypes and is evident from the greater significant interaction for single cross hybrids × environments than three-way crosses × environments and double crosses × environments.

The best double cross (BML-32 × BML-6) × (BML-10 × BML-7) at Hyderabad and Karimnagar locations recorded mean grain yields of 8501 and 7747 kg ha^{-1}, respectively while (BML-51 × BML-14) × (BML-10 × BML-7) with mean grain yields of 8715 and 10054 kg ha^{-1}, respectively, was the best at Hyderabad and Palem location. These two double crosses also showed good performance at locations combined. The predicted grain yields of the double cross hybrids were found to be lower than the actual in majority of the hybrids tested at Karimnagar and Palem locations and the locations combined, but a reverse trend was observed at Hyderabad location. The correlation coefficient between the actual and predicted performance based on single crosses was -0.002, 0.17, 0.15 and 0.21, respectively at Hyderabad, Karimnagar, Palem and the locations combined. Significant correlation was observed only at Karimnagar location and locations combined. Similar trend was observed for the correlation coefficient between the actual and predicted performance based on three-way crosses at locations and locations combined except at Karimnagar with significant positive correlation (Table 3).

Top twenty six double crosses comprising 25% of the total possible 105 double crosses are listed (Table 4) in order of their expected yields as predicted by $D^{\wedge s}$. The means as predicted by $D^{\wedge t}$ and $D^{\wedge t\text{-}s}$ also are listed. The epistatic effects biased many of the double cross means predicted by $D^{\wedge s}$ and by $D^{\wedge t}$, which was evident from highly significant simple phenotypic correlation between the two methods at individual locations and locations combined (Table 3). Of these 26 double crosses predicted to rank in the top 25% on the basis of method $D^{\wedge s}$, 12 were predicted to be in the top 25% by method $D^{\wedge t}$ and 4 by method $D^{\wedge t\text{-}s}$. The hybrid ranked fourth by method $D^{\wedge t\text{-}s}$ was ranked 17th by $D^{\wedge s}$ and 2nd by $D^{\wedge t}$. The difference between the mean for a hybrid as predicted by $D^{\wedge t\text{-}s}$ and the mean predicted by $D^{\wedge s}$ ranged from 1825 kg ha^{-1} (7704 -5897) for (BML-51 × BML-10) × (BML-14 × BML-7) to -1192 kg ha^{-1} for (BML-32 × BML-13) × (BML-14 × BML-7) (6818 – 8010; data was not shown in the table as it is not in top 25% of total 105 double crosses) with an average difference of 317 kg ha^{-1} [1825 + (-1192)/2].

Comparison of the actual yield of double crosses with non-parental single crosses revealed that the average double cross yields were high or similar to average of non-parental single crosses at Karimnagar, Palem and locations combined, whereas at Hyderabad an average decrease in yield of 5.85% was noted in actual mean of double crosses as against predicted mean of double crosses based on average of non-parental single crosses (Table 3). Similarly, average double cross yields are high or similar to the average of predicted yields based on three-way crosses at all locations and locations combined.

It is expected that the set of inbred lines derived from a population with linkage equilibrium will provide single cross hybrids with the same mean as that of all possible three-way crosses from the same set of lines (Eberhart *et al*., 1964). When selected lines are used, the difference in the mean for single crosses and for three-way crosses depends upon the amount and nature of epistatic deviations present. Apparently, combinations of loci which have favorable epistatic effects were fixed in at least

Table 2. Mean values for grain yield measured on double cross maize hybrids and check varieties at Hyderabad, Karimnagar, Palem and locations combined.

Hyderabad		Karimnagar		Palem		Locations combined	
Double cross/Check hybrid	Grain yield (kg ha^{-1})	Double cross/Check hybrid	Grain yield (kg ha^{-1})	Double cross/Check hybrid	Grain yield (kg ha^{-1})	Double cross/Check hybrid	Grain yield (kg ha^{-1})
(14 × 6) × (13 × 7)	8891	(51 × 6) × (32 × 10)	8549	(51 × 14) × (10 × 7)	10054	(51 × 14) × (10 × 7)	8362
(14 × 13) × (10 × 7)	8852	(51 × 14) × (13 × 6)	8157	(51 × 13) × (32 × 7)	9938	(32 × 6) × (13 × 10)	8223
(51 × 14) × (10 × 7)	8715	(51 × 13) × (32 × 10)	8046	(51 × 14) × (13 × 7)	9627	(14 × 6) × (13 × 7)	8190
(32 × 14) × (13 × 6)	8607	(51 × 32) × (13 × 6)	8040	(51 × 13) × (32 × 14)	9345	(51 × 10) × (32 × 7)	8086
(32 × 10) × (13 × 7)	8547	(32 × 6) × (13 × 10)	8019	(51 × 10) × (32 × 7)	9170	(51 × 13) × (32 × 14)	8081
(51 × 14) × (13 × 10)	8541	(51 × 7) × (32 × 14)	7925	(32 × 7) × (14 × 13)	9154	(51 × 32) × (13 × 6)	8044
(32 × 6) × (14 × 7)	8515	(13 × 7) × (10 × 6)	7851	(32 × 10) × (7 × 6)	9093	(51 × 6) × (32 × 10)	7997
(32 × 6) × (10 × 7)	8501	(51 × 10) × (7 × 6)	7780	(32 × 14) × (13 × 7)	9082	(32 × 14) × (13 × 6)	7993
(32 × 10) × (13 × 6)	8384	(32 × 6) × (10 × 7)	7747	(51 × 6) × (32 × 14)	8919	(51 × 7) × (32 × 14)	7966
(51 × 7) × (13 × 10)	8205	(51 × 6) × (14 × 10)	7699	(32 × 10) × (14 × 7)	8884	(32 × 6) × (10 × 7)	7934
900M Gold	5921	900M Gold	5478	900M Gold	7480	900M Gold	6293
NK6240	7597	NK6240	6184	NK6240	7671	NK6240	7150
Ekka 2288	5551	Ekka 2288	7866	Ekka 2288	8134	Ekka 2288	7183
KNMH-4010131	5175	KNMH-4010131	7324	KNMH-4010131	9502	KNMH-4010131	7334
DHM-117	6604	DHM-117	6722	DHM-117	6576	DHM-117	6634
L.S.D. (0.05)	983	-	1265	-	1310	-	1329
CV (%)	7.20	-	9.36	-	8.37	-	11.06

Table 3. Predicted mean and actual mean performance of double cross hybrids and their correlations at each of the three locations and locations combined.

Performance	Hyderabad	Karimnagar	Palem	Locations combined
Actual	6884	6813	7892	7197
Predicted (D^s)	7312	6427	7740	7160
Correlations ®	-0.002	0.169*	0.152	0.208*
Predicted (D^t)	6601	6605	7844	7017
Correlations ®	-0.069	0.261**	0.088	0.124
Predicted (D^{t-s})	5891	6784	7949	6874
Correlations ®	-0.069	0.190*	0.024	0.039
Correlation between single cross and three-way cross prediction	0.263**	0.284**	0.350**	0.526**

Table 4. Predicted means of 26 double crosses (25%) from seven inbred lines of maize based on the average single cross ($D^{\wedge s}$) and three-way cross ($D^{\wedge t}$) performance in locations combined.

No.	Double cross	Actual yield (kg ha^{-1})	Predicted yield (kg ha^{-1})		
			$D^{\wedge s}$	$D^{\wedge t}$	$D^{\wedge t-s}$
1	(BML-51 × BML-32) × (BML-14 × BML-6)	6996	7824	7408	6991
2	(BML-51 × BML-13) × (BML-32 × BML-14)	8081	7817	7409	7001
3	(BML-51 × BML-13) × (BML-14 × BML-6)	7538	7784	7307	6829
4	(BML-51 × BML-6) × (BML-32 × BML-14)	7805	7728	7479	7231
5	(BML-51 × BML-10) × (BML-14 × BML-7)	7351	7704	6791	5879
6	(BML-51 × BML-7) × (BML-32 × BML-14)	7966	7690	7615	7541
7	(BML-51 × BML-32) × (BML-13 × BML-6)	8044	7679	7276	6874
8	(BML-51 × BML-7) × (BML-14 × BML-6)	6795	7657	7624	7590
9	(BML-51 × BML-32) × (BML-7 × BML-6)	6921	7645	7174	6704
10	(BML-51 × BML-7) × (BML-14 × BML-10)	6476	7642	6961	6280
11	(BML-51 × BML-14) × (BML-7 × BML-6)	6991	7575	7662	7749
12	(BML-51 × BML-10) × (BML-32 × BML-14)	7482	7569	7380	7191
13	(BML-51 × BML-13) × (BML-32 × BML-6)	7063	7566	7332	7099
14	(BML-51 × BML-13) × (BML-14 × BML-7)	7008	7563	6800	6038
15	(BML-51 × BML-32) × (BML-14 × BML-13)	7555	7554	7345	7135
16	(BML-51 × BML-32) × (BML-14 × BML-7)	6916	7520	6950	6379
17	(BML-51 × BML-10) × (BML-14 × BML-6)	7212	7502	7689	7876
18	(BML-51 × BML-14) × (BML-13 × BML-7)	7934	7475	7209	6942
19	(BML-51 × BML-7) × (BML-14 × BML-13)	7908	7471	7070	6669
20	(BML-51 × BML-32) × (BML-10 × BML-6)	7305	7462	6931	6400
21	(BML-51 × BML-10) × (BML-32 × BML-7)	8086	7438	6990	6542
22	(BML-51 × BML-6) × (BML-14 × BML-13)	6863	7426	6818	6210
23	(BML-51 × BML-14) × (BML-32 × BML-7)	6295	7402	7250	7098
24	(BML-32 × BML-14) × (BML-13 × BML-6)	7993	7399	7004	6610
25	(BML-51 × BML-6) × (BML-14 × BML-7)	7214	7391	6650	5909
26	(BML-51 × BML-6) × (BML-32 × BML-13)	7045	7378	7294	7211
Average of 105 double crosses		7197	7160	7017	6874

some of these inbred lines by the selection procedures used. Because recombination in the parental single cross of each three-way cross provided an opportunity for the loss of some of these favorable epistatic combinations, the average three-way cross yields were less than the single cross yields. Similarly, a corresponding reduction from three-way to double cross performance is also expected. But, in this study actual double cross performance is numerically higher than the predicted performance based on single crosses and three-way crosses. This could be due to fixation of favorable loci in few of the inbreds. Sujiprihati *et al*. (2003) also observed higher actual yields of double crosses than predicted yields at Field 2, Share Farm and locations combined. In thisstudy, high genotypic correlation between single cross and three-way cross predictions suggests that additive and dominance effects are of greater importance than epistasis in predicting double cross performance for this set of seven inbred lines.

CONCLUSION

The mean yields of all possible single crosses and three-way crosses from seven inbred lines of maize were used to predict double cross performance. No deviation in the average grain yield of double crosses was observed from single crosses at Karimnagar and Palem locations and the locations combined. It indicated that with the appropriate use of single cross data, the highest yielding double cross combination may be predicted. The actual yields of some of the double crosses were less than the predicted means because of epistatic bias. The genotype by environmental interactions and the plot error may affect the accuracy of the prediction formulae to a greater extent than the epistatic bias. This can be overcome by increasing the number of locations for evaluating the single cross or three-way crosses.

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