RESEARCH

Estimates of heterosis parameters in elephant grass (*Pennisetum purpureum* Schumach.) for bioenergy production

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With a high growth rate and a DM yield of up to 80 t ha\(^{-1}\) yr\(^{-1}\), elephant grass (*Pennisetum purpureum* Schumach.) has been utilized as an alternative source of energy. However, genotypes adapted to and productive in the different regions of Brazil need to be developed. Thus, the objectives of the present study were to estimate and evaluate heterotic effects in elephant-grass hybrids obtained in a partial diallel cross (5 × 5), with the aim of assisting the superior hybrids selection for bioenergy production. The experiment was conducted in Campos dos Goytacazes, Rio de Janeiro, Brazil. The following traits were evaluated: plant height (HGT), stem diameter (SD), leaf blade width (LBW), number of tillers per linear meter (NT), percentage of DM (%DM), and DM yield (DMY). The experiment was conducted in a randomized block design, with 35 treatments (five female parents, five male parents, and 25 hybrid combinations) and three replicates. The adopted statistical model was that of Miranda Filho and Geraldi, in an adaptation of Gardner and Eberhart. Significant heterosis was observed for most traits in the rainy and dry seasons. Hybrid combinations H1 (‘Cubano Pinda’ × ‘Mercker’), H7 (‘Cameroon-Piracicaba’ × ‘Três Rios’), H8 (‘Cameroon-Piracicaba’ × ‘Mercker 86-México’), H17 (‘IAC-Campinas’ × ‘Três Rios’), H18 (‘IAC-Campinas’ × ‘Mercker 86-México’), and H25 (‘Guacu/IZ.2’ × ‘Roxo’) showed potential for use in breeding programs that aiming at develop clones with a energy biomass production capacity high.

Key words: Alternative energy, elephant grass, hybrids.

INTRODUCTION

Elephant grass (*Pennisetum purpureum* Schumach.) is a forage grass that contributes greatly to livestock farming and as biomass for energy purposes. It adapts very well to the climate and soil conditions of practically the entire Brazilian territory (Saraiva and Konig, 2013). There is a need at develop of improved genotypes with higher DM yield all year long, growth vegetative faster, and that are adapted to the different ecosystems of the country (Souza Sobrinho et al., 2005). There are nine elephant grass cultivars registered with the Ministry of Agriculture, but which were developed for animal feed (Ministério da Agricultura, Pecuária e Abastecimento, 2015). In Brazil there are specifically registered cultivars for the production of energy biomass. In the United States until the 1960s research has focused on animal feed. It was in the 1980s funding for renewable energy, which currently the main objective is to identify plants with higher biomass production (Woodard and Sollenberger, 2015).

Heterosis is the natural phenomenon through which the hybrid progeny displays genetically improved traits in relation to its parents, and it has been utilized in agriculture for the development of cultivars with better performance (Fu et al., 2014). The breeding of elephant grass, for energy purposes, is aimed at improving biomass production. These improvements can be achieved by exploiting the additive and non-additive effects of nuclear genes (Bhandari et al., 2014).

Analyses diallel crosses are useful in the estimation of parameters for selection of parents and to determine the gene action that controls the trait. Thus, the presence of deviations of dominance indicates that the exploitation of the hybrid is favorable, because heterosis is positive (Cruz et al., 2012). Heterosis, or hybrid vigor, is the manifestation of the beneficial effects of hybridization, i.e., when the performance of a hybrid is superior to the average performance of its parents (Falconer, 1987). The greater the divergence between the parents used in most crossing is expected heterosis. This divergence can be estimated with the use of molecular markers (Lima et al., 2011). Therefore, these analyses are important in...
choosing the method to direct populations in a breeding program (Pimentel et al., 2013).

A restriction to the use of complete diallel crosses is the number of crossings performed, whose alternative is the use of partial diallel (Silva et al., 2013). Partial diallel consists of the evaluation of parents arranged in two groups and their hybrid combinations (Cruz et al., 2012). Miranda Filho and Geraldi (1984) adapted the model of Gardner and Eberhart (1966) to estimate heterotic effects in partial diallel crosses. Using the methodology of Gardner and Eberhart (1966) of diallel crosses, Assunção et al. (2010) identified positive heterosis for the majority of the traits of agronomic interest and of grain quality in sweet corn. Nevertheless, no studies utilizing this methodology for elephant grass have been found.

Thus, the objectives of this study were to estimate and evaluate the heterotic effects in elephant grass hybrids obtained in a partial diallel cross aiming to superior hybrids select for bioenergy production.

**MATERIALS AND METHODS**

The female parents were selected based on late flowering, high DM yield, stem diameter (Rossi, 2010), and genetic divergence in relation to male parents, in accordance with Lima et al. (2011). Male parents were selected based on the genetic divergence in relation to the female parents, and genetic divergence in relation to female parents (Lima et al., 2011), and also based on their morpho-agronomic traits (DM yield, stem diameter, number of tillers) (Rossi, 2010). Among these genotypes, ten parents were chosen, five females (P1, P2, P3, P4, and P5) (group I) and five males (P6, P7, P8, P9, and P10) (group II), forming a 5 × 5 partial diallel (Table 1).

The hybrid seed obtained was sown in planting trays. Seedlings were transplanted to the “hybrid bank” between October and November 2011, with 0.20-m spacing within the row, from the moment the plantlets reached 20 cm in height, approximately 40 d after emergence. Rows had 5 m in length, and were spaced 1 m apart. Experimental planting was made in June 2012. The basal part in contact with the apex of the other cutting was distributed in 10-cm-deep furrows. After 90 d, a plot-leveling cut was made and, three evaluation cuts were made with 6-mo intervals: two in April (April 2013 and April 2014), which were considered of the rainy season (from October to April); and one cut in the dry season (October 2013).

The experiment was carried out at the experimental station of the State Center for Research on Agro-Energy and Waste Use of PESAGRO-Rio, located in Campos dos Goytacazes (21°19′23″ S, 41°19′40″ W, 20 m a.s.l.), Rio de Janeiro, Brazil, where the climate is classified as Koppen’s Aw. The soil is classified as a Dystrophic Argisols (Embrapa, 1997). The field experiment was carried out in a randomized complete block design, with 35 treatments and three replicates. The experimental unit consisted of one 3-m row, with 1.5 m spacing between rows, 1.5 m of central part each row, disregarding both ends, was used for evaluations.

The following morpho-agronomic traits were evaluated: a) plant height (HGT, m) was measured three random plants from each plot with a graduated ruler, b) stem diameter (SD, cm) was measured with a digital caliper of three random plants from each plot at approximately 20 cm above the soil, c) leaf blade width (LBW, cm) was measured in the central portion of the first fully expanded leaf of three random plants from each plot, d) number of tillers per linear meter (NT) was evaluated in 1.5 m of the row from the plot e) percentage of DM (%DM) was obtained by multiplying the values of the air-dry sample and oven-dried sample; and f) DM yield (DMY) was estimated from the %DM and the weight of tillers in 1.5 mm of each plot. The results were transformed and expressed in t ha⁻¹.

The adopted statistical model was that of Miranda Filho and Geraldi (1984), in an adaptation of Gardner and Eberhart (1966):

\[
Y_{ij} = u + \alpha d + \frac{1}{2}(v_i + v_j) + \theta (\bar{h} + h_i + h_j + s_{ij}) + \bar{e}_{ij}
\]

where: i = 0, 1, ..., p (p = number of parents in group I); j = 0, 1, ..., q (q = number of parents in group II); Y ij is the genotype mean; u is a constant associated the mean of the parental genotype; d is the difference between means of the two groups; \(v_i\) is the effect of the ith parent of group I; \(v_j\) is the effect of the jth parent of group II; \(\bar{h}\) is the effect of the average heterosis; \(h_i\) is the effect of heterosis attributed to the ith parent of group I; \(h_j\) is effect of heterosis attributed to the jth parent of group II; \(s_{ij}\) is effect of the specific heterosis resulting from the crossing between parents of order i and j, of groups I and 2, respectively; and \(\bar{e}_{ij}\) is average experimental error. Since the hybrid combination was treatment \(\alpha = 0\) and \(\theta = 1\); parent group I (female parent) \(\alpha = 1\) and \(\theta = 0\); and parent group II (male parent) \(\alpha = -1\) and \(\theta = 0\).

Table 1. Arrangement of the partial diallel crosses with ten elephant grass parents (Campos dos Goytacazes/Rio de Janeiro, Brazil, 2012).

<table>
<thead>
<tr>
<th>Male parents</th>
<th>Female parents</th>
</tr>
</thead>
<tbody>
<tr>
<td>'Mercer' (P6)</td>
<td>'Cubano Pinda' (P1)</td>
</tr>
<tr>
<td>'Três Rios' (P7)</td>
<td>'Cameroon-Piracicaba' (P2)</td>
</tr>
<tr>
<td>'Mercer 86-México' (P8)</td>
<td>'P241-Piracicaba' (P3)</td>
</tr>
<tr>
<td>'Taiwan A-144' (P9)</td>
<td>'IAC-Campinas' (P4)</td>
</tr>
<tr>
<td>'Roxo' (P10)</td>
<td>'Guacú/I.2' (P5)</td>
</tr>
</tbody>
</table>
ANOVA and the study of heterosis were conducted with the average of the cuts during the rainy and dry seasons using the GENES software (Cruz, 2013).

### RESULTS AND DISCUSSION

#### ANOVA for parents and heterosis

Significant effects for genotypes in the six traits in the cuts of the rainy season used in this study enabled the deployment of the source of variation among groups, for groups I and II and heterosis (Table 2).

The mean squares of traits HGT and LBW for source of variation between groups (G1 and G2) were significant ($P < 0.01$), whereas a nonsignificant effect ($P > 0.05$) was observed for SD. For HGT, the mean square of specific heterosis was significant ($P < 0.01$). According to Nascimento et al. (2010), the significant difference between groups and the significant effect of specific heterosis on HGT, indicates the participation of additive and non-additive effects on this trait.

Regarding trait SD, despite the significant effects for groups I and II ($P < 0.01$ and $P < 0.05$, respectively), there was nonsignificant effect by the F test for the source of variation heterosis, demonstrating that gains might not be obtained with the exploitation of hybrid combinations (Cruz et al., 2012) in programs aimed at improving this trait in elephant grass.

For NT and %DM in group I (female parents) and in group II (male parents) there were highly significant differences ($P < 0.01$). Significant differences ($P < 0.05$) for DMY, by the F test were detected only in group II. This indicates that there are differences in the genetic frequency between the parents within groups I and II in traits NT and %DM; and only in group II, in DMY (Viana, 2007).

The ANOVA for genotypes effects, parents (group I and II), among groups and heterosis referring to the cut for evaluation in the dry season are shown in Table 3.

Significant effect was found for genotype, except for the HGT trait ($P > 0.05$). The source of variation average heterosis was significant for traits HGT ($P < 0.05$), SD ($P < 0.01$), NT ($P < 0.05$), and DMY ($P < 0.05$). For %DM, there was no significance for average heterosis. There was also no significance for heterosis specific. According to Maciel et al. (2010) the superiority of the hybrids in relation the mean of the parents occurs with the average heterosis significant. Still according to those authors, the no significance of the specific heterosis values reflects the greater importance of the additive variance, with the possibility of gains with the evaluation of the parents per se.


<table>
<thead>
<tr>
<th>Source of variation</th>
<th>DF</th>
<th>HGT</th>
<th>SD</th>
<th>LBW</th>
<th>NT</th>
<th>%DM</th>
<th>DMY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genotypes</td>
<td>34</td>
<td>0.0885**</td>
<td>0.0239**</td>
<td>0.2513**</td>
<td>128.6645</td>
<td>11.4811**</td>
<td>28.1699*</td>
</tr>
<tr>
<td>Group I</td>
<td>4</td>
<td>0.0634**</td>
<td>0.0695**</td>
<td>0.3279**</td>
<td>140.6259</td>
<td>26.2446*</td>
<td>20.5278ns</td>
</tr>
<tr>
<td>Heterosis</td>
<td>25</td>
<td>0.0863**</td>
<td>0.0150**</td>
<td>0.1288**</td>
<td>86.9203*</td>
<td>5.3426ns</td>
<td>28.0361*</td>
</tr>
<tr>
<td>Average heterosis</td>
<td>1</td>
<td>0.0956**</td>
<td>0.0466**</td>
<td>0.3019**</td>
<td>85.3175*</td>
<td>3.0205ns</td>
<td>167.6186</td>
</tr>
<tr>
<td>Variety (I) heterosis</td>
<td>4</td>
<td>0.0553**</td>
<td>0.0133**</td>
<td>0.3894**</td>
<td>131.4916</td>
<td>4.8004**</td>
<td>8.5896**</td>
</tr>
<tr>
<td>Variety (II) heterosis</td>
<td>4</td>
<td>0.1055*</td>
<td>0.0129**</td>
<td>0.0419*</td>
<td>87.0847*</td>
<td>1.7478**</td>
<td>16.6511**</td>
</tr>
<tr>
<td>Specific heterosis</td>
<td>16</td>
<td>0.0928*</td>
<td>0.0165**</td>
<td>0.0933*</td>
<td>80.2191*</td>
<td>6.5219**</td>
<td>27.2021*</td>
</tr>
<tr>
<td>Error</td>
<td>68</td>
<td>0.0281*</td>
<td>0.0125</td>
<td>0.0565</td>
<td>34.7463*</td>
<td>3.6021</td>
<td>10.6586</td>
</tr>
</tbody>
</table>

HGT: Plant height (m); SD: stem diameter (cm); LBW: leaf blade width (cm); NT: Number of tillers per linear meter; %DM: percentage of DM; DMY: DM yield (t ha$^{-1}$).

**,** Significant at 0.05 and 0.01 probability levels, respectively; *nonsignificant according to the F test ($P > 0.05$).


<table>
<thead>
<tr>
<th>Source of variation</th>
<th>DF</th>
<th>HGT</th>
<th>SD</th>
<th>LBW</th>
<th>NT</th>
<th>%DM</th>
<th>DMY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genotypes</td>
<td>34</td>
<td>0.0874**</td>
<td>0.1742**</td>
<td>1.1307**</td>
<td>200.7629</td>
<td>47.8085*</td>
<td>12.3003**</td>
</tr>
<tr>
<td>Among groups</td>
<td>1</td>
<td>0.0059**</td>
<td>0.0000**</td>
<td>6.9697**</td>
<td>1.5323**</td>
<td>183.9173</td>
<td>20.5278**</td>
</tr>
<tr>
<td>Group I</td>
<td>4</td>
<td>0.0265**</td>
<td>0.3400**</td>
<td>1.1825**</td>
<td>271.9684</td>
<td>27.2414**</td>
<td>13.2702**</td>
</tr>
<tr>
<td>Group II</td>
<td>4</td>
<td>0.1554*</td>
<td>0.3673**</td>
<td>1.9851**</td>
<td>531.7050</td>
<td>36.2262**</td>
<td>3.5661**</td>
</tr>
<tr>
<td>Heterosis</td>
<td>25</td>
<td>0.0896**</td>
<td>0.1238**</td>
<td>0.7517**</td>
<td>144.3885</td>
<td>50.7081*</td>
<td>13.2135*</td>
</tr>
<tr>
<td>Average heterosis</td>
<td>1</td>
<td>0.2844*</td>
<td>0.5976**</td>
<td>0.8675**</td>
<td>336.4417</td>
<td>6.1591**</td>
<td>28.9312**</td>
</tr>
<tr>
<td>Variety (I) heterosis</td>
<td>4</td>
<td>0.0214**</td>
<td>0.1024**</td>
<td>0.2065**</td>
<td>95.8192*</td>
<td>65.0210**</td>
<td>11.2534**</td>
</tr>
<tr>
<td>Variety (II) heterosis</td>
<td>4</td>
<td>0.0272**</td>
<td>0.1109**</td>
<td>1.2011**</td>
<td>95.8192*</td>
<td>65.0210**</td>
<td>11.2534**</td>
</tr>
<tr>
<td>Specific heterosis</td>
<td>16</td>
<td>0.1101*</td>
<td>0.1028**</td>
<td>0.7685*</td>
<td>142.4873</td>
<td>29.0942**</td>
<td>11.7857**</td>
</tr>
<tr>
<td>Error</td>
<td>68</td>
<td>0.0581*</td>
<td>0.0808</td>
<td>0.2260</td>
<td>76.4648</td>
<td>27.2435</td>
<td>6.3327</td>
</tr>
</tbody>
</table>

HGT: Plant height (m); SD: stem diameter (cm); LBW: leaf blade width (cm); NT: Number of tillers per linear meter; %DM: percentage of DM; DMY: DM yield (t ha$^{-1}$).

**,** Significant at 0.05 and 0.01 probability levels, respectively; *nonsignificant according to the F test ($P > 0.05$).
With regard to traits HGT, SD, and NT, there was nonsignificant effect for the sources of variation variety heterosis I and II. For traits LBW, %DM, and DMY, there was significance for variety heterosis II, and group II was the more contributed for manifestation of heterosis in these traits. The no significance for variety heterosis shows that heterosis is evenly distributed among crossings, with no differentiated heterotic contribution of each variety (Ferreira et al., 2009).

**Effect of varieties in the rainy season**

The estimates of the effect of variety ($\hat{v}_i$ and $\hat{v}_j$) of the six evaluated traits, in the 10 parents of elephant grass in the dry-season cut are shown in Table 4.

The outstanding parents in terms of DMY were P1 (‘Cubano Pinda’) and P6 (‘Mercker*’) in the values of $\hat{v}_i$ (2.0684) and $\hat{v}_i$ (3.6410) in the rainy season cuts. Thus, superior parents can be identified and selected to compose base-populations through crossings (Cruz et al., 2012). The female parent P1 (group I) would increase the DMY and also HGT, SD, LBW, and %DM, but there would be a decrease of NT in hybrids. In case of male parent P6 (group II), it would be expected to increase in all traits.

**Effect of varieties in the dry season**

The estimates of the effect of variety ($\hat{v}_i$ and $\hat{v}_j$) of the six evaluated traits, in the ten parents of elephant grass in the dry-season cut are shown in Table 5.

Concerning the HGT trait, the parents that stood out in group I (in which there were nonsignificant differences by the F-test) and II were, again, P2 (‘Cameroon-Piracicaiba’), with a $\hat{v}_i$ of 0.1040, and P6 (‘Mercker*’), with a $\hat{v}_i$ of 0.3220. The response in relation to the rainy season cut was different, wherein parent P9 (Taiwan A-144) stood out in group II. However, in the cut for evaluation in the dry season, this parent presented a negative estimate for $\hat{v}_i$ (-0.0280), indicating that its hybrids tended to reduce HGT in conditions of lower availability.

Table 4. Estimates of the average of variety effects ($\hat{v}_i$ and $\hat{v}_j$), according to the methodology of Gardner and Eberhart (1966) adapted by Miranda Filho and Geraldi (1984), for the six traits evaluated in ten parents of elephant grass in the rainy season cuts (Campos dos Goytacazes/Rio de Janeiro, Brazil, 2013-2014).

<table>
<thead>
<tr>
<th>Traits</th>
<th>HGT</th>
<th>SD</th>
<th>LBW</th>
<th>NT</th>
<th>%DM</th>
<th>DMY</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>0.0560</td>
<td>0.1700</td>
<td>0.3900</td>
<td>-4.4920</td>
<td>1.7140</td>
<td>2.0684</td>
</tr>
<tr>
<td>P2</td>
<td>0.0760</td>
<td>0.0900</td>
<td>0.3200</td>
<td>-0.0720</td>
<td>-1.8660</td>
<td>0.7654</td>
</tr>
<tr>
<td>P3</td>
<td>-0.0240</td>
<td>-0.1700</td>
<td>-0.2400</td>
<td>-3.7220</td>
<td>-0.8760</td>
<td>-2.5076</td>
</tr>
<tr>
<td>P4</td>
<td>0.0460</td>
<td>-0.0800</td>
<td>-0.6800</td>
<td>9.6780</td>
<td>1.0740</td>
<td>0.2454</td>
</tr>
<tr>
<td>P5</td>
<td>-0.1540</td>
<td>-0.0100</td>
<td>0.2100</td>
<td>-1.3920</td>
<td>-0.0460</td>
<td>-0.5716</td>
</tr>
<tr>
<td>P6</td>
<td>0.1460</td>
<td>0.0240</td>
<td>0.5120</td>
<td>6.7940</td>
<td>1.4940</td>
<td>3.6410</td>
</tr>
<tr>
<td>P7</td>
<td>-0.0540</td>
<td>-0.0600</td>
<td>-0.2280</td>
<td>8.1640</td>
<td>-1.3160</td>
<td>-0.8730</td>
</tr>
<tr>
<td>P8</td>
<td>-0.2340</td>
<td>-0.1040</td>
<td>-0.2280</td>
<td>-13.8760</td>
<td>0.7640</td>
<td>-1.2130</td>
</tr>
<tr>
<td>P9</td>
<td>0.2560</td>
<td>-0.1160</td>
<td>-0.2880</td>
<td>5.7940</td>
<td>2.1240</td>
<td>2.4540</td>
</tr>
<tr>
<td>P10</td>
<td>-0.1140</td>
<td>-0.0600</td>
<td>0.2320</td>
<td>-6.8760</td>
<td>-3.0660</td>
<td>-0.0090</td>
</tr>
</tbody>
</table>

HGT: Plant height; SD: stem diameter; LBW: leaf blade width; NT: number of tillers per linear meter; %DM: percentage of DM; DMY: DM yield.

As regards SD, female parents (group I) P1 (’Cubano Pinda’), P2 (’Cameroon-Piracicaiba’) and P4 (’IAC-Campinas’) and male parents (group II) P8 (’Mercker 86-México’) and P9 (’Taiwan A-144’) submitted negative estimates of the effects of variety ($\hat{v}_i$ and $\hat{v}_j$), with the values of -0.2640, -0.1440, -0.1940, -0.5860, and -0.1260, respectively, different from what occurred in the cut for evaluation in the rainy season, wherein all parents showed positive estimates of effects $\hat{v}_i$ and $\hat{v}_j$.

Analyzing the DMY trait, the potential parents in groups I and II for the estimates of the variety effects $\hat{v}_i$ and $\hat{v}_j$ were female parents P2 (’Cameroon-Piracicaiba’), with 1.5112, and male parent P6 (’Mercker’), with 2.7796. Parent P2 was the one that stood out I group I for trait LBW (0.3880) and NT (6.4580), and parent P6, in group II, for the %DM (7.1880).

**Effects of average, variety and specific heterosis**

The values of the effects of average ($\bar{h}$), variety (h) and specific ($\hat{s}$) heterosis in the cut for evaluation in the rainy season are displayed in Table 6.

With respect to the effect of $\bar{h}$, the only negative value (-0.0096) was obtained with the LBW trait. The negative $\bar{h}$ value indicates bidirectional dominance, with the occurrence of positive and negative heterosis (Assunção et al., 2010).

In the case of breeding of elephant grass for bioenergy production, parents P4 (’IAC-Campinas’), P8 (’Mercker 86-México’) and P10 (’Roxo’) stood out with the greater and positive magnitudes of variety heterosis $h_i$ in the DMY trait. These values were 1.3321 for female parent P4, 2.1975 for P8, and 1.1459 for P10. In addition to DMY, female parent P4 also showed HGT, LBW and %DM with remarkable $h_i$ effect values of 0.1098, 0.3436, and 1.2554, respectively. Male parent P8, however, showed the highest values of $h_i$ effect for the HGT (0.2018) and NT (5.6960) traits.

Hybrid H18, resulting from the ‘IAC-Campinas’ × ‘Mercker 86-México’ crossing, obtained the highest effect...
Table 6. Estimates of the effects of average (h), variety (ĥ), and specific (ŝ) heterosis, according to the methodology of Gardner and Eberhart (1966) adapted by Miranda Filho and Geraldi (1984), for the six traits evaluated in ten parents and 25 hybrid combinations of elephant grass in the rainy season cuts (Campos dos Goytacazes/Rio de Janeiro, Brazil, 2013-2014).

<table>
<thead>
<tr>
<th>Effects</th>
<th>Traits</th>
<th>HGT</th>
<th>SD</th>
<th>LBW</th>
<th>NT</th>
<th>%DM</th>
<th>DMY</th>
</tr>
</thead>
<tbody>
<tr>
<td>heterosis (h)</td>
<td></td>
<td>0.1152</td>
<td>0.1670</td>
<td>0.2012</td>
<td>3.9624</td>
<td>0.5796</td>
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<td>0.0094</td>
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<td>-0.8846</td>
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<td>-0.1264</td>
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<td>-0.1156</td>
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<td>-0.0566</td>
<td>0.0476</td>
<td>-0.1604</td>
<td>0.0014</td>
<td>1.1459</td>
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Specific heterosis (ŝij)

| H1 | 0.0150 | -0.1250 | -0.1350 | -0.2500 | 1.3500 | 4.9280 |
| H2 | -0.4250 | 0.0700 | 0.1550 | -0.6850 | -0.3650 | 3.3130 |
| H3 | 0.2950 | 0.0500 | -0.1350 | 3.0850 | 2.3350 | 5.4690 |
| H4 | 0.0300 | -0.0150 | -0.2650 | 4.4200 | 2.2650 | 2.6600 |
| H5 | 0.0050 | -0.1900 | 0.1350 | -0.3650 | -3.3800 | 0.2730 |
| H6 | -0.2050 | -0.0950 | -0.2100 | -0.9600 | 1.9000 | 2.0770 |
| H7 | 0.0650 | 0.0000 | 0.2600 | 13.1850 | 0.1950 | 5.2400 |
| H8 | -0.0750 | 0.0450 | -0.2000 | 12.7050 | -0.5050 | 5.7210 |
| H9 | 0.0200 | 0.1650 | 0.0000 | -0.7900 | -0.2600 | 0.0200 |
| H10 | -0.2250 | -0.1100 | -0.2400 | 3.8750 | 1.7360 | 4.4290 |
| H11 | -0.1450 | 0.0850 | -0.3500 | -0.1350 | -0.2450 | -1.4570 |
| H12 | 0.1250 | -0.0100 | 0.1000 | 8.3500 | 4.0000 | 3.0830 |
| H13 | 0.2350 | 0.0550 | 0.3400 | 12.7000 | -1.9700 | 5.2070 |
| H14 | 0.0200 | 0.0450 | 0.3400 | 7.8650 | -0.5100 | 2.9900 |
| H15 | 0.0650 | -0.0400 | 0.2900 | 7.5000 | 0.8150 | 5.7810 |
| H16 | 0.0750 | 0.0390 | 0.3300 | 10.6650 | 1.6200 | 1.5440 |
| H17 | 0.3000 | 0.1050 | 0.4100 | 0.2300 | 1.5550 | 5.2940 |
| H18 | 0.5200 | -0.0300 | 0.3000 | 5.3300 | 0.2550 | 8.2670 |
| H19 | -0.1950 | 0.0900 | 0.4200 | -4.1650 | 1.7250 | 2.7800 |
| H20 | 0.0400 | 0.1050 | 0.3400 | -10.2500 | 3.0000 | 2.7620 |
| H21 | 0.0600 | 0.0350 | -0.1850 | -3.9700 | 0.7800 | -0.0780 |
| H22 | 0.1000 | 0.1300 | -0.1850 | 6.5150 | 0.4850 | 0.5950 |
| H23 | 0.2200 | 0.0350 | -0.5050 | 5.2050 | -1.8450 | 0.3090 |
| H24 | -0.1350 | 0.0150 | -0.2650 | -0.4700 | -0.6850 | 0.2560 |
| H25 | 0.3300 | 0.0400 | -0.0650 | 5.5350 | -0.3100 | 6.4700 |

HGT: plant height; SD: stem diameter; LBW: leaf blade width; NT: number of tillers per linear meter; %DM: percentage of DM; DMY: DM yield. of specific heterosis ŝij for the DMY trait, with 8.2670. This hybrid showed the highest effect of ŝij (0.5200) for trait HGT. The specific heterosis is important in the definition of the best hybrid combinations in breeding programs; thus, the highest estimates are expected among more divergent parents and among genes that show dominance effect (Pereira et al., 2008).

Hybrid combination H25 (‘Guazu IZ.2’ × ‘Roxo’) showed the second highest effect of șij for trait DMY (6.4700), and the tenth highest for the NT trait (5.5350). Another hybrid combination that demonstrated potential for use in breeding programs aimed at increasing biomass production in elephant grass was H15 (‘P241-Piracicaba’ × ‘Roxo’), which showed the third highest value of șij effect for DMY (5.7810), and the seventh for NT (5.7000). Other noteworthy combinations for the effect of șij on DMY, referring to the cuts in the rainy season, were H1 (‘Cubano Pinda’ × ‘Mercker’), H8 (‘Camoero-Piracicaba’ × ‘Mercker 86-México’), and H17 (‘IAC-Campinas’ × ‘Três Rios’), with 4.9280, 5.7210, 5.4690, and 5.2940, respectively.

Regarding the evaluation cut that corresponds to the growth period in the dry season, there was no average heterosis (ĥ) effect with negative values (Table 7).

As occurred in the cuts for evaluation in the rainy season, the potential parents with variety heterosis effect ĥ of high and positive magnitude for DMY were P4 (‘IAC-Campinas’), with 1.8993, P8 (‘Mercker 86-México’), with 1.8859, and P10 (‘Roxo’), with 1.3424. In addition to the higher ĥ effect for DMY, parent P4 also showed values of higher and positive magnitude of ĥ for traits SD (0.1810), LBW (0.0708), NT (6.3166) and %DM (6.4354) (Table 7). Positive values for ĥ indicate that the dominance effects have a large influence on the performance of this trait (Vieira et al., 2009).

According to Bernini and Paterniani (2012), the more productive hybrids have positive and high specific heterosis, while the less productive ones have negative and...
high specific heterosis. Higher DM yield is the objective of breeding in elephant grass for energy purposes. In this sense, in the present study, in the dry-season cut, hybrid combinations H8 (‘Cameroon-Piracicaba’ × ‘Mercker 86-México’), H17 (‘IAC-Campinas’ × ‘Três Rios’), and H18 (‘IAC-Campinas’ × ‘Mercker 86-México’) were selected for high and positive magnitude displaying specific heterosis effects ($\hat{s}_{ij}$) of 6.2810, 5.4600 and 4.7680, respectively. These hybrid combinations also showed significant ($\hat{s}_{ij}$) effect for NT, 6.2810, 5.4600 and 4.7680, respectively. These hybrid combinations also showed significant heterosis effects ($\hat{s}_{ij}$) for the DMY trait also in the rainy season cuts (Table 6). Thus, it can be stated that these hybrid combinations have potential to improve biomass production in elephant grass in periods of lower and higher water availability.

Hybrid combinations H1 (‘Cubano Pinda’ × ‘Mercker’), H7 (‘Cameroon-Piracicaba’ × ‘Três Rios’), H8 (‘Cameroon-Piracicaba’ × ‘Mercker 86-México’), H17 (‘IAC-Campinas’ × ‘Três Rios’), H18 (‘IAC-Campinas’ × ‘Mercker 86-México’) and H25 (‘Guacu/Iz.2’ × ‘Roxo’) can serve as a basis for breeding programs of elephant grass cultivation for energy purposes, however, because of its heterogeneity and the fact that most cultivars of this species are clones, one should seek to assess superior clones within these hybrid combinations by the selection between and within families.

CONCLUSIONS

Regarding the effects of heterosis evaluated by the methodology of Gardner and Eberhart (1966) adapted for partial diallel crosses, significant heterosis was detected in most of the traits in the cuts for evaluation of the rainy and dry seasons.


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LITERATURE CITED


