Acta Scientiarum. Agronomy
ISSN: 1679-9275
eduem@uem.br
Universidade Estadual de Maringá
Brasil

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Acta Scientiarum. Agronomy, vol. 33, núm. 2, abril-junio, 2011, pp. 243-249
Universidade Estadual de Maringá
Maringá, Brasil

DOI: 10.4025/actasciagron.v33i2.9607

Heterotic parameterizations of crosses between tropical and temperate lines of popcorn

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ABSTRACT. We examined the heterotic parameterizations of diallel crosses among 10 popcorn inbred lines in two different environments (municipalities of Campos dos Goytacazes and Itaocara, Rio de Janeiro State) and originating from tropical, temperate and subtropical germoplasm. Traits, including grain yield (GY), plant height (PH), ear height (EH), days to silking (FL) and popping expansion (PE), were measured. The inbred lines and the hybrids were evaluated in a randomized complete block design with three replications. The sources of genotypic variation, inbred lines and heterosis had significant effects on all traits. When the sources of heterotic variation were compared separately, estimated mean heterosis was found to be significant for all traits. When inbred lines and specific heterosis was investigated, only popping expansion was not significantly different, demonstrating that heterotic effects are favorable for developing superior hybrids. A direct relation between $\hat{g}_i$ and $\hat{V}_i$ was made clear, especially for traits that were slightly influenced by the effects of dominance. Additivity was determined to have the best effect for improving popping expansion. The hybrid combinations had positive estimates of heterosis for the GY but not for PE. The hybrids P_1 x P_3 and P_2 x P_4 had the best responses for the GY and PE. The superiority of the combination P1 x P3 shows that the addition of genomes with different edaphoclimatic adaptations is an important factor in obtaining superior hybrids.

Keywords: *Zea mays* L., diallel crosses, yield and popping expansion.

RESUMO. Parametrizações heteróticas de cruzamentos entre linhagens tropicais e temperadas de milho pipoca. O presente trabalho teve com objetivo averiguar as parametrizações heteróticas de cruzamentos dialélicos entre dez linhagens de milho pipoca oriundas de genótipos tropicais, temperados e semi-temperados, em dois ambientes (municípios de Campos dos Goytacazes e Itaocara, Estado do Rio de Janeiro), em relação às características rendimento de grãos; altura média de planta e da inserção da primeira espiga; número médio de dias para florescimento e capacidade expansão. As linhagens e os híbridos foram avaliados em delineamento em blocos ao acaso, com três repetições. Para as fontes de variação linhagens e heterose houve significância, pelo teste F, para todas as características. No desdobramento da fonte de variação heterose, estimativas de heterose média foram significativas para todas as características. Em relação à heterose de linhagens e específica, apenas a característica capacidade de expansão não expressou diferença significativa, o que confirma que os efeitos heteróticos não são favoráveis para síntese de híbridos com superioridade. A relação direta entre $\hat{g}_i$ e $\hat{V}_i$ ficou claro, especialmente para as características pouco influenciadas pelos efeitos de dominância. O efeito gênico aditivo foi confirmado para capacidade de expansão. As combinações híbridas revelaram estimativas positivas de heterose para GY, mas não para PE. Os híbridos P_1 x P_2 e P_3 x P_4 tiveram as melhores respostas para GY e PE. A superioridade da combinação P_1 x P_3, demonstra que a adição de genomas com adaptação edafoclimáticas diferentes é importante para a obtenção de híbridos superiores.

Palavras-chave: *Zea mays* L., cruzamento dialélicos, produção e capacidade de expansão.

Introduction

Popcorn is quite popular in Brazil, and the crop area required for its growth has been expanding mainly due to the increased consumption of this product and of industrialized derivatives (CATAPATTI et al., 2008; FREITAS JÚNIOR et al., 2009; RANGEL et al. 2008; RINALDI et al., 2007; SCAPIM et al., 2002). However, production can be considered low with respect to the vast market potential of this crop (ARNHOLD et al., 2009).

One of the limiting factors for increasing the yield of this crop is that there are very few cultivars that have both favorable agronomic traits and high popping expansion (FREITAS JÚNIOR et al., 2009; MIRANDA et al., 2003; RINALDI et al., 2007). Currently, only four hybrids (IAC 112, IAC 125, Zélia and Jade) and three varieties (BRS ANGELA, RS 20 and UFVM2-Barão de Viçosa) are recommended and/or registered by the National System for Protection of Cultivars of the Ministry of Agriculture, Livestock and Supply (PACHECO et al., 2000; RANGEL et al., 2008; SAWAZAKI, 2001; SCAPIM et al., 2002, 2010; TRINDADE et al., 2010; VIEIRA et al., 2009).

Though rare, diallel studies of popcorn in Brazil have been nearly exclusively done with crosses between varieties (ANDRADE et al., 2002; FREITAS JÚNIOR et al., 2006; MIRANDA et al., 2008; RANGEL et al., 2008; SCAPIM et al., 2002, 2006; ZANETTE, 1989). Miranda et al. (2008), working with five genitors in a diallel cross with advanced generations of hybrids (IAC 112 and Zélia) and three varieties (RS 20, Branco and SAM), concluded the following: a) there is sufficient variability in Brazilian lines to allow for exploration of the non-additive effects for grain production, and b) there is little possibility of obtaining commercial varieties directly from local varieties because local varieties have poor popping expansion. Consequently, developing popcorn line hybrids can be considered a relevant strategy for crop improvement programs (MIRANDA et al., 2008; RANGEL et al., 2008; SILVA et al., 2010; VIEIRA et al., 2009).

To date, popcorn hybrids have not been evaluated in Brazil by diallel cross analysis. For hybrid production, the few existing published studies have been based on testcrosses to infer the combining capacity of lines at generations S_3, S_5 and/or S_6 (SAWAZAKI et al., 2000; SEIFERT et al., 2006; VIANA et al., 2007). For this reason, we decided to determine the heterotic parameterizations of diallel crosses between 10 inbred lines of popcorn derived from tropical, subtropical and temperate zone genotypes. Experiments were conducted in two different environments, examining five agronomic characteristics in total.

Material and methods

Ten pre-selected lines, originating from tropical, temperate and subtropical genotypes (Table 1), were crossed in a complete diallel scheme resulting in 45 F_1 hybrids. In March 2007, seeds of the inbred lines were planted with a spacing of 0.9 m between rows and 0.4 m between plants in the row to obtain the hybrids. Pollen grains for the crosses between lines were collected in brown paper bags during flowering.

Table 1. Origin of the popcorn inbred lines.

Parental inbreds	Description of the population which the inbred were obtained
P_1 (PR 023)	from the three-way hybrid 'Zélia', which belongs to Pioneer Seeds, and consists of temperate and tropical inbreds
P_2 (PR 024)	from the composite of yellow grains 'CMS-42', which belongs to Embrapa-Maize and Sorghum, and consists of tropical inbreds
P_3 (PR 036)	from the composite of white grains 'CMS-42', which belongs to Embrapa-Maize and Sorghum, and consists of tropical inbreds
P_4 (UEM J1)	from South American races of tropical regions
P_5 (PR 045-1) P_6 (PR 045-2) P_7 (PR 045-3)	from the three-way hybrid 'Zaeli', which consists of temperate inbreds
P_8 (PR 087-1) P_9 (PR 087-2) P_{10} (PR 087-3)	from the modified one-way hybrid 'IAC112', adapted to tropical regions, and which consists of inbreds from the open pollinated variety 'South Americam Mushroom' with inbreds from the South American intervarietal hybrid 'Guarani' x 'Amarela'

In November 2007, two trials were run in the following environments: i) in the experimental fields of the Colégio Estadual 'Antônio Sarlo', in the municipality of Campos dos Goytacazes, in the northern region of Rio de Janeiro State (21° 45' south latitude, 41° 20' W longitude and 11 m altitude), and ii) in the experimental fields of PESAGRO-RIO, in the municipality of Itaocara, in the northeastern region of the state of Rio de Janeiro (21° 39' 12" south latitude, 42° 04' 36" W longitude and 60 m altitude), 120 km away from Campos dos Goytacazes.

In both fields, the trials were carry out in a complete block experimental design with three replications. The treatments were the 45 F_1 hybrids and the 10 genitor lines. Randomization of the treatments was done separately for the group of inbred lines and for the group of hybrids so that the hybrids and inbred lines were not in neighboring plots, avoiding competition effects. The experimental plots consisted of planted rows 10.0 m long with 0.90 m spacing between rows and 0.20 m spacing between plants.

Several agronomic traits were evaluated, including the following: i) grain yield (GY), for which ears were harvested by hand in each parcel, and the production values were corrected to a standardized humidity of 15% and transformed into kg ha^{-1}, ii) mean plant height (PH), in m, of the point of insertion of the flag leaf in six competitive plants within the parcel, iii) ear height (EH), in m, in the same six plants per parcel, and iv) days to silking (FL). Popping expansion (PE), in mL g^{-1}, was also evaluated and estimated for a sample of 30.0 g of grains that were popped in a microwave oven (Panasonic, model NN-S65B) at 1000 W for 3 min. Six replications were conducted per treatment. The grains submitted to the popping test were taken from the central-basal part of the corn ears. These samples, and the 1.0 kg standard sample, were maintained in a cool, dry storage chamber. The expansion capacity estimate was made when the standard sample reached 14% humidity.

Analysis of the diallel was done using model II of Gardner and Eberhart (1966), with adaptations proposed by Morais et al. (1991) for analyses in various environments according to the statistical model.

$$Y_{ijj'} = m + \frac{(v_j + v_{j'})}{2} + e_i + \frac{(ev_{ij} + ev_{ij'})}{2} + \theta(\bar{h} + \bar{eh}_i + h_j + eh_{ij} + h_{j'} + eh_{ij'} + s_{jj'} + es_{ijj'}) + \bar{\varepsilon}_{ijj'},$$

Where: $Y_{ijj'}$ is the mean of the inbred lines if j = j' and of the cross if j ≠ j', in the i[th] environment; e_i is the environmental effect; ev_{ij} and $ev_{ij'}$ are the effects of the interaction environment x inbred lines, and h is the mean heterosis effect; h_i is the effect of the environment x mean heterosis; h_j and $h_{j'}$ are the heterosis effects of the inbred lines; eh_{ij} and $eh_{ij'}$ are the effects of the interaction environment x inbred lines heterosis; $s_{jj'}$ is the effect of specific heterosis; and $es_{ijj'}$ is the effect of the interaction environment x specific heterosis. The parameters of the model are defined by analogy to the model of Gardner and Eberhart (1966), in which for j = j', we have θ = 0 and for j ≠ j', θ = 1. The statistical analyses were done with the program GENES (CRUZ, 2006).

Results and discussion

The sources of variation genotype, inbred lines and heterosis had significant effects for all traits based on the F test (Table 2). With regard to the source of variation inbred lines, significant mean squares indicated that the lines did not constitute a uniform group, differing in the general combining capacity. The significant effect of heterosis demonstrates that heterosis affects the general combining capacity.

Separation of source of variation of heterosis revealed significant mean heterosis values for all of the traits, indicating that there is sufficient genetic divergence among the inbred lines that were evaluated to allow for genetic improvement. Inbred lines heterosis did not significantly affect PE, indicating that the lines were not significantly different for this trait. Among the other traits, the finding of most significance demonstrated that at least some of the genitors were different from each other in terms of mean genetic frequencies or in the degree of dispersion of these frequencies.

When specific heterosis was evaluated, it was found that only PE did not differ significantly, which demonstrates that these heterotic effects are not favorable for the synthesis of superior hybrids. This conclusion is similar to that of former studies that demonstrated the superiority of additivity for PE (DOFING et al., 1991; FREITAS JÚNIOR et al., 2006; LARISH; BREWBAKER, 1999; LYERLY, 1942; PACHECO et al., 1998; PEREIRA; AMARAL JÚNIOR, 2001; RANGEL et al., 2008; SCAPIM et al., 2006; SIMON et al., 2004; VIANA; MATTA, 2003).

However, it is important to understand that the lack of importance of heterosis for PE does not impede the ability to obtain superior hybrid combinations because if one has lines with elevated CE, due to successive expression of additivity in a series of selfings, this same additivity will help the hybrid express the mean of the estimates of PE in the genitor inbred lines.

Table 2. Combined analysis of variance of the five traits, using the methodology of Gardner and Eberhart (1966), in a diallel cross between 10 popcorn inbred lines. Campos dos Goytacazes and Itaocara, Rio de Janeiro State.

Source of variation	df	Mean square of traits[1/]				
		GY	PH	EH	FL	PE
Genotypes (G)	54	3294181.2991 **	0.2715 **	0.1159 **	136.5277 **	5.9008 **
Inbred Lines (L)	9	8013436.3216 **	0.4740 **	0.2637 **	57.9929 **	31.7997 **
Heterosis (H)	45	2350330.2946 **	0.2310 **	0.0863 **	152.2347 **	0.7211 **
Mean Heterosis (M)	1	55323786.1878 **	0.9500 **	0.6530 **	2413.6706 **	12.7574 **
Inbred Lines Heterosis (IL)	9	2383559.1237 **	0.1430 **	0.0370 **	28.5926 **	0.3991 n.s.
Specific Heterosis (S)	35	828258.4273 **	0.2331 **	0.0829 **	119.4159 **	0.4599 n.s.
Environment (E)	1	7015589.8315 **	14.8952 **	2.1749 **	84.5830 **	0.0318 n.s.
G x E	54	457732.9609 **	0.1765 **	0.0597 **	112.8340 **	0.0941 n.s.
L x E	9	608958.3015 **	0.1407 **	0.0499 **	121.8820 **	0.0700 n.s.
H x E	45	427487.8927 **	0.1837 **	0.0616 **	111.0244 **	0.0989 n.s.
M. Heterosis x E	1	3825176.2117 **	0.0015 n.s.	0.0233 n.s.	8.4162 n.s.	0.8849 n.s.
IL. Heterosis x E	9	212041.4128 **	0.0914 **	0.0390 **	51.5329 **	0.1884 n.s.
S. Heterosis x E	35	385811.6070 **	0.2126 **	0.0685 **	129.2539 **	0.0535 n.s.
Error	216	83668.8350	0.0250	0.0080	4.5100	0.3514

[1]GY = Grain Yield; PH = Plant Height; EH = Ear Height; FL = Days to silking; and PE = popping expansion. n.s = not significant (p > 0.05); ** = significant at p ≤ 0.01; * = significant at p ≤ 0.05.

Analysis of the sources of environmental variation, including genotype x environment, inbred lines and heterosis x environment interactions gave significant values for all traits but PE (Table 2). Alexander and Creech (1977) indicated that inheritance of PE is polygenic with little environmental influence. When heterosis was partition in mean heterosis x environments, inbred lines heterosis x environments and specific heterosis x environments, the following results were found: i) in mean heterosis x environments, only GY was significantly affected, and ii) in inbred lines heterosis x environments and specific heterosis x environments, only PE was not significantly affected.

For grain yield, the inbred lines P_3, P_5, P_2 and P_4 were the most promising *per se* for use due to the high values expressed for the $\hat{V}_i$ estimate (Table 3). Despite the reduced values, the characteristics PH and EH had higher magnitudes of $\hat{V}_i$ for the inbred lines P_4 and P_5, indicating that these lines contributed to increases in the value of this trait. On the other hand, considering the interest in the reduction of plant size and height of the first ear because of the high winds that are common in Campos dos Goytacazes and Itaocara, the line with the best performance *per se* was P_1. Although P_7 also resulted in negative values for both traits, they were of low magnitude (Table 3).

Table 3. Estimates of the means of the inbred lines effects ($\hat{V}_i$) and the corresponding standard deviations (SD), using the methodology of Gardner and Eberhart (1966), for five traits evaluated in 10 popcorn inbred lines. Campos dos Goytacazes and Itaocara, Rio de Janeiro State.

Inbred Lines effects (V_i)[1]	Traits[2]				
	GY	PH	EH	FL	PE
P1	-786.7490	-0.5400	-0.3460	1.4325	-0.7280
P2	318.2510	0.1420	0.0240	-0.0675	1.1453
P3	339.9160	-0.0900	0.0340	-0.2325	-1.0880
P4	267.4160	0.1620	0.1240	-0.5675	-0.8113
P5	324.0810	0.1670	0.1190	-0.0675	-1.3113
P6	-14.2540	-0.0400	0.0090	1.1025	-1.1213
P7	-350.9140	-0.0900	-0.1160	-0.3975	-1.3213
P8	159.0860	0.1570	0.0990	-0.4025	2.4120
P9	-212.5840	0.1070	0.0590	-0.5675	1.3287
P10	-44.2490	0.0420	-0.0060	-0.2325	1.4953
Mean	1475.0840	1.8930	1.0910	60.0675	33.1710
SD (Mean)	2788.9611	0.0008	0.0003	0.1503	0.0117
SD ($\hat{V}_i$)	25100.6505	0.0075	0.0024	1.3530	0.1054
SD ($\hat{V}_i$-$\hat{V}_J$)	55779.2233	0.0166	0.0053	3.0060	0.2342

[1]P_1 = PR 023; P_2 = PR 024; P_3 = PR 036; P_4 = UEM J1; P_5 = PR 045-1; P_6 = PR 045-2; P_7 = PR 045-3; P_8 = PR 087-1; P_9 = PR 087-2; P_{10} = PR 087-3. [2]GY = Grain Yield; PH = Plant Height; EH = Ear Height; FL = Days to silking; and PE = popping expansion.

Inbred Lines P_4 and P_9 stood out as being exceptional for the FL trait because they gave high negative values for the estimate $\hat{V}_i$, which revealed potential for reducing the number of days to flowering in intrapopulational breeding programs. Six Inbred lines gave negative estimates of $\hat{V}_i$ for PE, including the following: P_1, P_3, P_4, P_5, P_6, and P_7. Based on these results, a direct relation between $\hat{g}_i$ and $\hat{V}_i$ was made clear, especially for traits that were little influenced by the effects of dominance, such as PE, in which dominance contributed only 10% towards total inherent heterosis of the sum of squares of the genotypes.

We can affirm that inbred lines P_2, P_3, P_4 and P_5 were the most promising for the greatest number of traits, especially for grain yield. Nevertheless, these inbred lines did not have good values for PE, demonstrating that the best genitors for production are not the best for grain quality.

In terms of the amplitude of variation in the effects of genitors and between genitors, it can be concluded that the genitors differ when the amplitude of variation is greater than twice the standard deviation; that is, there is genetic variability between the inbred lines (SINGH; CHAUDHARY, 1985). The characteristics PH, EH and PE had differences greater than two. Characteristic GY gave the lowest value (0.0202). This leads to the idea that allelic complementations contributed more than differences between the inbred lines for heterotic expression of these characteristics.

The characteristic GY gave high positive values for mean heterosis, demonstrating the expected hybrid vigor. FL gave negative heterosis values, demonstrating the possibility of selecting for precocity (Table 4). On the other hand, the mean negative heterosis for PE indicated that genetic improvement through heterosis of these inbred lines will not be viable. Consequently, it is necessary to follow the premise of Scapim et al. (2006), who indicated that when there is a low level of heterosis predictions about the hybrid should be made based on a mean of the genitors.

Table 4. Estimates of mean heterosis ($\bar{h}$), and inbred lines ($\hat{h}_i$) effects, and the corresponding standard deviations (SD), using the methodology of Gardner and Eberhart (1966), for five traits evaluated in 10 popcorn inbred lines. Campos dos Goytacazes and Itaocara, Rio de Janeiro State.

Effects	Traits[2]				
	GY	PH	EH	FL	PE
Mean Heterosis ($\bar{h}$)	1061.5866	0.1391	0.1153	-7.0119	-0.5098
SD ($\bar{h}$)	3408.7300	0.0010	0.0003	0.1837	0.0143
Inbred lines Heterosis (h_i)[1]					
P1	265.6626	0.1966	0.0728	0.8675	-
P2	369.2026	0.0573	0.0459	-0.2570	-
P3	515.3720	0.0441	0.0084	-0.4460	-
P4	525.8713	0.0529	0.0515	-0.1530	-
P5	-441.3160	-0.0965	-0.0635	1.7630	-
P6	-492.1480	-0.1033	-0.0547	-2.5700	-
P7	-86.1942	0.0123	0.0103	0.7400	-
P8	-171.4210	-0.0321	-0.0103	1.3470	-
P9	-254.8570	-0.1102	-0.0585	-1.6700	-
P10	-230.1700	-0.0208	-0.0016	0.3862	-
SD ($\hat{V}_i$)	9412.7439	0.0028	0.0009	0.5073	-
SD ($\hat{V}_i$-$\hat{V}_J$)	20917.2080	0.0062	0.0020	1.1270	-

[1]P_1 = PR 023; P_2 = PR 024; P_3 = PR 036; P_4 = UEM J1; P_5 = PR 045-1; P_6 = PR 045-2; P_7 = PR 045-3; P_8 = PR 087-1; P_9 = PR 087-2; P_{10} = PR 087-3. [2]GY = Crop Yield; PH = Plant Height; EH = Ear Height; FL = Days to silking; and PE = popping expansion.

In the case of GY, for which there were environmental effects both for the inbred lines and for heterosis and its components, an indication of genitors for producing hybrids based on the performance of inbred lines heterosis is a fragile strategy, especially when the participation of this effect in total heterosis is markedly inferior. This became clear when the sum of squares of the inbred lines heterosis contributed only 2.03% to the sum of squares of total heterosis. Consequently, the logical strategy for this characteristic is to choose genitors for crosses based on estimates of $\hat{V}_i$ because it is clear that genetic divergence strongly contributes to the expression of hybrid vigor.

For PH and EH, the positive values for the estimates of mean heterosis can be explained by the higher percentage of the contribution of the sum of the genotypes to the sum of squares of total heterosis. Examining the environments together, 70.90 and 62.05%, respectively, of the sum of the squares effects of total heterosis of PH and EH contributed to the sum of squares of the genotypes. This degree of heterotic expression makes it difficult to produce hybrids with reduced ear insertion height. When we examined the number of days to flowering, the inbred lines with negative values for the estimate $\hat{h}_i$, including: P_2, P_3, P_4, P_6 and P_9, tended to promote precocity in the resulting hybrids.

For grain yield, the expectations for the best hybrids were based on the most highly positive estimates of $\hat{s}_{ij}$, which were found in the following: P_1 x P_9, P_2 x P_9, P_3 x P_7, P_5 x P_9, and P_6 x P_7 (Table 5).

Table 5. Estimates of the effects of specific heterosis ($\hat{s}_{ij}$) and corresponding standard deviation (SD), using the methodology of Gardner and Eberhart (1966), for four characteristics evaluated in 45 F_1 hybrids. Campos dos Goytacazes and Itaocara, Rio de Janeiro State.

Genotypes[1]	Traits[2]			
	RG	AP	AE	FLOR
P1 x P2	-148.9510	0.0395	-0.0080	0.3169
P1 x P3	222.3763	0.0526	0.0435	-0.5760
P1 x P4	-171.8730	-0.1110	-0.0640	-5.5300
P1 x P5	243.6519	0.0257	-0.0020	0.7963
P1 x P6	60.3169	0.0926	0.0491	5.2160
P1 x P7	-590.6420	-0.1170	-0.0780	1.3190
P1 x P8	-155.4090	0.0563	0.0000	-2.2800
P1 x P9	498.8606	0.1245	0.0879	2.1540
P1 x P10	41.6713	-0.1620	-0.0260	-1.4000
P2 x P3	-481.9980	-0.0500	-0.0640	0.4638
P2 x P4	-57.9130	-0.0890	-0.1070	1.0070
P2 x P5	-98.2230	0.0176	-0.0150	-1.6000
P2 x P6	49.2769	0.1195	0.0510	-0.5700
P2 x P7	50.8176	-0.0510	-0.0460	-0.9700
P2 x P8	-151.4540	-0.2210	-0.0280	-1.9000
P2 x P9	701.1506	0.2013	0.1597	3.3500
P2 x P10	137.2963	0.0345	0.0604	-0.0300
P3 x P4	-593.2440	-0.0560	-0.0550	0.1090
P3 x P5	-129.3890	-0.0140	-0.0170	-1.2000
P3 x P6	295.6100	0.0976	0.0735	3.1900
P3 x P7	702.3206	-0.0470	0.0010	-1.0000
P3 x P8	-88.4518	0.0063	-0.0350	-1.6000
P3 x P9	124.1488	0.0495	0.0373	1.4600
P3 x P10	-51.3705	-0.0370	0.0179	-0.7600
P4 x P5	33.8607	-0.1620	0.0492	-0.5100
P4 x P6	263.0256	0.2088	0.0754	-1.0000
P4 x P7	168.7313	0.0482	0.0329	-0.6500
P4 x P8	82.2988	0.0776	0.0110	2.2300
P4 x P9	244.0694	0.1557	0.1242	4.8400
P4 x P10	31.0451	-0.0710	-0.0652	-0.3800
P5 x P6	-628.9540	-0.0640	-0.0720	3.9000
P5 x P7	-137.4130	-0.0340	-0.0045	-0.3200
P5 x P8	146.1488	-0.0900	-0.0664	-0.5900
P5 x P9	428.7544	0.1876	0.0717	-0.3200
P5 x P10	141.5650	0.1357	0.0573	-0.0500
P6 x P7	402.5863	0.0870	0.0967	0.9230
P6 x P8	271.1488	0.2213	0.1898	5.6500
P6 x P9	-826.2455	-0.9200	-0.5370	-21.0000
P6 x P10	113.2351	0.1576	0.0735	3.8600
P7 x P8	-16.4756	-0.0140	-0.0377	-2.5000
P7 x P9	-553.8699	0.0888	0.0554	5.0200
P7 x P10	-26.0543	0.0420	-0.0189	-1.7000
P8 x P9	-158.6424	0.0882	0.0335	2.5900
P8 x P10	70.8382	-0.1230	-0.0658	-1.4000
P9 x P10	-458.2261	0.0245	-0.0327	1.9600
SD (S_{IJ})	21691.9201	0.0064	0.0021	1.1600
SD (S_{IJ}-S_{IK})	48806.8204	0.0145	0.0047	2.6300
SD (S_{IJ}-S_{KL})	41834.4175	0.0125	0.0040	2.2550

[1]P_1 = PR 023; P_2 = PR 024; P_3 = PR 036; P_4 = UEM J1; P_5 = PR 045-1; P_6 = PR 045-2; P_7 = PR 045-3; P_8 = PR 087-1; P_9 = PR 087-2; P_{10} = PR 087-3. [2]GY = Crop Yield; PH = Plant Height; EH = Ear Height; FL = Days to silking; and PE = popping expansion.

By associating the characteristics PH and EH, it was found that the most promising combinations were P_6 x P_9, P_2 x P_8, P_1 x P_7 and P_2 x P_4 because they gave high negative values for the estimate $\hat{s}_{ij}$. For the characteristic FL, the combinations that gave the highest negative values for the estimate $\hat{s}_{ij}$, were the following: P_6 x P_9, P_1 x P_4, P_1 x P_8, and P_7 x P_8.

Conclusion

The inbred lines did not have good values "per se" for popping expansion, demonstrating that the best genitors for production are not the best for grain yield. The hybrids P_1 x P_3 and P_2 x P_4 had the best responses for the grain yield and popping expansion.

Acknowledgements

We thank UENF for supplying a scholarship, and Faperj and CNPq for financial support for the field studies and laboratory analyses.

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Received on March 11, 2010.
Accepted on May 13, 2010.