

Combining ability in elephant grass (*Pennisetum purpureum* Schum.) for energy biomass production

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Abstract

The objective of this study was to estimate and evaluate the general and specific combining abilities of hybrid combinations for energy biomass production, adopting the methodology of Griffing as adapted by Geraldi and Miranda Filho in evaluation cuts referring to two periods, the wet and dry seasons, and in relation to total dry matter yield (TDMY). The experiment was conducted at Pesagro Rio, located in Campos dos Goytacazes, RJ, Brazil, in a randomized block design with three replicates. Crosses were performed in a partial diallel system. Treatments consisted of 10 parents, 25 hybrid combinations, and 1 control. Three evaluation cuts were made: two in the wet season and one in the dry season. The following traits were evaluated: plant height, stem diameter, leaf width, number of tillers, percentage of dry matter, dry matter yield, and TDMY. Regarding the general combining ability effects, the parents “Cameroon-Piracicaba” and “Mercker” showed outstanding positive values. Of the hybrid combinations, “Cubano Pinda”×“Mercker”, “Cameroon-Piracicaba”×“Três Rios”, “Cameroon-Piracicaba”×“Mercker 86-México”, “IAC-Campinas”×“Três Rios”, “IAC-Campinas”×“Mercker 86-México”, and “Guaçu IZ.2”×“Roxo” showed superior productive performance. Hybrids can be obtained with superior energy biomass production to that of the currently available elephant grass cultivars.

Keywords: alternative energy; bioenergy; diallel; plant breeding; *Pennisetum purpureum*.

Introduction

Global warming in recent years has been a worldwide concern due to its effects on life on Earth. Such heating is derived from the high emission of greenhouse gases, such as carbon dioxide (CO₂), nitrogen atom oxides (NO_x), and methane (CH₄), into the atmosphere after the Industrial Revolution. The amount of CO₂ is a recognized measure of environmental sustainability, and there is a common concern to reduce CO₂ emissions (Liu, 2014).

Some crops have been used to achieve sustainable energy (bioenergy). Among them are castor bean and soybean, vegetable oil producers (Vaz et al., 2010), sugarcane (Viator et al., 2012), and elephant grass (Menezes et al., 2015). The elephant grass species (*Pennisetum purpureum* Schum.) is highly efficient in the fixation of atmospheric CO₂, and it can produce 60 t ha⁻¹ of biomass per year (Morais et al., 2009). Biomass energy production is already a reality in Brazil, and there is a current demand for species and varieties for cultivation in different regions. Biomass is a promising source of renewable energy, as it has significant economic and environmental advantages, e.g., it is low cost and can be used to reduce CO₂ emissions (Ibrahim et al., 2014).

With the employment of perennial plants for biomass production and efficient systems in this conversion, approximately 250 million hectares in the world could be used in the development of the bioenergy industry. The improvement in biomass production and quality can be achieved with advances in plant breeding (Samson et al., 2005). According to Allwright and Taylor (2016), the main goal of the improvement of bioenergy plants has been increasing yield per unit area without environmental degradation or the increase of agricultural inputs. The study of productive traits in elephant grass is of great importance for the success of breeding programs that aim at increasing yields (Silva et al., 2008). According to Menezes et al. (2014), features such as high stem diameter (SD) and number of tillers per linear meter (NT) are positively correlated with the production of dry matter, i.e., plants with the highest SD and NT are more productive.

Diallel analyses are useful in the estimate of parameters for the selection of parents for the hybridization and determination of the gene action controlling a trait. Thus, the presence of dominance deviations indicates that the exploration of the hybrid is favorable (Cruz et al., 2012).

Therefore, these analyses are important in the choice of the method for directing populations in a breeding program (Pimentel et al., 2013). Among the most commonly used crossing arrangements is the Griffing (1956) method, which provides the estimate of the specific and general combining abilities (SCA and GCA, respectively) and a reduction in the number of crosses.

The objective of this study was to estimate and evaluate the GCA of parents and SCA of hybrid combinations for energy biomass production, adopting the methodology of Griffing (1956) as adapted by Geraldi and Miranda Filho (1988) in evaluation cuts referring to two periods, the wet and dry seasons, and in relation to total dry matter yield (TDMY).

Results and Discussion

Analysis of variance for combining ability

Observing the results of the analysis of variance of the mean of the two evaluation cuts in the wet season, the mean squares of GCA of Group 1 (female parents) were significant at 1% probability level for the traits SD, leaf width (LW), NT, and percentage of dry matter (%DM) and at 5% for the trait plant height (HGT). Only for the trait dry matter yield (DMY) was there no significance for GCA of Group 1. Regarding GCA of Group 2 (male parents), significance was detected for all traits evaluated in the wet-season cuts. For the traits LW, NT, and %DM, this significance was obtained at 1% probability, whereas, for the traits HGT, SD, and DMY, this significance was at the level of 5% probability (Table 1). According to Rangel et al. (2007), significance for GCA indicates sufficient variability in the parents due to additive genetic effects. These results may represent the existence of variability resulting from the gene action of additive and non-additive effects on the control of gene expression (Freitas Júnior et al., 2006). The presence of significant effects for GCA for the evaluated traits indicates that the parents differed from each other in the frequency of favorable alleles, with some more promising than others for the production of superior hybrids (Pfann et al., 2009).

The mean squares for SCA of the traits SD and %DM were not significant at 5% probability level by the *F* test in the wet-season evaluation cuts. The mean squares for SCA of the other morphoagronomic traits evaluated showed significance at 1% probability. The significance of the mean squares for SCA indicates the presence of non-additive gene effects involved in the control of these traits (Sibiya et al., 2011) and that some hybrid combinations tend to show different performance than the expected based on GCA. In the contrast between groups for the morphoagronomic traits in the mean between the two evaluation cuts in the wet season, only the mean squares of the traits HGT and LW were significant at the level of 1% probability by the *F* test (Table 1). This fact evidences that, for the traits SD, NT, %DM, and DMY, the average number of favorable alleles is similar in both groups of parents as a result of the presence of productive genotypes in both groups (Pimentel et al., 2013).

In the evaluation cut corresponding to the growth period in the dry season, it was observed that, regarding Group 1 (female parents), significance was present at 1% probability level for the traits SD, LW, and NT. For the traits HGT, %DM, and DMY, no significant differences were detected (Table 1). The same occurred in the evaluation cut of the wet season, in which the mean squares of the trait DMY were not significant according to the *F* test.

Concerning GCA of Group 2 (male parents), the traits %DM and DMY were significant at 1% and HGT at 5%

probability by the *F* test. For GCA of Group 2 in the dry-season cut, %DM and DMY were not significant.

This did not occur in the evaluation cut corresponding to the growth of elephant grass in the wet season, in which %DM and DMY displayed significance by the *F* test. In this period, the mean squares of GCA, for Group 2, of all evaluated morphoagronomic traits were significant at 1% or 5% probability (Table 1). Adverse conditions (lack of precipitation, low or decreased temperature, and light interception), as observed in the dry season, facilitate the selection of superior genotypes because of the greater variability, which did not occur in the present study.

As regards SCA, only the trait HGT did not show significant differences by the *F* test. The other traits showed significance at 1% (LW and DMY) or 5% (SD, NT, and %DM) probability, unlike what occurred in the wet-season cut, in which the mean squares of the traits SD and %DM were not significant. The presence of significant mean squares for SCA indicates the prevalence of non-additive effects and that the hybrids can be explored (Medeiros et al., 2014). No significance of the mean squares between the groups was detected for the traits HGT, SD, NT, and DMY. Only the mean squares of the traits LW and %DM showed significance by the *F* test in the dry-season evaluation cut (Table 1); this result was different in the evaluation cuts corresponding to the wet season.

Estimates of the effects of GCA

Analyzing GCA estimates (\hat{g}_i) in the cuts referring to the growth period during the wet season, it was observed that, for the trait HGT, the genotypes that stood out with positive values were parent P4 with 0.0840 and parent P9 with 0.0784. Parent P7 stood out with a negative estimate of -0.0716 for \hat{g}_i . These results indicate that, when genotypes P4 and P9 are selected as parents in crosses, hybrids with higher HGT will be produced, unlike what occurs when genotype P7 is selected; in the latter case, there is a trend towards decreased HGT in its progeny. The trait SD in the wet-season cuts showed parents P8 and P1 as noteworthy, with positive values of 0.0544 and 0.0469, respectively, and parent P3 with the negative value of -0.0798 (Table 2). High \hat{g}_i values, either positive or negative, indicate that a certain parent is superior or inferior, resulting in desirable or undesirable combinations when associated with different parents (Vivas et al., 2012).

In the cuts during the wet season, the positive and negative highlights for the trait LW were parent P6 with the value of 0.1858 and parent P4 with -0.1491. When aiming to increase this trait, parent P6 is recommended. The use of parent P10 in crosses may lead to a reduction in NT, %DM, and DMY, which is not desirable in elephant grass genetic breeding programs for biomass energy purposes in growth periods during the wet season. However, observing the results, parents P4, P6, and P9 show potential to be used in these breeding programs because of the outstanding positive \hat{g}_i values for %DM and DMY. The %DM values for these genotypes were 1.1389 for parent P6, 1.2344 for parent P4, and 1.1344 for parent P9. As regards DMY, the values were 1.0459 for parent P6, 0.8628 for parent P4, and 0.7110 for parent P9. Parent P2 displayed an outstanding high \hat{g}_i value for DMY (0.7692), but this same effect was negative for %DM (Table 2).

In the analysis of the \hat{g}_i effects in the evaluation cut made during the dry season, parent P2, despite not standing out for the traits HGT, SD, LW, NT, and %DM, showed the highest \hat{g}_i value (1.1501) for DMY. This means that the use of parent P2 is promising in elephant grass breeding programs aimed at

Table 1. Estimates of mean squares of elephant grass genotypes (parents and hybrids) for GCA and SCA and residual of six traits evaluated during the wet and dry season cuts.

Mean squares	Traits/season											
	HGT (m)		SD (cm)		LW (cm)		NT		%DM		DMY (t ha ⁻¹)	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Genotype	0.0886**	0.0875 ^{ns}	0.0239*	0.1743**	0.2513**	1.1307**	128.6645**	200.7629**	11.4811**	47.8085*	28.1700**	12.3004**
GCA ₍₁₎	0.0634*	0.0265 ^{ns}	0.0695**	0.3400**	0.3280**	1.1852**	140.6259**	271.9685**	26.2446**	7.2414 ^{ns}	24.8812 ^{ns}	13.2702 ^{ns}
GCA ₍₂₎	0.0889*	0.1554*	0.0389*	0.3673**	0.6198**	1.9851**	408.6123**	531.7050**	36.8124**	36.2262 ^{ns}	32.7716*	3.5661 ^{ns}
SCA	0.0863**	0.0896 ^{ns}	0.0150 ^{ns}	0.1238*	0.1288**	0.7518**	86.9203**	144.3885*	5.3426 ^{ns}	50.7081*	28.0361**	13.2136**
Group 1 vs Group 2	0.2430**	0.0059 ^{ns}	0.0043 ^{ns}	0.0000 ^{ns}	1.5323**	6.9697**	4.6335 ^{ns}	1.5323 ^{ns}	4.5630 ^{ns}	183.9173*	26.2660 ^{ns}	20.5278 ^{ns}
Residual	0.0281	0.0581	0.0125	0.0808	0.0565	0.2261	34.7464	76.6458	3.6021	27.2435	10.6586	6.3327

**Significant at 1% probability level; *significant at 5% probability level; ^{ns}not significant at 5% probability level according to the *F* test.

Table 2. Estimates of effects of GCA of Groups 1 and 2 (\hat{g}_i and \hat{g}_j) and SCA (\hat{s}_{ij}) for six morphoagronomic traits in 25 hybrid combinations resulting from partial diallel crosses in the wet-season cuts.

Genotype	Traits					
	HGT (m)	SD (cm)	LW (cm)	NT	%DM	DMY
Effects of GCA of Groups 1 and 2 (\hat{g}_i e \hat{g}_j)						
P1	-0.0016	0.0469	0.1431	-3.7582	0.8933	0.4424
P2	-0.0216	0.0358	0.0642	1.9051	-0.7989	0.7692
P3	-0.0271	-0.0798	-0.0347	0.7984	-0.8144	-1.0739
P4	0.0840	-0.0164	-0.1491	1.4984	1.2344	0.8628
P5	-0.0338	0.0136	-0.0236	-0.4438	-0.5144	-1.0005
P6	0.0296	-0.0056	0.1858	0.4498	1.1389	1.0459
P7	-0.0716	0.0200	-0.0842	4.8653	-0.7222	-1.0035
P8	-0.0049	0.0544	-0.1309	-3.7736	-0.0189	0.6144
P9	0.0784	-0.0344	-0.1131	2.4876	1.1344	0.7110
P10	0.0253	0.0898	0.3320	-2.9624	-0.3124	-0.4664
SCA (\hat{s}_{ij})						
H1	0.0614	-0.0819	-0.0060	2.7030	0.6535	4.2966
H2	-0.3775	0.0726	0.1840	-11.4625	-0.6054	-6.1699
H3	0.1859	0.0281	-0.0594	-0.0737	2.4313	2.8422
H4	0.0825	-0.0130	-0.2371	4.8352	1.8880	2.4285
H5	-0.0175	-0.1330	-0.1027	0.9619	-3.6854	-1.7696
H6	-0.1286	-0.0808	-0.0371	-1.4603	1.1057	0.4667
H7	0.0125	-0.0263	-0.1871	8.9542	-0.1432	3.4232
H8	-0.1541	0.0392	-0.0805	6.0930	-0.5065	2.1153
H9	0.1025	0.1381	0.0718	-3.8281	-0.7398	-1.8714
H10	-0.0175	-0.0819	-0.1638	1.0186	1.3568	1.4075
H11	-0.1130	0.0847	-0.3582	-1.3537	-0.5287	-2.8602
H12	-0.0919	-0.0508	-0.0082	3.4009	0.5724	1.4723

H13	0.1115	0.0347	0.2784	5.3697	-1.4609	1.8084
H14	0.0581	0.0036	0.2306	4.1086	-0.4742	1.3277
H15	0.0281	-0.0264	0.1851	2.1252	0.9224	2.9666
H16	0.0259	0.0114	0.0862	-5.8836	0.2624	-0.4199
H17	0.2570	0.0459	0.1962	1.2809	0.6535	3.1226
H18	0.3204	-0.0686	0.1328	3.9997	-0.3098	4.3077
H19	-0.2330	0.0303	0.2051	-1.9214	0.6869	0.5580
H20	-0.0730	0.1003	0.1295	-7.8247	2.0335	-0.6131
H21	0.0336	0.0214	0.0207	-2.7814	0.6113	-0.5865
H22	0.0747	0.0759	-0.0793	3.9731	-0.1976	-0.1210
H23	0.0381	0.0014	-0.3527	0.2819	-1.2209	-2.1949
H24	-0.1553	-0.0397	-0.1604	-1.8192	-0.5342	-0.5116
H25	0.2347	0.0403	0.0440	4.3675	-0.0876	4.5503

Table 3. Estimates of effects of GCA of Groups 1 and 2 (\hat{g}_i and \hat{g}_j) and SCA (\hat{s}_{ij}) for six morphoagronomic traits in 25 hybrid combinations resulting from partial diallel crosses in the dry-season cut.

Genotype	Traits					
	HGT (m)	SD (cm)	LW (cm)	NT	%DM	DMY
Effects of GCA of Groups 1 and 2 (\hat{g}_i e \hat{g}_j)						
P1	-0.0042	-0.1042	0.0400	-3.4918	0.7582	-0.2622
P2	0.0536	0.0069	0.0967	2.3627	-0.4107	1.1501
P3	-0.0287	-0.0287	0.1444	3.7216	0.2504	0.0990
P4	-0.0098	-0.0609	-0.3689	-2.9251	-0.0896	-0.6907
P5	-0.0109	0.1869	0.0878	0.3327	-0.5084	-0.2962
P6	0.1164	0.0431	0.1164	-4.2247	1.9364	0.3324
P7	-0.0713	0.0831	-0.1047	4.0420	-0.9902	0.3855
P8	-0.0602	-0.1924	-0.3958	-2.3558	0.0942	-0.2260
P9	-0.0102	-0.0236	0.0520	5.5009	-0.728	-0.0255
P10	0.0253	0.0898	0.3320	-2.9624	-0.3124	-0.4664
SCA (\hat{s}_{ij})						
H1	0.0135	-0.0132	-0.0901	4.3002	-4.6767	-0.6744
H2	-0.2987	-0.0632	0.1710	-12.3965	1.5300	-3.0716
H3	0.1002	0.4123	0.2822	4.2013	-2.3645	-0.2561
H4	0.0402	-0.0266	-0.2656	8.1446	-2.2222	0.9834
H5	0.1046	0.0401	-0.1256	-1.3920	3.2822	1.8403
H6	0.0057	0.0857	-0.1068	-3.1243	0.9022	-1.5236
H7	0.3435	0.2057	-0.2057	2.4090	0.2289	2.4902
H8	0.0124	0.2212	0.2555	10.4068	6.1544	4.0117
H9	-0.2376	-0.0077	0.3077	-6.3798	-5.3033	-2.9628
H10	0.0468	0.0490	-0.3523	-1.1165	3.8911	1.2151
H11	0.0379	0.0313	-0.1046	0.9568	-1.7889	-1.1325
H12	0.1557	-0.2687	-0.7235	4.9901	-1.1422	-0.0927

H13	0.1646	0.2468	1.5677	1.1479	6.0133	1.4258
H14	-0.1354	-0.0721	0.0299	-0.9388	-0.0444	0.5423
H15	0.0790	-0.0454	-0.0602	6.3546	-2.5600	-0.0168
H16	0.0490	-0.0765	0.0387	-1.4965	-0.7989	-1.1258
H17	-0.1568	0.2135	0.3598	5.1668	-0.1322	3.7140
H18	0.1543	-0.0910	0.1610	9.6346	4.6933	1.8385
H19	0.1057	0.3901	0.1932	3.7779	-0.8144	0.9580
H20	0.0201	-0.0532	-0.0568	-1.2987	6.5100	0.4889
H21	-0.1199	-0.0643	-0.1679	1.7057	0.5600	1.8796
H22	-0.1421	-0.1043	0.0032	4.4390	-3.8933	-1.9306
H23	-0.0432	-0.1488	-0.4056	-5.6932	0.6322	-1.1761
H24	0.4068	0.1123	-0.2734	-13.6799	-0.3755	-0.2696
H25	0.1112	0.2190	1.0066	8.1835	-4.1411	1.1083

Table 4. Estimates of mean squares of elephant grass genotypes (parents and hybrids) for GCA and SCA and residual, GCA effects of Groups 1 and 2 (\hat{g}_i and \hat{g}_j) of 10 elephant grass parents, and effects of SCA (\hat{s}_{ij}) and relative heterosis for the trait TDMY in 25 hybrid combinations for the trait TDMY of the three evaluation cuts.

Mean square	TDMY (t ha ⁻¹)		
Genotype	162.4579**		
GCA(1)	32.6918 ^{ns}		
GCA(2)	122.5286 ^{ns}		
SCA	146.6131*		
Group 1 vs Group 2	176.5724**		
Residual	57.7377		
Effects of GCA of Groups 1 and 2 (\hat{g}_i e \hat{g}_j)			
Parents	TDMY (t ha ⁻¹)		Parents
P1	0.6232		P6
P2	2.6876		P7
P3	-2.0472		P8
P4	1.0342		P9
P5	-2.2979		P10
			-3.2035
Hybrid	SCA (\hat{s}_{ij})		Relative heterosis
H1	7.9221		8.2455
H2	-15.4134		-13.7495
H3	5.4254		11.8485
H4	5.8463		7.1445
H5	-1.7003		3.2505
H6	-0.5922		2.7905
H7	9.3423		14.0655
H8	8.2441		17.7265
H9	-6.7080		-2.3505
H10	4.0314		12.0415
H11	-6.8544		-4.5115

H12	2.8571	6.5405
H13	5.0459	13.4885
H14	3.1938	6.5115
H15	5.9162	12.8865
H16	-1.9689	2.7805
H17	9.9616	16.0515
H18	10.4574	21.3065
H19	2.0693	7.7935
H20	-0.7353	8.6415
H21	0.7062	0.9835
H22	-2.1723	-0.5545
H23	-5.5605	0.8165
H24	-1.2886	-0.0365
H25	10.2108	15.1155

**Significant at 1% probability level; *significant at 5% probability level; ^{ns}not significant at 5% probability level according to the *F* test.

Table 5. Partial diallel crosses with 10 parents.

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

increased biomass production. This female parent obtained the third highest value (0.7692) for the \hat{g}_i effect in the wet-season cuts. The second (0.3855) and third (0.3324) highest positive values of the \hat{g}_i effect belonged to parents P7 and P6 (Table 3). Parent P4 in the wet-season cut obtained a negative \hat{g}_i estimate (-0.6907) for DMY (Table 2). Because in elephant grass there are no recommended genotypes for growth in different periods (wet and dry), when aiming at improving biomass energy production, one should select genotypes with stable production in different environments.

Estimates of the effects of specific capacity and analysis of heterosis

The effects of SCA (\hat{s}_{ij}) are measurements of non-additive genetic effects. The negative sign indicates the existence of unidirectional dominance deviations; the higher the divergence of the parent in relation to the other evaluated parents, the higher will be the absolute value of \hat{s}_{ij} (Cruz et al., 2012). According to Griffing (1956), the best hybrid combinations are those with higher \hat{s}_{ij} effects, with parents showing high GCA.

The \hat{s}_{ij} effects of the highest positive magnitude for the trait HGT were found in hybrid combinations H17, H18, and H25 in the evaluation cuts made during the wet season. The respective values were 0.2570 for H17, 0.3204 for H18, and 0.2347 for H25. However, only combinations H17 and H18 had a parent with noteworthy \hat{g}_i effect for HGT among the parents evaluated in the wet-season cuts. Combinations H2 and H20 had outstanding positive values for the trait LW: 0.1840 and 0.1295, respectively. However, these hybrid combinations showed negative \hat{s}_{ij} values of -11.4625 and -7.8247 for the trait NT and -6.1699 and -0.6131 for DMY, respectively (Table 2). Thus, these hybrid combinations are not promising, as the objective is the positive association between these evaluated traits (Gonçalves et al., 2014).

Regarding biomass production (DMY), hybrid combinations H16, H20, H22, H21, and H24 generated a negative \hat{s}_{ij} effect, with -0.4199, -0.6131, -0.1210, -0.5865, and -0.5116, respectively, in the evaluation cut referring to the wet season. These results indicate the use of these hybrid combinations in breeding programs for energy biomass production, as the possibility of genetic gain is low because of the negative \hat{s}_{ij} estimates, although these values were of low magnitude. Hybrids H1, H7, H17, H18, and H25 obtained positive values of high magnitude (divergence between parents) for \hat{s}_{ij} in the evaluation cuts in the wet season. The values of the \hat{s}_{ij} effect for combinations H1, H7, H17, H18, and H25 were 4.2966, 3.4232, 3.1226, 4.3077, and 4.5503 (Table 2). These positive outstanding \hat{s}_{ij} values indicate the possibility of genetic gains for DMY in these hybrid combinations.

In the dry-season cut, with regard to the trait SD, the highest values for \hat{s}_{ij} effect were found within combinations H3 and H19, whose parents showed negative \hat{g}_i values. The \hat{s}_{ij} effect values were 0.4123 for H3 and 0.3901 for H19. The trait HGT showed the highest positive effects of SCA for hybrids H7, H12, H13, H18, and H24, with 0.3435, 0.1557, 0.1646, 0.1543, and 0.4068, respectively (Table 3). These results are favorable when using elephant grass for energy production, as, according to Rossi et al. (2014), who analyzed the canonical correlation between the morphoagronomic and biomass quality traits, there is a positive correlation between HGT and the percentage of cellulose and lignin. This is

because, as the plant ages, the proportion of stem in the harvested material also increases.

In the dry-season cut, for the trait NT, the hybrid combinations that showed the highest positive values for the \hat{s}_{ij} effect were H4, H8, H18, and H25, with 8.1446, 10.4068, 9.6346, and 8.1835, respectively. Combinations H8 and H18 presented, in addition to NT, the traits %DM and DMY with outstanding values for the \hat{s}_{ij} effect. Combination H8 displayed an \hat{s}_{ij} value of 6.1544 for %DM and 4.6933 for DMY. Combination H18 showed 4.6933 for %DM and 1.8385 for DMY (Table 3). In the analysis of the trait DMY separately, in the dry-season cut, it was observed that the hybrid combinations H7, H8, and H17 showed outstanding positive values for the \hat{s}_{ij} effect: 2.4902, 4.0117, and 3.7140, respectively (Table 3). Evaluating the combining ability of interspecific hybrids between elephant grass and millet in a partial diallel system, Pereira et al. (2006) observed that the breeding strategy of intraspecific crossing in elephant grass, for the traits NT, %DM, and DMY, may provide gains resulting from the greater variability existing among elephant grass genotypes.

Combining ability analysis for the production of total dry matter

Analyzing the results of the analysis of variance for TDMY, it was observed that the hybrid combinations were not similar to the parents, so good hybrids can be obtained from the set of parents evaluated in the present study. This is because of the presence of significant differences ($P < 0.05$) for SCA (Table 4). For the \hat{g}_i effects for TDMY, parents P2 and P6 showed outstanding positive values (2.6876 and 2.4241, respectively). These same parents showed noteworthy \hat{g}_i effects in the evaluation during the wet and dry seasons (Tables 2 and 3), i.e., these genotypes can be used in breeding programs aiming to obtain hybrid combinations with high biomass energy production. This result corroborates the findings of Oliveira et al. (2014), in which the genotype "Cameroon-Piracicaba" was classified into the elite group for the production of alternative energy from biomass. According to Souza Sobrinho et al. (2005), hybrids with stable performance in successive cuts should be selected, especially for DMY. Based on this information, on the effects of \hat{s}_{ij} , and on the relative heterosis for the trait, it is concluded that, for biomass energy production, combinations H1, H7, H8, H17, H18, and H25 showed the highest \hat{s}_{ij} and relative heterosis values for TDMY (Table 4), i.e., genetic gain can be obtained using these materials in genetic breeding programs. However, the selection of these genotypes in this study was based on the average of the plot, and hybrid combinations are heterogeneous. Because of these two factors, it is recommended to evaluate these genotypes within and between families, as occurs in the sugarcane crop. Knowing the potential of genotypes as parents and the best hybrid combinations is important in the generation of superior families, although, after this selection, superior clones within the same family should be evaluated and identified (Lucius et al. 2014).

Materials and Methods

Growth condition and genetic materials

The experiment was conducted in the experimental station of Pesagro Rio, located in Campos dos Goytacazes, RJ, Brazil (21°19'23"S and 41°19'40"W; 20 m altitude), where the

climate is classified as a Köppen A_w type. The soil is classified as a dystrophic Ultisol. Total precipitation recorded during the first, second, and third cuts were 556.8, 322.8, and 648 mm, respectively. The female parents were chosen based on the flowering period (late flowering) and on their morphoagronomic traits (DMY, SD, and NT). The male parents were chosen based on the genetic divergence in relation to the female parents (Lima et al., 2011) and on their morphoagronomic traits (DMY, SD, and NT). Crosses were made between these groups of parents in a 5×5 partial diallel system (Table 5). Planting took place in June 2012. After the establishment phase, in October 2012 (90 days after planting), all genotypes were cut near the soil level (plot-leveling cut). Three evaluation cuts were made every 6 months such that the first, second, and third cuts would be made in April 2013, October 2013, and April 2014, respectively. Thus, two cuts were made in the wet season (from October 2012 to April 2013 and from October 2013 to April 2014) and one in the dry season (from April to October 2013).

Morphoagronomic traits evaluated

The following traits were evaluated: HGT, measurements of three random plants were taken per plot; SD, diameters of the stem of three plants were measured at random in each plot, approximately 20 cm above the soil; LW, measured in the central part of the first fully expanded leaf of three plants at random per plot; NT, by counting the NT in a 1.5-m row of the plot and converting the result to NT; %DM, obtained by multiplying the air- and oven-dried sample values; DMY, estimated from the %DM and the weight of tillers in 1.5 m in each plot; and TDMY, the sum of the DMY from the three evaluation cuts. Results were transformed to be expressed as t ha⁻¹.

Statistical analysis

A randomized block design with three replicates was adopted. The experimental unit consisted of 3-m rows spaced 1.5 m apart, in which only 1.5 m within the rows were considered useful area, discarding the extremities. The diallel analysis methodology proposed by Griffing (1956) was employed, adapted to partial diallel crosses by Geraldi and Miranda Filho (1988), which estimates GCA and SCA. In the case of the trait TDMY, the relative heterosis was also estimated. Analyses were performed on the Genes computer software (Cruz, 2013).

Conclusions

The presence of non-additive genetic effects involves the control of most of the evaluated traits. Parents “Cameroon-Piracicaba” and “Mercker” show outstanding positive values for GCA. Aiming at genetic gains for biomass energy production, the selection of “Cubano Pinda”×“Mercker”, “Cameroon-Piracicaba”×“Três Rios”, “Cameroon-Piracicaba”×“Mercker 86-México”, “IAC-Campinas”×“Três Rios”, “IAC-Campinas”×“Mercker 86-México”, and “Guaçu IZ.2”×“Roxo” is recommended.

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References

- Allwright MR, Taylor G (2016) Molecular breeding for improved second generation bioenergy crops. *Trends Plant Sci.* 21(1):43–54.
- Cruz CD (2013) Genes—a software package for analysis in experimental statistics and quantitative genetics. *Acta Sci Agron.* 5:271–276.
- Cruz CD, Regazzi AJ, Carneiro PCS (2012) Modelos biométricos aplicados ao melhoramento genético. Universidade Federal de Viçosa, Brasil.
- Freitas Júnior SP, Amaral Júnior AT, Pereira MG, Cruz CD, Scapim CA (2006) Capacidade combinatória em milho-pipoca por meio de diallelo circulante. *Pesqui Agropecu Bras.* 41:1599–1607.
- Geraldi IO, Miranda Filho JB (1988) Adapted models for the analysis of combining ability of varieties in partial diallel crosses. *Braz J Genet.* 11:419–430.
- Gonçalves LSA, Freitas Júnior SP, Amaral Júnior AT, Scapim CA, Rodrigues R, Marinho CD, Pagliosa ES (2014) Estimating combining ability in popcorn lines using multivariate analysis. *Chil J Agr Res.* 74:10–15.
- Griffing B (1956) Concept of general and specific combining ability in relation to diallel crossing systems. *Aust J Biol Sci.* 9:463–493.
- Ibrahim N, Kamarudin SK, Minggu LJ (2014) Biofuel from biomass via photo-electrochemical reactions: an overview. *J Power Sources.* 259:33–42.
- Lima RSN, Daher RF, Gonçalves LSA, Rossi DA, Amaral Júnior AT, Pereira MG, Léo FJS (2011) Rápido and ISSR markers in the evaluation of genetic divergence among accessions of elephant grass. *Genet Mol Res.* 10:1304–1313.
- Liu CH (2014) Approximate trade-off between minimisation of total weighted tardiness and minimisation of carbon dioxide (CO₂) emissions in bi-criteria batch scheduling problem. *Int J Comput Integ M.* 27:759–771.
- Lucius ASF, Oliveira RA, Daros E, Zambon JLC, Bespalhok Filho JC, Verissimo MAA (2014) Desempenho de famílias de cana-de-açúcar em diferentes fases no melhoramento genético via reml/blup. *Semin-Cienc Agrar.* 35:101–112.
- Medeiros AM, Rodrigues R, Gonçalves LSA, Pombo SC, Oliveira HS, Santos MH (2014) Gene effect and heterosis in *Capsicum baccatum* var. *pendulum*. *Cienc Rural.* 44:1031–1036.
- Menezes BRS, Daher RF, Gravina GA, Amaral Júnior AT, Oliveira AV, Schneider LSA, Silva VB (2014) Correlações e análise de trilha em capim-elefante para fins energéticos. *Rev Bras Cienc Agrar.* 9:465–470.
- Menezes BRS, Daher RF, Gravina GA, Pereira AV, Sousa LB, Rodrigues EV, Silva VB, Gottardo RD, Schneider LSA, Novo AAC (2015) Estimates of heterosis parameters in elephant grass (*Pennisetum purpureum* Schumach.) for bioenergy production. *Chil J Agr Res.* 75:395–401.
- Morais RF, Souza BJ, Leite JM, Soares LHB, Alves BJR, Boddey RM, Urquiaga S (2009) Elephant grass genotypes for bioenergy production by direct biomass combustion. *Pesqui Agropecu Bras.* 44:133–140.
- Oliveira MLF, Daher RF, Gravina GA, Silva VB, Viana AP, Rodrigues EV, Shimoya A, Amaral Júnior AT, Menezes BRS, Rocha AS (2014) Pre-breeding of elephant grass for energy purposes and biomass analysis in Campos dos Goytacazes-RJ, Brazil. *Afr J Agric Res.* 9:2743–2758.
- Pereira AV, Daher RF, Pereira MG, Léo FJS, Souza Sobrinho F, Amaral Júnior AT, Freitas VP, Pereira TNS, Ferreira CF (2006) Análise de cruzamentos dialélicos entre capim-elefante (*Pennisetum purpureum* Schum.) e milheto

- (*Pennisetum glaucum* (L.) R. Br.). 1. Características morfoagronômicas. *Acta Sci Agron*. 28:267–275.
- Pfann AZ, Faria MV, Andradei AA, Nascimento IR, Faria CMDR, Bringhenti RM (2009) Capacidade combinatória entre híbridos simples de milho em dialelo circulante. *Cienc Rural*. 39:635–641.
- Pimentel AJB, Souza MA, Carneiro PCS, Rocha JRASC, Machado JC, Ribeiro G (2013) Análise dialélica parcial em gerações avançadas para seleção de populações segregantes de trigo. *Pesqui Agropecu Bras*. 48:1555–1561.
- Rangel RM, Amaral Júnior AT, Viana AP, Freitas Júnior SP, Pereira MG (2007) Prediction of popcorn hybrid and composite means. *Crop Breed Appl Biot*. 7:287–295.
- Rossi DA, Menezes BRS, Daher RF, Gravina GA, Lima RSN, Léo FJS, Gottardo RD, Campostrini E, Souza CLM (2014) Canonical correlations in elephant grass for energy purposes. *Afr J Biotechnol*. 13:3666–3671.
- Samson R, Mani S, Boddey RM, Sokhansanj S, Quesada DM, Urquiaga S, Reis V, Lem CH (2005) The potential of c_4 perennial grasses for developing a global bioheat industry. *Crit Rev Plant Sci*. 24:461–495.
- Souza Sobrinho F, Pereira AV, Ledo FJS, Botrel MA, Oliveira JS, Xavier DF (2005) Avaliação agronômica de híbridos interespecíficos entre capim-elefante e milheto. *Pesqui Agropecu Bras*. 40:873–880.
- Sibiya J, Tongona P, Derera J, Rij NV, Makanda I (2011) Combining ability analysis for *Phaeosphaeria* leaf spot resistance and grain yield in tropical advanced maize inbred lines. *Field Crop Res*. 120:86–93.
- Silva MA, Lira MA, Santos MVF, Dubeux Júnior JCB, Cunha MV, Freitas EV (2008) Análise de trilha em caracteres produtivos de *Pennisetum* sob corte em Itambé, Pernambuco. *Rev Bras Zootecn*. 37:1185–1191.
- Vaz PHPM, Sampaio YSB, Sampaio EVSB (2010) Análise da competitividade da mamona e da soja para produção de biodiesel no nordeste do Brasil. *Rev Econ Agríc*. 57:35–48.
- Viator RP, White Jr PM, Hale AJ, Waguespack HL (2012) Screening for tolerance to periodic flooding for cane grown for sucrose and bioenergy. *Biomass Bioenerg*. 44:56–63.
- Vivas M, Silveira SF, Cardoso DL, Pereira MG, Vivas JMS, Ferregueti GA (2012) Capacidade combinatória em mamoeiro para resistência a oídio. *Bragantia*. 71:455–459.