

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 ('Guaçu/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 König, 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

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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 A_w. The soil is classified as a Dystrophic Argisol (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):

$$Y_{ij} = u + \alpha d + \frac{1}{2}(v_i + v'_j) + \theta(\bar{h} + h_i + h'_j + s_{ij}) + \bar{\epsilon}_{ij}$$

where: $i = 0, 1, \dots, p$ (p = number of parents in group I); $j = 0, 1, \dots, q$ (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 i^{th} parent of group I; v'_j is the effect of the j^{th} parent of group II; \bar{h} is the effect of the average heterosis; h_i is the effect of heterosis attributed to the i^{th} parent of group I; h'_j is effect of heterosis attributed to the j^{th} 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 1 and 2, respectively; and $\bar{\epsilon}_{ij}$ 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).

Male parents	Female parents				
	'Cubano Pinda' (P1)	'Cameroon-Piracicaba' (P2)	'P241-Piracicaba' (P3)	'IAC-Campinas' (P4)	'Guaçu/IZ.2' (P5)
'Mercker' (P6)	H1	H6	H11	H16	H21
'Três Rios' (P7)	H2	H7	H12	H17	H22
'Mercker 86-México' (P8)	H3	H8	H13	H18	H23
'Taiwan A-144' (P9)	H4	H9	H14	H19	H24
'Roxo' (P10)	H5	H10	H15	H20	H25

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 2. Summary of ANOVA for a partial diallel of ten genotypes of elephant grass during the rainy season in Campos dos Goytacazes/Rio de Janeiro, Brazil, 2013-2014. Mean squares for plant height, stem diameter, and leaf blade width, number of tillers, percentage of dry matter, and dry matter yield, following Gardner and Eberhart (1966) adapted by Miranda Filho and Geraldi (1984).

Source of variation	DF	Traits					
		HGT	SD	LBW	NT	%DM	DMY
Genotypes	34	0.0885**	0.0239*	0.2513**	128.6645	11.4811**	28.1699*
Among groups	1	0.2430**	0.0043 ^{ns}	1.5323**	4.6334 ^{ns}	4.5630 ^{ns}	26.2660 ^{ns}
Group I	4	0.0634 ^{ns}	0.0695**	0.3279**	140.6259	26.2446*	24.8812 ^{ns}
Group II	4	0.0889*	0.0389*	0.6198**	408.6123	36.8124*	32.7716*
Heterosis	25	0.0863*	0.0150 ^{ns}	0.1288**	86.9203*	5.3426 ^{ns}	28.0361*
Average heterosis	1	0.0296 ^{ns}	0.0066 ^{ns}	0.0019 ^{ns}	95.3117 ^{ns}	3.0230 ^{ns}	167.6186
Variety (I) heterosis	4	0.0553 ^{ns}	0.0133 ^{ns}	0.3894**	131.4916*	4.8004 ^{ns}	8.5896 ^{ns}
Variety (II) heterosis	4	0.1055*	0.0129 ^{ns}	0.0419 ^{ns}	107.0847	1.7478 ^{ns}	16.6511 ^{ns}
Specific heterosis	16	0.0928*	0.0165 ^{ns}	0.0933 ^{ns}	70.2119*	6.5219*	27.0201*
Error	68	0.0281	0.0125	0.0565	34.7463	3.6021	10.6586

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; ^{ns}nonsignificant according to the F test ($P > 0.05$).

Table 3. Summary of ANOVA for a partial diallel of ten genotypes of elephant grass during the dry season in Campos dos Goytacazes/Rio de Janeiro, Brazil, 2013-2014. Mean squares for plant height, stem diameter, and leaf blade width, number of tillers, percentage of dry matter, and dry matter yield, following Gardner and Eberhart (1966) adapted by Miranda Filho and Geraldi (1984).

Source of variation	DF	Traits					
		HGT	SD	LBW	NT	%DM	DMY
Genotypes	34	0.0874 ^{ns}	0.1742**	1.1307**	200.7629	47.8085*	12.3003*
Among groups	1	0.0059 ^{ns}	0.0000 ^{ns}	6.9697**	1.5323 ^{ns}	183.9173	20.5278 ^{ns}
Group I	4	0.0265 ^{ns}	0.3400*	1.1852**	271.9684	7.2414 ^{ns}	13.2702 ^{ns}
Group II	4	0.1554*	0.3673*	1.9851**	531.7050	36.2262 ^{ns}	3.5661 ^{ns}
Heterosis	25	0.0896 ^{ns}	0.1238 ^{ns}	0.7517**	144.3885	50.7081*	13.2135*
Average heterosis	1	0.2844*	0.5976**	0.8675 ^{ns}	336.4417	7.1986 ^{ns}	28.6932*
Variety (I) heterosis	4	0.0214 ^{ns}	0.1024 ^{ns}	0.2065 ^{ns}	95.8102 ^{ns}	65.0210 ^{ns}	11.2534 ^{ns}
Variety (II) heterosis	4	0.0272 ^{ns}	0.1109 ^{ns}	1.2011**	152.5582 ^{ns}	133.7279	17.0151*
Specific heterosis	16	0.1101*	0.1028 ^{ns}	0.7685**	142.4873	29.0942 ^{ns}	11.7857*
Error	68	0.0581	0.0808	0.2260	76.6458	27.2435	6.3327

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; ^{ns}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}_j (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-Piracicaba'), with a \hat{v}_i of 0.1040, and P6 ('Mercker'), with a \hat{v}_j 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}_j (-0.0280), indicating that its hybrids tended to reduce HGT in conditions of lower water 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).

Parents	Traits					
	HGT	SD	LBW	NT	%DM	DMY
P1	0.0560	0.1700	0.3900	-4.4920	1.7140	2.0684
P2	0.0760	0.0900	0.3200	-0.0720	-1.8660	0.7654
P3	-0.0240	-0.1700	-0.2400	-3.7220	-0.8760	-2.5076
P4	0.0460	-0.0800	-0.6800	9.6780	1.0740	0.2454
P5	-0.1540	-0.0100	0.2100	-1.3920	-0.0460	-0.5716
P6	0.1460	0.0240	0.5120	6.7940	1.4940	3.6410
P7	-0.0540	-0.0060	-0.2280	8.1640	-1.3160	-0.8730
P8	-0.2340	0.1040	-0.2280	-13.8760	0.7640	-1.2130
P9	0.2560	-0.1160	-0.2880	5.7940	2.1240	2.4540
P10	-0.1140	-0.0060	0.2320	-6.8760	-3.0660	-4.0090

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

Table 5. 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 dry-season cut (Campos dos Goytacazes/Rio de Janeiro, Brazil, 2013).

Parents	Traits					
	HGT	SD	LBW	NT	%DM	DMY
P1	0.0940	-0.2640	0.2380	-5.5820	4.1560	0.8912
P2	0.1040	-0.1440	0.3880	6.4580	-3.3440	1.5112
P3	-0.1260	0.1160	0.0780	4.0180	0.6760	0.6612
P4	-0.0260	-0.1940	-0.9420	-10.9120	-4.4940	-3.4918
P5	-0.0460	0.4860	0.2380	6.0180	3.0060	0.4282
P6	0.3220	0.2240	0.5920	-6.7900	7.1880	2.7796
P7	-0.1680	0.2940	0.1320	8.6100	0.1380	1.0426
P8	-0.0780	-0.5860	-1.5780	-11.7300	-6.9620	-2.5474
P9	-0.0280	-0.1260	0.2520	18.3700	3.3380	1.1496
P10	-0.0480	0.1940	0.6020	-8.4600	-3.7020	-2.4244

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-Piracicaba') 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 cuts 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-Piracicaba'), 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_i) and specific (\hat{s}_{ij}) 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 \hat{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 \hat{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 (\bar{h}), variety (\hat{h}_i) and specific (\hat{s}_{ij}) 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).

Effects average	Traits					
	HGT	SD	LBW	NT	%DM	DMY
heterosis (\bar{h})	0.1152	0.1670	0.2012	3.9624	0.5796	1.1571
Variety heterosis (\hat{h}_i)						
P1	-0.0532	-0.0686	-0.0934	-2.7220	0.0654	-1.0653
P2	-0.1072	-0.0166	-0.1724	3.4940	0.2414	0.6957
P3	0.0778	0.0094	0.1536	0.4540	-0.6776	0.3238
P4	0.1098	0.0424	0.3436	-6.0130	1.2554	1.3321
P5	-0.0272	0.0334	-0.2314	4.7870	-0.8846	-1.2865
P6	-0.0782	-0.0316	-0.1264	-5.3050	0.7054	-1.3942
P7	-0.0802	0.0414	0.0536	1.4100	-0.1156	-1.0206
P8	0.2018	0.0044	-0.0304	5.6960	-0.7216	2.1975
P9	-0.0892	0.0424	0.0556	-0.7370	0.1304	-0.9287
P10	0.0458	-0.0566	0.0476	-1.0640	0.0014	1.1459
Specific heterosis (\hat{s}_{ij})						
H1	0.0150	-0.1250	-0.1350	-0.2500	1.3500	4.9280
H2	-0.4250	0.0700	0.1550	-10.6850	-0.3650	-5.3310
H3	0.2950	0.0050	-0.1350	3.0850	2.3350	5.4690
H4	0.0300	-0.0150	-0.2650	4.4200	2.2650	3.3190
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	5.2410
H8	-0.0750	0.0450	-0.2000	12.7050	-0.5050	5.7210
H9	0.0200	0.1650	0.0000	-0.2650	-0.2650	-0.0030
H10	-0.0250	-0.1100	-0.2400	3.8750	1.7600	4.4290
H11	-0.1450	0.0850	-0.3500	-0.1350	-0.2450	-1.4570
H12	-0.1250	-0.0100	0.1000	8.3500	0.4000	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	5.7000	0.8150	5.7810
H16	0.0700	0.0300	0.2000	-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	0.01500	-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 \hat{s}_{ij} for the DMY trait, with 8.2670. This hybrid showed the highest effect of \hat{s}_{ij} (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 ('Guaçu IZ.2' × 'Roxo') showed the second highest effect of \hat{s}_{ij} 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 \hat{s}_{ij} effect for DMY (5.7810), and the seventh for NT (5.7000). Other noteworthy combinations for the effect of \hat{s}_{ij} on DMY, referring to the cuts in the rainy season, were H1 ('Cubano Pinda' × 'Mercker'), H8 ('Cameroon-Piracicaba' × 'Mercker 86-México'), H3 ('Cubano Pinda' × '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 (\bar{h}) effect with negative values (Table 7).

As occurred in the cuts for evaluation in the rainy seasons, the potential parents with variety heterosis effect \hat{h}_i 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 \hat{h}_i effect for DMY, parent P4 also showed values of higher and positive magnitude of \hat{h}_i for traits SD (0.1810), LBW (0.7078), NT (6.3166) and %DM (6.4354) (Table 7). Positive values for \hat{h}_i 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

Table 7. Estimates of the effects of average (\bar{h}), variety (\hat{h}_i) and specific (\hat{s}_{ij}) 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 dry-season cut (Campos dos Goytacazes/Rio de Janeiro, Brazil, 2013).

Effects average	Traits					
	HGT	SD	LBW	NT	%DM	DMY
heterosis (\bar{h})	0.1152	0.1670	0.2012	3.9624	0.5796	1.1571
Variety heterosis (\hat{h}_i)						
P1	-0.0922	0.0500	-0.1422	-4.8174	2.3756	-1.2739
P2	0.0028	0.1420	-0.1752	4.5556	2.2704	0.7100
P3	0.0618	-0.1560	0.1898	3.0826	0.1576	-0.4169
P4	0.0218	0.0650	-0.0562	-1.2614	3.8834	1.8993
P5	0.0058	-0.1010	0.1838	-1.5594	3.6206	-0.9184
P6	-0.0802	-0.1240	-0.3232	2.2816	2.9836	-1.9033
P7	0.0228	-0.1150	-0.3072	-6.6314	1.9066	-0.2444
P8	-0.0382	0.1810	0.7078	6.3166	6.4354	1.8859
P9	0.0888	0.0710	0.0558	-0.4734	4.3146	-1.0805
P10	0.0068	-0.0130	-0.1332	-1.4934	2.7694	1.3424
Specific heterosis (\hat{s}_{ij})						
H1	0.0000	0.0650	-0.2050	5.6000	-2.4600	-1.6130
H2	-0.2550	0.0200	0.0650	-10.5300	3.2680	-3.0890
H3	0.1100	0.6600	0.7400	9.8400	-4.3340	0.9110
H4	0.0750	0.1600	-0.2750	6.5900	0.5860	0.5020
H5	0.1850	0.1800	-0.0300	2.0050	2.9420	2.7050
H6	0.0450	0.2150	-0.2400	-1.9900	1.0540	-1.3600
H7	0.4400	0.3400	-0.3300	4.1100	-0.0980	3.5760
H8	0.0750	0.5200	0.6950	15.8800	2.1200	6.2810
H9	-0.1500	0.2300	0.2800	-8.1000	-4.5600	-2.3420
H10	0.1800	0.2400	-0.2750	2.1150	1.4860	3.1820
H11	0.1100	-0.0050	-0.0350	4.6700	-0.5580	-1.5950
H12	0.2850	-0.3000	-0.6450	9.2700	-0.3900	0.3670
H13	0.2600	0.3800	2.2100	9.2000	3.0580	3.0690
H14	-0.0150	0.0000	0.2050	-0.0800	1.7780	0.5370
H15	0.2450	-0.0200	0.2200	12.1650	-3.8860	1.3240
H16	0.0900	0.0100	0.1050	3.0350	-1.3640	-0.3020
H17	0.2550	0.3050	0.4350	10.2650	-1.1760	5.4600
H18	-0.0900	0.1650	0.8000	18.5050	-0.0580	4.7680
H19	0.1950	0.5850	0.3650	5.4550	-0.7880	2.2400
H20	0.1550	0.0950	0.2200	5.3300	3.3880	3.1170
H21	-0.0700	-0.0700	-0.2350	1.0300	3.3300	1.1390
H22	-0.0350	-0.1050	-0.0550	4.3300	-1.6020	-1.7500
H23	0.0300	0.0150	0.1000	-2.0300	-0.7840	0.1880
H24	0.5050	0.2150	-0.2350	-17.2100	2.9860	-0.5540
H25	0.2550	0.2750	1.1500	9.6050	-4.2000	2.1710

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

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 show remarkable positive values for (\hat{s}_{ij}) effect for NT, wherein H8 obtained 15.8800; H17, 10.2650; and H18, 18.5050 (Table 7). Hybrids H8, H17 and H18 showed outstanding effects of \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 both 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 ('Guaçu/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.

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 ('Guaçu/IZ.2' × 'Roxo') showed potential for use in breeding programs aimed at producing elephant grass clones with a high biomass production capacity.

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LITERATURE CITED

Assunção, A., E.M. Brasil, J.P. Oliveira, A.J.S. Reis, A.F. Pereira, L.G. Bueno, et al. 2010. Heterosis performance in industrial and yield components of sweet corn. *Crop Breeding and Applied Biotechnology* 10:183-190. doi:10.1590/S1984-70332010000300001.

Bernini, C.S., e M.E.A.G.Z. Paterniani. 2012. Estimativas de parâmetros de heterose em híbridos de populações F₂ de milho. *Pesquisa Agropecuária Tropical* 42:56-62. doi:10.1590/S1983-40632012000100008.

Bhandari, H.S., S.L. Webb, J.H. Bouton, and M.C. Saha. 2014. Reciprocal effects for biomass yield in lowland switchgrass. *Crop Science* 54:955-962. doi:10.2135/cropsci2013.08.0532.

Cruz, C.D. 2013. GENES - a software package for analysis in experimental statistics and quantitative genetics. *Acta Scientiarum. Agronomy* 35:271-276. doi:10.4025/actasciagron.v35i3.21251.

Cruz, C.D., A.J. Regazzi, e P.C.S. Carneiro. 2012. Métodos biométricos aplicados ao melhoramento genético. 514 p. Editora UFV, Viçosa, Brasil.

Embrapa. 1997. Manual de métodos de análise de solos. 212 p. Empresa Brasileira de Pesquisa Agropecuária (Embrapa), Centro Nacional de Pesquisa de Solos, Rio de Janeiro, Brasil.

Falconer, D.S. 1987. Introdução à genética quantitativa. 279 p. Universidade Federal de Viçosa, Viçosa, Brasil.

Ferreira, J.M., R.M.P. Moreira, e J.A.F. Hidalgo. 2009. Capacidade combinatória e heterose em populações de milho crioulo. *Ciência Rural* 39:332-339. doi:10.1590/S0103-84782008005000058.

Fu, D., M. Xiao, A. Hayward, Y. Fu, G. Liu, G. Jiang, et al. 2014. Utilization of crop heterosis: a review. *Euphytica* 197:161-173. doi:10.1007/s10681-014-1103-7.

Gardner, C.O., and S.A. Eberhart. 1966. Analysis and interpretation of the variety cross diallel and related populations. *Biometrics* 22:439-452. doi:10.2307/2528181.

Lima, R.S.N., R.F. Daher, L.S.A. Gonçalves, D.A. Rossi, A.T. Amaral Júnior, M.G. Pereira, et al. 2011. RAPD and ISSR markers in the evaluation of genetic divergence among accessions of elephant grass. *Genetics and Molecular Research* 10:1304-1313. doi:10.4238/vol10-3gmr1107.

Maciel, G.M., W.R. Maluf, V.F. Silva, A.C. Gonçalves Neto, D.W. Nogueira, e L.A.A. Gomes. 2010. Heterose e capacidade combinatória de linhagens de tomateiro ricas em alicatúcares. *Ciência e Agrotecnologia* 34:1161-1167. doi:10.1590/S1413-70542010000500012.

Ministério da Agricultura, Pecuária e Abastecimento. 2015. Registro Nacional de Cultivares. Ministério da Agricultura, Pecuária e Abastecimento, Brasília/DF, Brasil. Available at <http://www.agricultura.gov.br/vegetal/registros-autorizacoes/registro-registro-nacional-cultivares> (accessed July 2015).

Miranda Filho, J.B., and I.O. Geraldi. 1984. An adapted model for the analysis of partial diallel crosses. *Revista Brasileira de Genética* 14:677-688.

Nascimento, I.R., W.R. Maluf, L.D. Gonçalves, M.V. Faria, J.T.V. Resende, e D.W. Nogueira. 2010. Capacidade combinatória de linhagens de pimentão a partir de análise dialélica multivariada. *Acta Scientiarum. Agronomy* 32:235-240. doi:10.4025/actasciagron.v32i2.3768.

Pereira, J.A., O.P. Morais, e F. Bressegello. 2008. Análise da heterose de cruzamentos entre variedades de arroz-vermelho. *Pesquisa Agropecuária Brasileira* 43:1135-1142. doi:10.1590/S0100-204X2008000900006.

Pimentel, A.J.B., M.A. Souza, P.C.S. Carneiro, J.R.A.S.C. Rocha, J.C. Machado, e G. Ribeiro. 2013. Análise dialélica parcial em gerações avançadas para seleção de populações segregantes de trigo. *Pesquisa Agropecuária Brasileira* 48:1555-1561. doi:10.1590/S0100-204X2013001200004.

Rossi, D.A. 2010. Avaliação morfoagronômica e da qualidade da biomassa de acessos de capim-elefante (*Pennisetum purpureum* Schum.) para fins energéticos no norte fluminense. 66 p. Dissertação Mestrado em Produção Vegetal. Universidade Estadual do Norte Fluminense, Campos dos Goytacazes, Rio de Janeiro, Brasil.

Saraiva, V.M., e A. König. 2013. Produtividade do capim-elefante-iroxo irrigado com efluente doméstico tratado no semiárido potiguar e suas utilidades. *Revista Hollos* 1:28-46. Available at <http://www2.ifrn.edu.br/ojs/index.php/HOLLOS/article/view/1251/638> (accessed August 2014).

- Silva, G.O., V.G. Ney, L.R.T. Pereira, A. Silva, e F.A. Suinaga. 2013. Capacidade de combinação de genitores de batata para caracteres de aparência e rendimento de tubérculos. *Revista Ceres* 60:489-497. doi:10.1590/S0034-737X2013000400007.
- Souza Sobrinho, F., A.V. Pereira, F.J.S. Ledo, M.A. Botrel, J.S. Oliveira, e D.F. Xavier. 2005. Avaliação agronômica de híbridos interespecíficos entre capim-elefante e milho. *Pesquisa Agropecuária Brasileira* 40:873-880. doi:10.1590/S0100-204X2005000900006.
- Viana, J.M.S. 2007. Heterosis and combining ability analyses from the partial diallel. *Bragantia* 66:641-647. doi:10.1590/S0006-87052007000100007.
- Vieira, R.A., I.L. Souza Neto, L.S. Bignotto, C.D. Cruz, A.T. Amaral Júnior, and C.A. Scapim. 2009. Heterotic parametrization for economically important traits in popcorn. *Acta Scientiarum. Agronomy* 31:411-419. doi:10.4025/actasciagron.v31i3.4689.
- Woodard, K.R., and L.E. Sollenberger. 2015. Production of biofuel crops in Florida: Elephantgrass. SS-AGR-297, Agronomy Department, University of Florida (UF)/Institute of Food and Agricultural Sciences (IFAS) Extension, Gainesville, Florida, USA. Available at https://edis.ifas.ufl.edu/ag302#FOOTNOTE_1 (accessed July 2015).