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Article

Heterotic pattern in su1 sweet corn hybrids originating from native breeds

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Abstract

The introgression of genes originating from native Maíz Dulce breeds from Mexico to non-sweet parent lines was carried out; as a hypothesis, the use of recurrent selection is an alternative for the transfer of the sweetness gene to non-sweet lines for the formation of hybrids. In the research, we look for parent lines with general and specific combining ability with the aim of creating a heterotic pattern for the formation of sweet corn hybrids with su1 sweetness gene because in Mexico there is no seed production of this genetic material. Lines CML311, CML78, LUG282, LUG03, and LUG20 and the breeds Dulcillo del Noroeste and Maíz Dulce. Genetic crossbreeding designs, line by progeny tester and North Carolina Design II; we measured the effects of general and specific combining ability of lines and crosses; a combined analysis of variance of three evaluations in two evaluation cycles and multiple selection indices of the variables of the best crosses were performed to establish heterotic groups; years of evaluation, from 2017 to 2021 in Zapopan, Jalisco. In conclusion, we found three parent lines that belong to the maternal heterotic group with germplasm of Dulcillo del Noroeste and LUG282 and four parent lines for the paternal heterotic group with germplasm of maize dulce and CML311. The results showed a contribution to the transfer of the su1 sweetness gene to non-sweet lines; the hybrid crosses developed presented quality in plant and ear.

Keywords:

ASCA, Ducillo del Noroeste, genetic improvement, GCA..

Introduction

The states of production of sweet corn varieties grown in Mexico are Jalisco, Zacatecas, Sinaloa, Nayarit, Michoacán, Guanajuato, Sánchez *et al*. (2000); Ruiz *et al*. (2013). In Mexico, there are two native breeds, Dulcillo del Noroeste and Maíz Dulce (Tracy, 1997). This grain has several uses, mainly growing tender ears of corn or shelled ears processed in industry, preparation of typical regional food, cattle feed. It is rich in carotenoids, phenolic components, phosphorus, potassium and magnesium (Lau *et al*., 2019).

Authors such as Elayaraja *et al*. (2014) suggest that, for the formation of hybrids, tests of combining ability with each other should be carried out, and form heterotic groups with heterosis, in this case of grain sweetness; that is, cumulative, dominant and recessive quantitative traits. Revilla and Tracy (1997) mention that heterotic groups improve agronomic and adaptive behavior.

Materials and methods

The work was carried out at the University Center for Biological and Agricultural Sciences (CUCBA), for its acronym in Spanish, of the University of Guadalajara (U de G), for its acronym in Spanish in Jalisco. Coordinates (20° 44’ 42.7” north latitude and 103° 30’ 54.1” west longitude), altitude of 1 658 m, the pollen donor germplasm was the breeds Maíz Dulce and Dulcillo del Noroeste with su1 gene to recurrent pure non-sweet lines of the International Maize and Wheat Improvement Center (CIMMYT), for its acronym in Spanish, CML311 and CML78, and of the University of Guadalajara, LUG282, LUG03, and LUG20. The introgression of the recessive gene su1 and the formation of heterotic patterns is shown in Figure 1.

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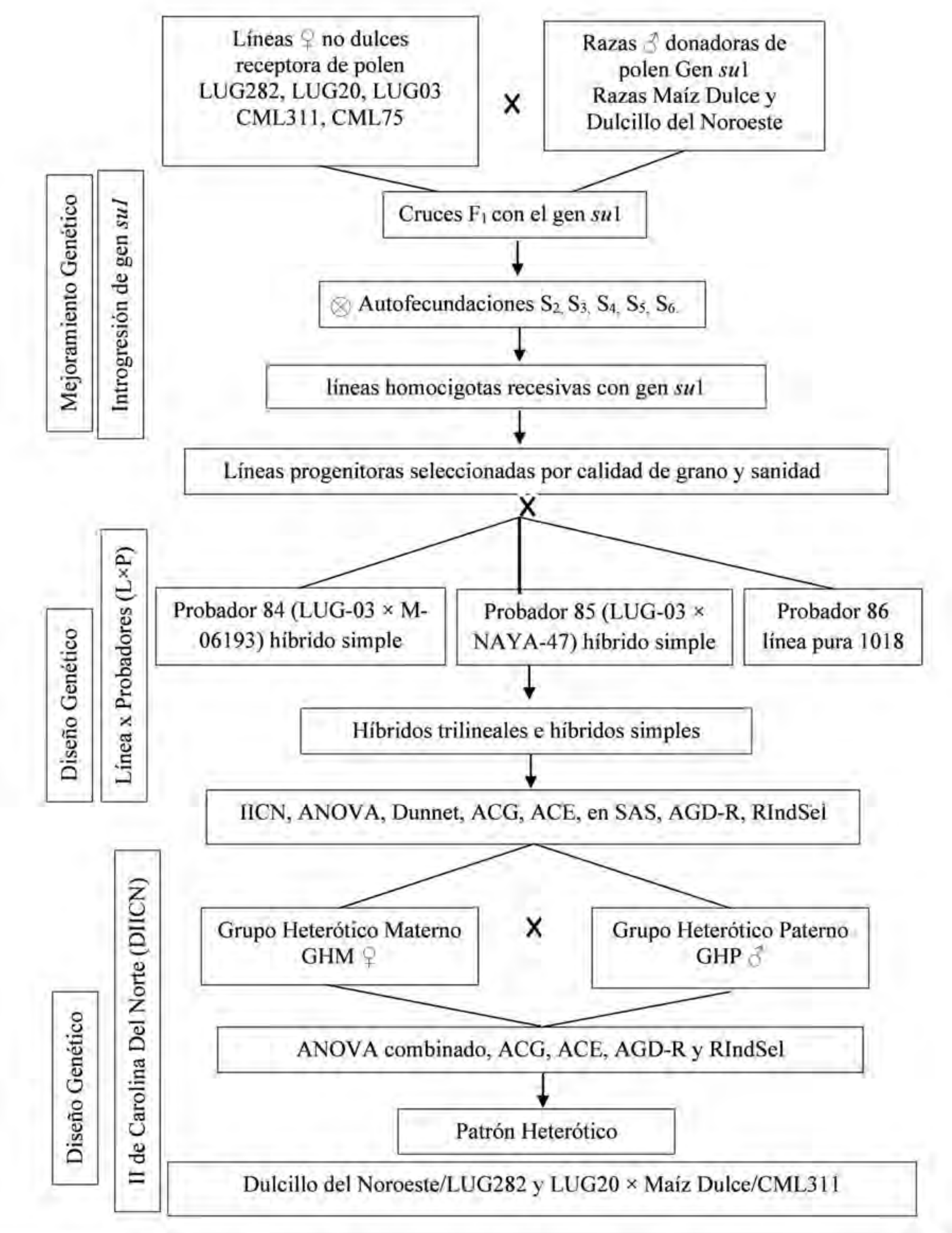
Figure 1. Formation of the heterotic pattern in sweet corn with su1.



In 2017, 399 S_6 parent lines with su1 gene were obtained to select only 20% for germination, adaptation, flower synchrony, grain and plant health; there were 83 parent lines and they were analyzed with a genetic statistical design known as lines × progeny tester (L×P); two single crosses

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(P-84= LUG03×M-06193), (P-85= LUG03×NAYA-47) and a pure line (P- 86= 921/1018) were used as testers. A total of 249 hybrids, 166 three-way cross and 83 single-cross, were obtained, and an analysis of variance was performed with PROC GLM (SAS, 2007).

The experimental design was an arrangement of randomized incomplete blocks (756 plots, 252 treatments, 18 incomplete blocks with 42 treatments and three replications). The variables evaluated were male flowering (Dmf), female flowering (Dff), plant height (PlHei), ear height (EHei), ear length (ELeng), earn diameter (EDia), grain sweetness at 30 days after flowering (°Bx), and weight of 10 ears without bracts at 30 days after flowering (W10E), reference controls: Hortaflor, Golden Sweeter and Jayamitla.

Dunnet's test was performed; we measured the best values of selection indices of different variables simultaneously, yield, sweetness, length and diameter; the RIndSel software (CIMMYT, 2020) was used with the linear phenotypic selection index (LPSI) function (Smith, 1936). The test of general and specific combining abilities, (GCA) and (SCA), of 83 parents was also performed; we used the ADG-R software with the North Carolina (NCII) analysis of randomized incomplete blocks.

With the analyses, we selected 27 parents with the best averages; they were separated into two heterotic groups, the females with 16 maternal lines (GHM) and 11 paternal lines (GHP). These groups were crossed 16 x 11 with the North Carolina genetic design II (NCDII) (Female×Male); the F_1 hybrids were evaluated with a randomized incomplete block design in three separate evaluations with two planting cycles in the years 2019 and 2020 in rainy season; the experimental design of randomized incomplete blocks (10×11) with three replications in each evaluation and SAS were used (SAS Institute, 2007).

The AGD-R software (CIMMYT, 2018), was used for the effects of GCA and SCA of the lines of both heterotic groups (GHP×GHM). A combined Anova of the three evaluations of the two cycles was also employed. The statistical models used were linear statistical model of randomized incomplete blocks, statistical model of the North Carolina genetic design II NCDII (m×h), and the model for the combined Anova.

Results and discussion

The L×P genetic design shows that it was highly significant (*p*# 0.01) for all the variables of the parents; there was diversity in the quality of the hybrids in variables such as W10E, length and °Bx. The testers presented significance (*p*# 0.01) for the variables EDia, PlHei, EHei and Dff, and there were no significant differences in the interaction of L×P; however, numerical differences were observed in the averages 21 °Bx in single crosses and 20.3 and 20.4 °Bx in three-way crosses.

Hallauer's (2001) findings showed genotypes with total WSP soluble solids that translate into values of 14.3 to 28.5 °Bx, we agreed in the ranges, but with lower values in the values of his evaluations. The averages are shown in Table 1.

Table 1. Analysis of variance of hybrids, genetic design L×P, 2018.

Source	DF	W10E (kg)	°Bx	Eleng (cm)	Edia (cm)	PlHei (m)	EHei (m)	Dmf (d)	Dff (d)
Model	285	0.21^{**}	11.54^{**}	3.03^{**}	0.12^{**}	0.06^{**}	0.04^{**}	21.02^{**}	15.54^{**}
MSE	413	0.06	6.82	1.31	0.02	0.02	0.01	11.22	2.44
MSR	2	1.08^{**}	34.55	2.18	0.02	0.01	0.01	47.16	176.93^{**}
MSB(r)	51	0.22^{**}	11.99	2.18	0.07^{**}	0.05^{**}	0.03^{**}	14.62	5.53^{**}
MSL	82	0.45^{**}	13.84^{**}	6.48^{**}	0.32^{**}	0.11^{**}	0.07^{**}	35.96^{**}	34.24^{**}
MST	2	0.4	31.33	0.83	0.44^{**}	0.4^{**}	0.4^{**}	18.49	34.58^{**}
MSL×T	149	0.06	9.54	1.46	0.04	0.03	0.01	13.3	4.29^{**}
CV		13.24	12.7	6.73	3.84	8.7	16.72	4.73	2.23
Mean		1.892	20.5	17.03	4.4	1.72	0.72	70.7	69.9

MSE= mean square error; MSR= mean square of replication; MSB(r)= mean square of blocks within replication; MSL= mean square of lines; MST= mean square of testers; MSL*T= mean square of lines by testers; CV= coefficient of variation; DF= degrees of freedom; **= highly significant; *= significant; W10E= weight of ten ears without bracts; °Bx= grain sweetness expressed in degrees Brix; EDia= ear diameter; ELeng= ear length; PlHei= plant height; EHei= ear height; Dmf= days to male flowering; Dff= Days to female flowering.

The researcher Tracy (2007) evaluated ear sweetness, size and diameter and obtained 15.7 cm in ear length and the present findings, 17.3 cm; in diameter, he obtained 4.2 cm and the present document, 4.4 cm. The simple hybrids managed to outperform the reference controls, sweetness 12.8 °Bx in Golden Sweet, 20.7 °Bx in Hortaflor, and 18.5 °Bx in Jayamitla. For the cross 1 003×1 024, 26.2 °Bx; Garay *et al*. (2012) obtained genotypes with 27.1 °Bx.

Analyses of the L×P genetic design showed that the model was highly significant ($p\leq 0.01$) due to the broad genetic base used in the formation of hybrids. Table 3 shows the GCA effects and the best crosses were shown in Table 5. The combined analysis of variance allowed us to distinguish highly significant statistical differences ($p\leq 0.01$) for hybrids, treatment above the general mean in different variables. Suzukawa *et al*. (2018) showed parent lines of hybrids with values above 15 °Bx, compared to these hybrids evaluated with a sweetness of 18.1 °Bx on average (Table 2).

Table 2

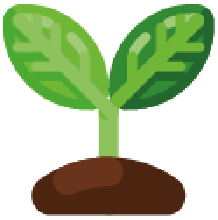
Combined Anova of three evaluations of two cycles, maternal x paternal groups.

V	DF	W10E (kg)	°Bx	Eleng (cm)	Edia (cm)	PlHei (m)	EHei (m)	Dff (d)	Dmf (d)	Row
M	376	1.21^{**}	9.12^{**}	6.33^{**}	0.14^{**}	0.09^{**}	0.05^{**}	22.09^{**}	16.9^{**}	3.58^{**}
E	426	0.07	4.89	1.19	0.04	0.02	0.01	5.6	3.58	0.84
H	130	0.58^{**}	12.16^{**}	10.49^{**}	0.24^{**}	0.11^{**}	0.09^{**}	31.11^{**}	24.3^{**}	7.40^{**}
A	2	127.6^{**}	131.1^{**}	136.4^{**}	2.27^{**}	1.44^{**}	0.42^{**}	338.4^{**}	289.9^{**}	6.48^{*}
HxA	162	0.13^{**}	5.71	2.05^{**}	0.05	0.03	0.01^{**}	7.28	6.1^{**}	1.07
R(A)	5	0.15	16.09	3.12	0.05	0.44^{**}	0.22^{**}	49.9^{**}	28.7^{**}	0.88
B(A×R)	77	0.09	4.14	1.44	0.05	0.07^{**}	0.02^{**}	13.55^{**}	9.15^{**}	0.85
CV		11	12.2	5.8	4.9	8.6	11.4	3.2	2.6	6.3
Mean		2.48	18.1	18.9	4.49	1.99	0.98	73.74	72.33	14.6

V= variables; M= model; E= error; H= hybrids; A= environments; HxA= hybrids x environments; R(A)= replication in environments; B(AxR)= environments by replication in blocks, DF= degrees of freedom; **= highly significant: *= significant; W10E= weight of 10 ears without bracts; °Bx= degrees of sweetness expressed in °Bx; ELeng= ear length; Edia= ear diameter; PlHei= plant height; EHei= ear height; Dff= days to female flowering; Dmf= days to male flowering; Row= ear rows; CV= coefficient of variation.

Table 3. General combining ability (GCA) of the top 15 females.

Rank	Females	GCA	Standard error	T value	Prob-T	Breed
1	1003	0.585	0.375	1.558	0.142	Maíz Dulce
2	1012	0.5	0.378	1.324	0.207	Dulcillo del Noroeste
3	1001	0.333	0.352	0.948	0.359	Maíz Dulce
4	1010	0.196	0.453	0.432	0.672	Maíz Dulce
5	1015	0.177	0.355	0.498	0.626	Maíz Dulce
6	1006	0.11	0.328	0.336	0.741	Maíz Dulce
7	1014	-0.02	0.372	-0.053	0.959	Maíz Dulce
8	1002	-0.033	0.331	-0.101	0.921	Maíz Dulce
9	1004	-0.092	0.331	-0.279	0.784	Maíz Dulce
10	1005	-0.099	0.337	-0.294	0.773	Maíz Dulce



Rank	Females	GCA	Standard error	T value	Prob-T	Breed
11	1008	-0.12	0.345	-0.347	0.734	Dulcillo del Noroeste
12	1016	-0.127	0.316	-0.401	0.695	Maíz Dulce
13	1009	-0.424	0.401	-1.058	0.308	Dulcillo del Noroeste
14	1011	-0.457	0.331	-1.380	0.189	Dulcillo del Noroeste
15	1007	-0.53	0.376	-1.412	0.18	Dulcillo del Noroeste

GCA= general combining ability.

The best values above 20 °Bx occurred in 12 of the 26 lines and in one of the controls, data that coincide with the results obtained by Luchsinger and Camilo (2008), who reported soluble solids values between 20 and 30 °Bx. Narváez (2007) pointed out that sweet corn is appropriate for tender ears, industrialized or grilled.

The parents presented GCA and SCA; in addition, we added one more line per group to each of the groups, ♀1016 to the GHM and ♂1027 to the GHP, used by their GCA; these lines correspond to parents of the testers (P.85 and P.86) of the L×P genetic design.

In the interaction between females and males, they only present high significance ($p \leq 0.01$) in the variables of ELeng and Row, which suggests that only some crosses will give greater length to the ear and greater thickness. In ear length, we obtained ranges of 15.8 and 19.6 cm, higher than the hybrids compared in the research by Choe *et al*. (2016), who obtained ranges of 16.6 and 19.4 cm.

In the combined analysis of variance, the hybrids showed highly significant genetic variance for the evaluation environments; however, the hybrids behaved similarly in both environments of the two cycles in °Bx, indicating that the sweetness gene is stable; Wong *et al*. (1994); Djemel *et al*. (2010) point out that the viability of the su1 gene depends on the gene × genotype interaction, it is regulated by dominant effects of recurrent selection in the process of genetic improvement, similar to this research.

The review conducted by Fan *et al*. (2003) mentions that the formation of commercial corn hybrids requires the generation of new lines with general and specific combining abilities to be successful in genetic improvement programs. According to the above assumptions, the results of the hybrids were favorable due to the relevant behavior of GCA and SCA of the parent lines and hybrids.

Heterotic patterns, selected for obtaining the best SCAs in hybridization and GCA by both parents based on AGD-R analyses and selection indices (Table 3, 4 and 5), showed a good source of favorable alleles that increased the additive and dominance effects of the genes. Heterotic patterns are germplasm combination models that expressed good combination and their expression is maintained over time; these pairs can be formed by two groups of different germplasm, two corn landraces or breeds, two improved populations, a single cross between two outstanding lines (Ramírez *et al*., 2007). According to Manjarrez *et al*. (2014), the GCA and SCA of agronomic traits and their genetic components are indicators of seed quality in corn grains.

Table 4. General combining ability (GCA) of the top 15 male parents.

Rank	Male	GCA	Standard error	T value	Prob-T	Breed
1	1023	0.769	0.339	2.266	0.047	Maíz Dulce
2	1019	0.657	0.321	2.05	0.068	Maíz Dulce
3	1 018	0.555	0.357	1.553	0.151	Maíz Dulce
4	1 024	0.358	0.353	1.015	0.334	Maíz Dulce
5	1 017	0.095	0.318	0.299	0.771	Maíz Dulce

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Rank	Male	GCA	Standard error	T value	Prob-T	Breed
6	1 027	-0.118	0.406	-0.291	0.777	Maíz Dulce
7	1 025	-0.137	0.392	-0.349	0.734	Maíz Dulce
8	1 026	-0.265	0.49	-0.54	0.601	Maíz Dulce
9	1 021	-0.425	0.346	-1.229	0.247	Maíz Dulce
10	1 022	-0.49	0.433	-1.132	0.284	Maíz Dulce
11	1 020	-0.998	0.325	-3.067	0.012	Maíz Dulce

GCA= general combining ability.

Table 5. GCA and SCA in AGD-R for the best crosses. Hybridizations of female and male heterotic groups.

SCA	GCA female	GCA male	Female	Male	W10E	°Bx	ELeng	EDia
0.254	0.333	0.095	1001	1017	1.31	21.9	16.1	4.4
0.224	0.585	0.358	1003	1024	1.61	26.2	19	4.7
0.202	0.585	0.095	1003	1017	1.2	20	15.8	4.8
0.223	0.5	0.657	1012	1019	1.617	22.7	19	4.1
0.254	0.196	0.095	1010	1017	1.742	19.7	17	4.6

SCA= specific combining ability; GCA= general combining ability; W10E= weight of 10 ears without bracts; °Bx= degrees of sweetness expressed in °Bx; ELeng= ear length; EDia= ear diameter.

The heterotic agronomic pattern was formed with four parent lines with SCA and GCA, females 1001, 1003, 1010, and 1012 with germplasm of LUG282 of the Maíz Dulce and Dulcillo del Noroeste breeds and three male parent lines, 1017, 1019 and 1024, with germplasm of CML311 of the Maíz Dulce breed, which together managed to form 12 simple quality hybrids (Table 6).

Table 6. Identification of female and male parents.

Parent	Genealogies	Breed
	Female	
1003	MD, (LUG-282xM09483)F1-1-3-2-1	Maíz Dulce
1012	DN, (LUG-282xNAY-47)F1-6-2-2-1-1	Dulcillo del N
1001	MD, (LUG-282xZAC-182)F1-3-1-3-1-1-1	Maíz Dulce
1010	LUG-03XM-06193-Planta12	Maíz Dulce
	Male	
1019	MD, (CML311xJal-78-PL34)F1-1-2-1-1	Maíz Dulce
1024	MD, (CML311xJal-78-PL7)F1-5-2-1-1	Maíz Dulce
1017	MD, (CML311xJal-78-PL33)F1-4-1-1	Maíz Dulce

Conclusions

Dulcillo del Noroeste and Maíz Dulce contributed the su1 sweetness gene for the formation of new hybrids, along with elite lines from the genetic improvement programs of CIMMYT and the University of Guadalajara. The parent lines obtained by recurrent selection involved in the hybridizations provided favorable agronomic traits such as plant quality, good yield weight for ear, and sweetness in °Bx in the F_1 generational progeny.

The outstanding variables in the present study were ear sweetness, measured in °Bx, and yield, which were represented by the heterotic pattern for the formation of sweet corn hybrids with values of W10E of 2.51 kg, sweetness of 21 °Bx, ear length of 26.2 cm, and ear diameter of 4.9 cm.

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