Australian Journal of Crop Science

AJCS

AJCS 14(12):1898-1904 (2020) ISSN:1835-2707
doi: 10.21475/ajcs.20.14.12.2700

Combining ability in maize hybrid for yield-related traits and silage production

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Abstract

Maize cultivars developed for silage production are desirable because ensiling enables the production of high-quality feed and, increases farmers profit. Diallel cross is an efficient and advantageous mating technique that allows the selection of the best parents and crossings. The objective of this study was to estimate the general combining ability (GCA) and specific combining ability (SCA) of hybrids and their parents and to evaluate promising hybrid crosses that can be used in breeding programs. Six genotypes were crossed in a complete diallel system. Fifteen hybrid combinations, six parents, and three commercial controls were evaluated in the 2017/2018 growing season in the north and northwest regions of Rio de Janeiro state, Brazil. Nine agronomic traits were analyzed at the silage stage: plant and ear height, stem diameter, stand, husk covering, number of cobs, husked ear weight, unhusked ear weight, and fresh mass yield. The study employed a completely randomized block design with four repetitions. The parents UENF 2210, Piranão 12, and UENF 2208 presented higher GCA values for fresh matter yield and were indicated for the generation of single cross (F_1) hybrids. The parental combinations of UENF 2208 × Piranão 12, UENF 2208 × UENF 2205, and UENF 2209 × UENF 2205 had high SCA for most of the evaluated traits and were promising for the use in breeding programs. The crosses with higher average yield were UENF 2208 × Piranão 12, UENF 2210 × Piranão 12, and UENF 2208 × UENF 2205.

Keywords: Diallel; Griffing method; Plant breeding; *Zea mays* L.
Abbreviations: GCA_general combining ability; SCA_specific combining ability; PH_plant height; EH_ear height; SD_stem diameter; STAND_stand; HC_husk covering; NE_number of ears; HEW_ husked ear weight; UEW_unhusked ear weight; FMY_fresh matter yield.

Introduction

Maize (*Zea mays* L.) is one of the oldest crops in the world and has wide genetic variability, allowing its cultivation in different edaphoclimatic and technological conditions (Môro and Fritsche Neto, 2015). The grains most commonly used in feed production are maize and soy.
In Brazil, during drought periods, adequate food supply to animals is limited, especially in tropical regions, and is strongly influenced by seasonal variations. In addition, forage plants do not provide sufficient nutrients to meet the demands for animal production throughout the year (Macêdo et al., 2017). Therefore, high-quality feed needs to be produced during the summer. Moreover, the feed can be stored, preserved, and given to animals, especially ruminants, to increase the efficiency of milk and meat production.
Ensiling (silage) allows production of high-quality feed and increases the potential of financial return to farmers during drought periods. Ensiling is the primary method of forage conservation, and silage is used as feed during periods of water shortage. Ensiling involves low-cost and simple equipment compared to haymaking (Edson et al., 2018; Wilkinson and Rinne, 2018), and increases forage availability in the north and northwest regions of the state of Rio de Janeiro, where the most prominent activity is livestock production.
Maize silage is the primary feed used in intensive ruminant production systems, especially in dairy farms. Silage production becomes more competitive by choosing hybrids with high yield, high digestible energy, and high fermentative capacity (Oliveira et al., 2017). The most favorable characteristics of maize hybrids used in breeding programs in Brazil are high grain and dry matter yield and high nutritional value (Marcondes et al., 2012). In addition, selecting grains with higher digestibility is crucial.
Maize genotypes are classified into three categories according to grain texture: dent, mid-dent, and flint. Dent kernels have a higher percentage of farinaceous endosperm, compared to hard endosperm genotypes (Piovesan et al.,

2011), making the former more suitable for silage production. The presence of a compact protein matrix in the vitreous portion of flint kernels limits enzymatic attack and may reduce ruminal digestibility (Majee et al., 2008).

In Brazil, there is great concern about the cultivation of maize for silage production because of the restricted availability of dent kernel cultivars with high digestibility (Pereira, 2013). In addition, suitable cultivars should have a low proportion of cobs and stalks, high digestibility of vegetative parts, and a good kernel to cob ratio (Pereira, 2013). One of the breeding strategies adopted to improve silage production and quality is inbred lines, and promising crosses produce hybrids that are superior to the original lines (Paterniani, 1974). Therefore, genetic improvement programs in Brazil should focus on selecting hybrids for silage maize production.

In this context, obtaining hybrids using diallel crosses is feasible and helps select parental lines based on the combining ability, which is essential in genetic improvement programs (Veiga et al., 2000) and allows identifying parameters that are useful for selecting parents for hybridization and development of productive hybrids (Cruz et al., 2012). The general combining ability (GCA) of the parental lines estimated from hybrid populations indicates the degree to which these lines differ from the overall GCA of the parents from the diallel population. The genetic effects of the specific combining ability (SCA) are non-cumulative. Hybrid combinations with the highest SCA estimates and that include at least one parent with a favorable GCA effect are desirable (Bordallo et al., 2005).

The importance of this study for the North and Northwest fluminence region is mainly the lack of forage hybrids adapted to this region, in which livestock is one of the main agricultural activities. In general, Brazilian maize breeding programs are focused on the production of hybrids for grain production (Gomes et al., 2004). There is a lack of information regarding agronomic response, productivity and nutritional value, which is an obstacle for the selection of corn hybrids for silage production. Therefore, we aimed to investigate the available genotypes of our germplasm bank, where initially a topcross with a high number of genotypes was carried out. From that test the most adapted, productive and best-suited genotypes reproduction (Crevelari et al., 2017; Crevelari et al., 2019) were selected to proceed to the second stage of investigation. In the second stage, a diallel cross was peformed, where we had a greater possibility of crossing since we had a smaller number of genotypes.

It is worth highlighting the importance of developing specific genotypes for silage production adapted to the edaphoclimatic conditions of the north and northwest regions of the state of Rio de Janeiro. The objective of this study is to estimate the GCA and SCA for agronomic traits of hybrids and to evaluate promising hybrid crosses, selecting them for breeding programs.

Results and Discussion

Analysis of variance

There were significant differences between the plots for most agronomic characteristics (Table 1), demonstrating that the evaluated environments were distinct. There were significant differences ($p<0.01$) in the source of variation between treatments for all nine traits, indicating the existence of genetic variability between treatments and the potential for genetic gains using these genotypes. The mean square effects of the treatments involving parents and hybrids were significant, indicating differences between genotypes in each of these two groups. There were significant effects on EH, NE, and HC in the commercial control.

Skonieski et al. (2014) showed that the morphological structures of maize plants grown for silage production are relevant because they affect grain quality. Considering the different treatments in crosses in the two study sites, there were significant effects on NE, HC, HEW, and UEW in the interaction H $\times$ L.

The combined ANOVA indicated a significant effect ($p<0.01$) on HC, HEW, and UEW in the interaction T $\times$ L, demonstrating that the response of these genotypes to environmental changes was different and that stability and adaptability analyses and environmental stratification were feasible (Carvalho et al., 2013). This result is relevant for developing genetic improvement programs because the evaluated environments affected the expression of genotypes equally. Therefore, the use of cultivars with high adaptability is crucial for farmers and breeders (Aguiar et al., 2017).

The experimental coefficient of variation (CV_e) ranged from 5.95% to 15.5%, indicating that the experimental precision was acceptable for all evaluated characters. This indicates that experimental conditions under which the genotypes evaluated were reliable (Table 1). The Ministry of Agriculture, Livestock, and Supply reported that only experiments, whose CV_e values are ≤20% should be considered for cultivar registration. This criterion is used for soybean, wheat, beans, maize, and sorghum crops (MAPA, 2012). Pimentel Gomes (2009) found that CV_e below 15% is associated with high experimental accuracy and reliability. Therefore, the data obtained in this study are reliable.

For estimating the mean square effects from diallel analysis, the existence of genetic variability among the 21 hybrid combinations was demonstrated by the significant effects on the traits between treatments, and these effects were classified into GCA and SCA.

Significant effects of GCA on all traits indicated that the allelic frequency of parents was different from that of other genotypes, and some genotypes were more promising for producing superior lineages (Table 1). There was a significant effect of SCA on six of the nine traits. This result showed that lineages produced from these parents might be useful in interpopulation improvement.

There was a significant effect on a few traits in the interaction GCA $\times$ L, suggesting that using different parents at specific sites was not necessary. There was a significant effect on two characteristics in the interaction SCA $\times$ L, indicating that using site-specific hybrid combinations was not necessary, and the breeding program could make decisions based on the SCA of crosses and average traits in the two study sites.

The mean square effect of SCA was higher than that of GCA on PH, EH, HEW, UEW, and FMW (Table 1), demonstrating that the genetic activity and structure of the hybrids favored the manifestation of non-cumulative genetic effects. Therefore, hybridization is the best strategy for genetic improvement and obtaining genetic gains for these traits. However, the estimated square effect of GCA was significantly higher than that of SCA on SD, NE, HC, and STAND, indicating the importance of genes with cumulative

Table 1. Combined analysis of variance and mean square effect of GCA and SCA on nine agronomic traits in six parental maize lines and 15 hybrids crossed in a complete diallel and cultivated for silage production in the 2017/2018 growing season in the municipalities of Campos dos Goytacazes and Itaocara, Rio de Janeiro, Brazil.

SOV	DF	Mean Squares								
		PH	EH	SD	NE	HC	STAND	HEW	UEW	FMY
Block/location	6	0.35**	0.20**	8.89**	3.83	0.19	3.26	5.97	1.59	93.28
Location (L)	1	0.02	0.09**	594.35**	432.00**	5.33**	121.92**	682.96**	268.52**	14992.02**
Treatment (T)	23	0.34**	0.27*	5.62**	56.83**	0.31**	8.06**	64.81**	50.24**	537.73**
Parental line (P)	5	0.31**	0.25**	13.59*	91.23**	0.18	18.87**	81.34**	50.30**	674.33**
Hybrid (H)	14	0.19**	0.17**	2.32	41.62**	0.3**	4.23	18.98**	17.36*	184.58**
Control (C)	2	0.01	0.16**	3.66	53.37*	0.87**	8.17	1.11	3.39	0.3
Interactions	2	1.76**	1.19**	10.80	80.77**	0.09	7.84	407.94**	327.14**	3205.79**
T x L	23	0.03	0.01	2.59	11.76	0.27**	3.12	7.56**	2.88*	64.77
P x L	5	0.06	0.02	2.12	5.63	0.23	2.94	1.67	2.35	23.19
H x L	14	0.03	0.01	2.57	16.69**	0.26*	3.23	9.7**	3.41*	75.58
C x L	2	0.01	0.01	5.9	3.37	0.29	3.5	4.1	0.33	46.94
Residual	138	0.02	0.01	2.48	8.78	0.12	3.15	3.77	1.69	48.35
Médias		2.61	1.59	16.53	20.91	4.78	20.26	13.14	8.51	47.23
CVe %		5.97	6.89	9.54	14.16	7.22	8.75	14.78	15.28	14.72
Diallel analysis (ANOVA)										
Genotype (G)	20	0.35**	0.26**	6.05**	59.81**	0.25	8.37**	69.33**	48.5**	616.93**
G x L	20	0.03	0.01	2.33	13.32	0.29**	3.17	7.93	3.21	65.46
CGA	5	0.53**	0.53**	13.62**	167.2**	0.3	13.96*	100.2**	86.39**	564.69**
SGA	15	0.28**	0.17**	3.53	24.02**	0.24	6.51	59.04**	35.99**	634.35**
GCA x L	5	0.99	0.02	1.99	30.09**	0.49**	5.15**	13.12**	4.29	113.63*
SCA x L	15	0.01	0.01	2.44	7.73	0.22	2.52**	6.2	2.85*	49.4
Residual	120	0.02	0.01	2.47	8.09	0.12	3.21	3.65	1.59	47.9
Average		2.63	1.61	16.5	20.86	4.79	20.23	12.87	8.14	47.08
CVe %		5.95	6.88	9.51	13.62	7.27	8.85	14.84	15.5	14.7
Mean square effect	GCA	0.0039	0.0056	0.1576	2.2373	0.0009	0.1163	0.6432	0.7875	-1.09
	SCA	0.0293	0.0177	-0.1755	0.9804	-0.0003	0.0119	6.4671	4.0996	67.32

SOV, source of variation; DF, degrees of freedom; PH, plant height (m); EH, ear height (m); SD, stem diameter (cm); NE, number of ears, HC, husk covering; STAND, number of plants at harvest; HEW, husked ear weight (kg.ha^{-1}), UEW, unhusked ear weight (kg.ha^{-1}); FMY, fresh matter yield (kg.ha^{-1}); GCA, general combining ability, SCA, specific combining ability; **significant at p<0.01 using the F-test; *significant at p<0.05 using the F-test; CV_e, experimental coefficient of variation.

Table 2. General combining ability ($\hat{g}_i$) of six parental maize lines in complete diallel crosses without reciprocals in the 2017/2018 growing season in the municipalities of Campos dos Goytacazes and Itaocara, Rio de Janeiro, Brazil.

Parental genotypes	MEAN SQUARE EFFECT OF GCA								
	PH	EH	SD	NE	HC	STAND	HEW	UEW	FMY
UENF 2202	- 0.12	-0.96	-0.21	0.96	0.05	0.44	-0.05	0.97	-1.78
UENF 2208	0.13	0.16	-0.53	-0.39	0.02	-0.51	-0.48	-1.19	0.68
UENF 2209	-0.06	-0.02	-0.31	-2.38	-0.13	-0.57	-1.83	-1.10	-4.71
UENF 2210	0.06	-0.01	0.57	-0.28	0.03	0.15	1.84	1.12	3.50
UENF 2205	-0.05	-0.07	0.56	-0.37	-0.01	-0.04	-0.33	-0.87	-0.15
Piranão 12	0.036	0.03	-0.08	2.47	0.03	0.53	0.85	1.07	2.46

PH, plant height; EH, ear height; SD, stem diameter; NE, number of ears, HC, husk covering; STAND, number of plants at harvest; HEW, husked ear weight, UEW, unhusked ear weight; FMW, fresh matter yield.

Table 3. Estimation of $\hat{s}_{ij}$ and the effects of $\hat{s}_{ii}$ in 15 hybrids and six parental maize lines in a complete diallel cross without reciprocals in the 2017/2018 growing season in the municipalities of Campos dos Goytacazes and Itaocara, Rio de Janeiro, Brazil.

Hybrids	Average effects of SCA								
	PH	EH	SD	NE	HC	STAND	HEW	UEW	FMY
UENF 2202	- 0.124	-0.107	-0.047	-0.947	-0.156	-0.39	-2.977	-2.832	-8.604
UENF 2202 × UENF 2208	0.009	-0.028	0.251	1.81	0.101	1.669	2.625	1.788	8.42
UENF 2202 × UENF 2209	0.053	0.049	0.571	-1.069	-0.209	0.515	0.515	0.78	4.007
UENF 2202 × UENF 2210	0.007	0.014	0.068	-1.046	0.126	-0.7	0.467	0.94	-0.745
UENF 2202 × UENF 2205	0.142	0.119	-0.589	-0.324	0.167	-0.009	0.362	0.637	2.222
UENF 2202 × Piranão 12	0.037	0.06	-0.207	2.522	0.127	-0.694	1.985	1.518	3.303
UENF 2208	-0.268	-0.16	-1.067	-3.701	0.04	-1.583	-4.855	-3.246	-17.173
UENF 2208 × UENF 2209	0.086	0.011	0.71	1.41	0.197	1.348	1.321	0.879	4.558
UENF 2208 × UENF 2210	-0.05	-0.056	-0.381	1.717	0.013	0.579	1.458	0.986	1.173
UENF 2208 × UENF 2205	0.248	0.186	1.028	1.155	-0.052	-0.676	1.914	1.197	9.607
UENF 2208 × Piranão 12	0.243	0.207	0.525	1.31	-0.341	0.247	2.392	1.641	10.588
UENF 2209	-0.267	-0.183	-1.2	-1.406	0.155	-1.096	-3.824	-2.982	-12.289
UENF 2209 × UENF 2210	0.024	0.045	0.227	0.659	-0.218	-0.728	0.8	0.899	0.353
UENF 2209 × UENF 2205	0.206	0.116	0.65	1.016	-0.02	0.504	3.395	2.528	9.5
UENF 2209 × Piranão 12	0.166	0.145	0.828	0.796	-0.059	0.553	1.617	0.877	6.16
UENF – 2210	-0.074	-0.082	-0.044	-0.933	0.15	0.348	-2.076	-2.238	-2.112
UENF 2210 × UENF 2205	0.075	0.089	0.206	0.094	-0.123	-0.308	0.018	0.072	-0.961
UENF 2210 × Piranão 12	0.092	0.072	-0.033	0.443	-0.099	0.462	1.409	1.578	4.405
UENF 2205	-0.265	-0.185	-0.38	-0.365	-0.019	0.23	-2.485	-2.051	-8.127
UENF 2205 × Piranão 12	-0.14	-0.141	0.049	-1.21	0.067	0.029	-0.718	-0.333	-4.114
Pinarão 12	-0.199	-0.172	-0.581	-1.93	0.152	-0.298	-3.342	-2.641	-10.171

PH, plant height; EH, ear height; SD, stem diameter; NE, number of ears, HC, husk covering; STAND, number of plants at harvest; HEW, husked era weight, UEW, unhusked ear weight; FMW, fresh matter yield.

Table 4. Results of the Scott-Knott cluster test for traits evaluated in six parental maize lines and respective crosses and three commercial controls in a complete diallel cross in the 2017/2018 growing season in the municipalities of Campos dos Goytacazes and Itaocara, Rio de Janeiro, Brazil.

Genotypes	Average traits								
	PH	EH	SD	NE	HC	STAND	HEW	UEW	FMY
UENF 2202	2.27d	1.31d	16.03a	21.83a	4.75a	20.73a	9.79b	7.26c	34.91b
UENF 2202 × UENF 2208	2.65b	1.65b	16.01a	23.23a	4.96a	21.83a	14.96a	9.71b	54.40a
UENF 2202 × UENF 2209	2.50c	1.54c	16.55a	18.37b	4.50a	20.62a	11.50b	8.79b	44.59a
UENF 2202 × UENF 2210	2.58b	1.52c	16.93a	20.50b	5.00a	20.12a	15.13a	11.18a	48.05a
UENF 2202 × UENF 2205	2.60b	1.57c	16.26a	21.12a	5.00a	20.62a	12.85a	8.89b	47.36a
UENF 2202 × Piranão 12	2.59b	1.61b	16.00a	26.81a	5.00a	20.51a	15.65a	11.70a	51.06a
UENF 2208	2.62b	1.77b	14.37a	16.37b	4.87a	17.62a	7.05c	2.50d	31.27c
UENF 2208 × UENF 2209	2.78b	1.76b	16.37a	19.50b	4.87a	20.50a	11.87b	6.72c	47.61a
UENF 2208 × UENF 2210	2.77b	1.71b	16.16a	21.90a	4.85a	20.44a	15.69a	9.05b	52.43a
UENF 2208 × UENF 2205	2.96a	1.89a	17.56a	21.25a	4.75a	19.00a	13.97a	7.28c	57.21a
UENF 2208 × Piranão 12	3.04a	2.01a	16.42a	24.25a	4.50a	20.50a	15.62a	9.66b	60.81a
UENF 2209	2.24d	1.38d	14.69a	14.69b	4.67a	18.00a	5.37c	2.95d	25.37c
UENF 2209 × UENF 2210	2.66b	1.63b	16.99a	18.86b	4.46a	19.08a	13.67a	9.06b	46.22a
UENF 2209 × UENF 2205	2.72b	1.64b	16.82a	19.12b	4.62a	20.12a	14.09a	8.70b	51.71a
UENF 2209 × Piranão 12	2.77b	1.76b	16.94a	21.75a	4.62a	20.75a	13.49a	8.98b	50.99a
UENF – 2210	2.68b	1.52c	17.59a	19.37b	5.00a	20.87a	14.48a	8.14c	51.95a
UENF 2210 × UENF 2205	2.72b	1.63b	17.84a	20.30b	4.68a	20.02a	14.40a	8.47b	49.46a
UENF 2210 × Piranão 12	2.82b	1.71b	16.96a	23.50a	4.75a	21.37a	16.96a	11.91a	57.44a
UENF 2205	2.26d	1.29d	17.24a	19.75b	4.75a	20.37a	9.72b	4.36d	38.64b
UENF 2205 × Piranão 12	2.47c	1.43c	17.03a	21.75a	4.87a	20.75a	12.66a	8.01c	45.27a
Piranão 12	2.50c	1.50c	15.76a	23.87a	5.00a	21.00a	11.21b	7.64c	41.83b
UENF – 506-11	2.46c	1.54c	16.1a	24.00a	4.37a	21.37a	14.68a	10.35a	48.47a
BM 3061	2.41c	1.25c	17.44a	20.87a	4.87a	20.62a	15.42a	11.65a	48.11a
AG 1051	2.41c	1.42c	16.63a	18.87b	5.00a	19.37a	15.09a	11.13a	48.15a

PH, plant height (m); EH, ear height (m); SD, stem diameter (cm); NE, number of ears, HC, husk covering; STAND, number of plants at harvest; HEW, husked ear weight ($kg.ha^{-1}$), UEW, unhusked ear weight ($kg.ha^{-1}$); FMW, fresh matter yield ($kg.ha^{-1}$). Means followed by the same letter were not significantly different from each other using the Scott-Knott test at a level of significance of 5%.

Table 5. Description of the 6 genetypes used for diallel and the 2 controls used in the experiments, concerning genetic basis, grain type and origin.

Identification	Genotype	Genetic basis	Grain Type	Origin
1	UENF 2202	Population	Dent	UENF
2	UENF 2208	Lines	Dent	UENF
3	UENF 2209	Lines	Dent	UENF
4	UENF 2210	Population	Dent	UENF
5	UENF 2205	Population	Dent	UENF
6	Piranão 12	Population	Dent	UENF
7	UENF 506-11*	Interpopulation hybrid	Semi-Dent	UENF
8	AG 1051*	Hybrid double	Dent	Commercial

* Controls;

effects. Therefore, intrapopulation selection strategies are recommended to improve these characteristics.

The variance of cumulative effects on the genetic control of traits indicated that it was easier to select lines produced by the combination of superior parental genotypes. The variance of non-cumulative effects indicated the feasibility of using hybrid crosses "per se" with parental genotypes (Freitas Junior et al., 2006).

Analysis of GCA and SCA

GCA is related to the cumulative genetic effects and frequency of desirable parental alleles, whereas SCA is associated with differences in traits of a cross from what would be expected based on the parent's GCA as a function of the non-cumulative genetic effect combined with the effects of dominance and epistasis (Hallauer et al., 2010).

The effect of GCA on PH and EH was negative in the parents UENF 2202, UENF 2209, and UENF 2205 (Table 2). In addition, the effect of GCA on SD was negative in genotypes UENF 2202, UENF 2209, and UENF 2208. The effect of GCA on NE was positive in UENF 2202 and Piranão, indicating that these genotypes had higher yields for NE. The effect of GCA on HC was negative in the parental genotypes UENF 2209 and UENF 2205, demonstrating the high degree of husk covering in harvests performed at this stage of ear development. The effect of GCA on STAND was positive in UENF 2202, UENF 2210, and Piranão 12, and these genotypes had the highest average STAND values.

It should be highlighted that the effect of GCA on FMY was positive in UENF 2210 and Piranão 12 and, consequently, FMY was increased in the crosses, in which they participated because of the presence of favorable alleles with a cumulative effect, and both HEW and UEW were increased. Therefore, these genotypes are promising in hybridizations intended to improve the analyzed traits and in genetic improvement programs because of higher average yield and higher GCA.

The effect of GCA was negative on almost all characters in genotypes UENF 2209 and UENF 2205 (Table 2). Cruz and Vencovsky (1989) reported that parents with lower frequencies of favorable alleles for the trait in question had lower $\hat{g}_i$.

With regard to the effect of SCA on FMY, the crosses UENF 2208 × Piranão 12, UENF 2208 × UENF 2205, UENF 2209 × UENF 2205, and UENF 2202 × UENF 2208 had high and positive values, indicating that these combinations enhanced the effects of dominance (Table 3). These combinations presented higher average FMY, and the averages in these crosses were grouped in the first category (Table 4). The interactions UENF 2208 × Piranão 12 and UENF 2208 × UENF 2205 were the most promising.

Cluster analysis (Table 4) indicated that the following combinations were favorable: UENF 2210 × Piranão 12 and UENF 2208 × UENF 2210, which presented higher average FMY despite the low SCA. In the cross UENF 2210 × Piranão 12, the effect of GCA on FMY was positive in both genotypes, indicating that this combination was promising. In the cross UENF 2208 × UENF 2210, the effect of GCA on FMY was very weak in UENF 2208 and weak in UENF 2210. Furthermore, the combination of the alleles from these genotypes increased FMY in the generated hybrid.

Among the 24 treatments, the parents UENF 2208 and UENF 2209 presented the lowest FMY, and cluster analysis assigned them to the category with the lowest averages. UENF 2202, UENF 2205, and Piranão 12 had intermediate FMY, whereas UENF 2210 had the highest FMY and was grouped with the hybrids with the highest FMY.

The combinations UENF 2208 × Piranão 12, UENF 2210 × Piranão 12, and UENF 2208 × UENF 2205 were promising, with average FMY of 60.81 t ha^{-1}, 57.44 t ha^{-1}, and 57.21 t ha^{-1}, respectively. The average FMY in these genotypes was higher than that considered adequate for silage production (40–50 t ha^{-1} of fresh matter), according to the recommendations of the seed companies (Piana et al., 2008).

Other crosses were promising for selecting hybrids for NE and HEW according to SCA estimates, including UENF 2202 × Piranão 12, UENF 2202 × UENF 2208, and UENF 2208 × UENF 2210, with positive and high $\hat{S}_{ij}$ values for these traits.

Cruz et al. (2012) reported that SCA is associated with differences in traits of a hybrid from what would be expected based on the parent's GCA, high absolute $\hat{S}_{ij}$ values, indicating that agronomic performance is better or worse than expected. Therefore, crosses with higher positive $\hat{S}_{ij}$ for these characters should be used in breeding programs to increase grain yield.

It is worth noting that, the participation of parents UENF 2208 and Piranão 12 in these hybrid crosses, and these genotypes presented the third highest and second highest positive GCA for FMY (0.685 and 2.462, respectively). Worku et al. (2008) have shown that SCA should be high in hybrid crosses, and at least one parental genotype with high GCA should be included in these crosses. Therefore, the superior performance of this combination can be attributed to higher FMY, which was inherited from the parents Piranão 12 and UENF 2208, allowing an increase in FMY in the hybrids generated from these crosses.

Moreover, the high $\hat{s}_{ii}$ values indicated that the gene frequencies of these parental lines are higher (i.e., more divergent) than those of the other parents. The selection of parental lines is a crucial step in genetic improvement programs because favorable alleles for the traits of interest should be concentrated in these lines, enabling producing superior hybrids (Oliboni et al., 2012).
In hybrids with the highest average yield-related traits, at least one of the parents presented high GCA (Table 4).

Materials and Methods

Plant materials

The genotypes used in this research were selected for these crosses based on the work previously developed by the research group for improvement of forage maize (Crevelari et al., 2017; Crevelari et al., 2019). Among all materials available in the UENF germplasm bank, these stood out as good breeders and with higher yield values. Therefore, the hybrids were obtained by crossing six of these best pre-selected genotypes (Table 5), in a complete diallel cross without reciprocals, totaling 15 hybrid combinations. This stage was conducted at the Antônio Sarlo State School of Agriculture, in Campos dos Goytacazes, Rio de Janeiro, Brazil, in 2017. The pre-selected genotypes belong to the maize collection of the North Fluminense Darcy Ribeiro University. All genotypes produced dent kernels. Each parental pair was pollinated manually by covering spikes with polyethylene bags. Subsequently, the mature tassels were covered with a "Kraft" paper bag. The hybrids were intercrossed to obtain a sufficient number of seeds necessary to maintain hybridization.

Field experiments

The evaluation assays were performed in the 2017/2018 growing season at the Antônio Sarlo State School of Agriculture, in Campos dos Goytacazes, state of Rio de Janeiro, and at the Barra do Pomba Island Experimental Station, in Itaocara, Rio de Janeiro. According to Köppen's classification, the climate of these two regions is Aw (humid tropical), with dry winter and wet summer. The average annual temperature is approximately 23.3 ºC, and annual rainfall is approximately 1.147 mm (INMET, 2019). The study adopted a completely randomized block design with four repetitions and 24 treatments (fifteen hybrids, six parents, and three commercial controls). The commercial controls were UENF 506-11, BM 3061, and AG 1051.
The experimental unit consisted of a crop row with a length of 4 m, an inter-row spacing of 1 m, and an inter-plant spacing of 0.2 m. The harvests were performed by cutting the plants at 20 cm from the ground when 50% of the ears reached the silage stage. A practice adopted in the field to confirm the silage stage is observing the kernel milk line and harvesting the ears when 1/3 to 2/3 (average of 1/2) of the kernel is filled with starch, i.e. the kernel consistency is changing from the dough to the dent stage.

Agronomic traits evaluated

Nine agronomic traits were evaluated, including six characters in six plants randomly chosen in each plot, and six traits in the entire study area. The traits analyzed in each plot were plant height (PH), measured from ground level to the tassel insertion node (m); ear height (EH), measured from ground level to the node of the upper ear (m); stem diameter (SD), measured randomly in the first internode above the ground (mm). The traits evaluated in the study area were the stand (STAND), which is total number of plants at harvest time; husk covering (HC), which was evaluated using a grading scale ranging from 1 to 5, in which 1 is significant kernel exposure with low husk covering and 5 is completely protected kernels; number of ears (NE), which is the total number of harvested ears; husked ear weight (HEW), obtained by weighing all ears with husks (ton ha^{-1}); unhusked ear weight (UEW), determined by weighing all ears without husks (ton ha^{-1}); fresh matter yield (FMY) from all plants in each plot, which were harvested and weighed using a dynamometer scale (ton.ha^{-1}).

Statistical analysis

Data were subjected to individual analysis of variance (ANOVA) in each experimental station. The joint analysis in both stations was performed after finding the homogeneity of the residual variances. Averages were grouped using the Scott-Knott test at a level of significance of 5%. A combined ANOVA was performed according to the equation:

$$Y_{ijk} = \mu + (\mathcal{B}/\mathcal{A})_{jk} + \mathcal{G}_i + \mathcal{A}_i + \mathcal{GA}_{ij} + \mathcal{E}_{ijk}$$

where:
Y_{ijk} is the observation in the kth block evaluated in the ith genotype and jth environment;
μ is the overall mean of the assay;
$(\mathcal{B}/\mathcal{A})_{jk}$ is the effect of block k on environment j;
$\mathcal{G}_i$ is the fixed effect of genotype i;
$\mathcal{A}_i$ is the random effect of environment j;
$\mathcal{GA}_{ij}$ is the effect of the interaction between genotype i and environment j; and
$\boldsymbol{\mathcal{E}_{ijk}}$ is the random error associated with observation Y_{ijk}.
GCA and SCA were analyzed using method 2 (progenitors + F1 without reciprocals) of the diallel analysis proposed by Griffing (1956), which includes p(p+1)/2 combinations. The statistical model used in the analysis was:

$$Y_{ij} = \mu + g_i + g_i + \mathcal{S}_{ij} + \mathcal{E}_{ij}$$

where:
Y_{ij} is the mean value of hybrid (i ≠ j) or parent (i = j);
μ is the overall mean;
g_i and g_j are the effects of the GCA of the ith or jth parent;
$\mathcal{S}_{ij}$ is the effect of the SCA of crosses between parents of order i and j; and
$\mathcal{E}_{ij}$ is the mean experimental error of observation of order ij.
Statistical analyses were performed using GENES software (Cruz, 2013).

Conclusions

The evaluated germplasm has the potential for selecting parental maize lines for producing high-quality silage and can be used for grain production through lines derived from superior genotypes.
The parents UENF 2210, Piranão 12, and UENF 2208 had the highest general combining ability for fresh matter yield and are indicated for producing open-pollinated varieties for silage production or be used in other crosses.
The results of cluster analysis indicated that the most promising hybrids were the crosses UENF 2208 × Piranão 12,

UENF 2210 × Piranão 12, and UENF 2208 × UENF 2205, which presented average yields of 60.81 t ha^{-1}, 57.44 t ha^{-1}, and 57.21 t ha^{-1}, respectively, and these values were higher than those in the commercial control.

Acknowledgements

The authors are grateful to the Research Support Foundation of Rio de Janeiro State (FAPERJ) for their financial support. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

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