Determination of discriminatory traits in maize hybrids

Carlos B. BANCHERO^{a*}, Norberto BARTOLONI^a, Miguel Angel RAPELA^b,
Gabriel MARRASSINI^a, Santiago RENTERÍA^a

^a Cátedra de Genética, Facultad de Agronomía, Universidad de Buenos Aires, Av. San Martín 4453 (1417), Buenos Aires, Argentina

^b Agar Cross S.A., División Semillas, Rosario, Santa Fe, Argentina

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Abstract – A discriminant analysis was performed on a set of morphological characteristics for a group of Argentine commercial maize (*Zea mays* L.) hybrids. In the discriminant analysis a set of canonical varieties was constructed to assess the discriminatory incidence of those characteristics among commercial hybrids. Discriminant analyses were performed on plant, ear and kernel characters. With the exception of whole plant traits, significant discriminations were found and the composition of the canonical variables explaining them was determined. For traits measured on the whole plant, ear insertion height was primarily responsible for the variation, and a noticeable level of uniformity was observed with respect to stalk diameters. Ear traits (ear medium diameter and ear length), kernel weight and number of kernels, exhibited the most significant discrimination among hybrids. Finally, with respect to kernel traits, significant distances among hybrids were detected, and kernel length and kernel breadth were the most important traits.

maize / hybrids / discriminant analysis / breeding / variability

Résumé – Détermination de caractères discriminants dans des hybrides de maïs. Une analyse discriminante a été faite pour un ensemble de caractères morphologiques chez un groupe d'hybrides commerciaux de maïs argentins (*Zea mays* L.). Avec cette analyse, une série de variables canoniques a été définie pour évaluer la capacité discriminante de ces caractères entre les hybrides. Des analyses discriminantes ont été réalisées pour des caractères de plante entière, de l'épi et du grain. À l'exception des caractères correspondants à la plante entière, des discriminations significatives ont été trouvées pour tous les caractères étudiés et la composition des variables canoniques pour les expliquer a été définie. Entre les caractères mesurés pour la plante entière, la hauteur d'insertion de l'épi a été le principal responsable de la variation, tandis que le diamètre de la tige a été le plus stable. Les caractères mesurés pour l'épi (diamètre moyen et longueur), le poids du grain et le nombre de grains ont été les plus significatives entre les hybrides. Finalement, des distances significatives entre hybrides ont été détectées avec la longueur et la largeur du grain.

maïs / hybrides / analyse discriminante / amélioration de plantes / variabilité

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* Correspondence and reprints
banchero@mail.agro.uba.ar

1. Introduction

The importance of genetic variability in commercial breeding has been repeatedly emphasized [9] as an essential requirement for the improvement of traits associated with crop production and quality. Thus, it would be interesting to know which traits show discrimination among populations such as commercial hybrids in order to use them in the outlining of breeding programs. Examples of the consequences of lacking such variability have been documented [1].

Assessing genetic variability has been greatly improved with the use of multivariate analysis techniques [14, 15]. Since the expansion of computers, their use has been greatly extended through a vast array of scientific as well as technological areas. In biology, applications such as numerical taxonomy, cladistics, and evolution are widely known [3, 8, 10, 11].

The variability of populations under breeding processes has been assessed in different species and environments [2, 4–6]. Our objective in this work was to determine whether there is any degree of statistically significant discrimination among maize (*Zea mays*) hybrids in current commercial production in Argentina and which traits most contribute to it. To do this, we applied discriminant analysis [15] to macroscopic traits of agronomic interest in some Argentine commercial hybrids. Discriminant functions allow the breeders to look over one aspect of the critical issue of variability inside commercial populations. This was possible with the collaboration of three international corn breeding companies that work in Argentina, namely: Dekalb Argentina SA, Pioneer Argentina SA and Cargill Argentina SACIF. These companies provided seeds from their most representative corn hybrids. Discriminant analysis allows us to get a general picture of differences eliminating the correlations that obscure the readings.

It has been frequently discussed whether the residual variability within the commercial populations of the most important plant species is currently under the threat of being lost given its dramatic reduction due to the utilization of a very narrow

genetic base and the subsequent breeding process [12]. Many corn hybrids currently under production are based on inbred lines that have a common germplasm. Under this assumption, it is expected that the hybrids were closely related and low discrimination would be found among their traits. Here we have tested such an hypothesis, i.e. that the discrimination among several traits is not statistically significant.

We have calculated canonical variates, which allow the reduction in data dimensions and the inference of a biological interpretation from the overall variation in the experiment. Then, if there were any degree of discrimination among the groups being surveyed, it might be summarized in a few variates.

2. Materials and methods

2.1. Genetic materials

The following fifteen hybrids from a sample provided by the companies were tested:

Dekalb Argentina SA: 638, 664, 752 (single-cross hybrids [2X]), 3F24, 3S41 (triple-cross hybrids [3X]) and 4F37, 4F91, 762 (double-cross hybrids[4X]).

Pioneer Argentina SA: 3456, 3162 (single-cross hybrids[2X]) and 3478 (triple-cross hybrid[3X]).

Cargill Argentina SA: M31, TH92, T327 (triple-cross hybrids[3X]) and SD5 (double-cross hybrids[4X]).

2.2. Experimental design

The experiment was developed in the corn nursery of the Facultad de Agronomía. A Randomized Complete Block Design was used. The experiment comprised 300 plants (20 plants per hybrid), in 2 complete blocks, with 10 plants (replicates) per block, i.e. 10 plants in a row with 0.70 m between rows. The groups (hybrids) were randomly distributed in the blocks. Data from individual plants were analyzed. A multivariate analysis of variance

(MANOVA) [15] among the hybrids for all the traits measured was calculated. Thus, there has been in the MANOVA a HYBRID term, a BLOCK term, an ERROR term and an INTERACTION (BLOCK $\times$ REPLICATE) term. There was no significance in the F Snedecor for the interaction term, nor for the blocks (probably due to the uniform environment in the nursery).

2.3. Morphological measurements

Measurements were taken on plant, ear, and kernels in the Facultad de Agronomía (Universidad de Buenos Aires) in 1996 and 1997.

(1) Measurements on plants: plant height (PH) in cm, lower major stalk diameter (DIAM2L) in cm, lower minor stalk diameter (DIAM2C) in cm, upper major stalk diameter (DIAM1L) in cm, upper minor stalk diameter (DIAM1C) in cm, and ear insertion height (EIH) in cm (the lower ear, where there were more than one); lower diameters were taken at the base of the stalk, while the upper ones were measured on the stalk upper portion above the ear. One ear per plant was measured.

(2) Measurements on ears: Ear architecture: ear length (EL) in cm, ear basal diameter (EBD) in cm and ear medium diameter (EMD) in cm; Measurements associated with yield: husk weight (HW) in g, number of husks (NH), mean number of kernels per row (NKR) (30 kernels per ear were sampled), kernel weight (KW) in g, cob weight (CW) in g, number of rows (NR) and total number of kernels (NK).

(3) Measurements on kernels: kernel breadth (KB) in cm, kernel length (KL) in cm and kernel thickness (KT) in cm.

2.4. Canonical analysis

To statistically test the degree and nature of discrimination among the groups of hybrids, canonical variates [3,16] accounting for most of the variation of the experiment were obtained (see appendix).

The discriminant analysis was performed with this canonical analysis providing a set of new vari-

ables extracted from the data. The original data matrix Y was transformed (see appendix) to obtain a set of fully non-correlated variables that maximize the variation among the groups while minimizing variation within them. Such canonical variates are linear combinations of the original ones, and they were standardized to make comparisons across them. Also, the corresponding χ^2 tests for each of the successive roots extracted were computed. Analyses were performed separately for each type of hybrid (whether 2X, 3X or 4X) computing for each case:

- (a) Wilks' λ significance tests to assess the global degree of discrimination;
- (b) χ^2 significance tests to calculate the number of canonical roots;
- (c) Standardized coefficients constituting each canonical root.

3. Results

3.1. Plant architecture traits

The general discriminant analysis corresponding to plant architecture characteristics shows a notable difference among types of hybrids. For the 2X hybrids there is significant discrimination ($p < 0.05$) for 3 traits (PH, DIAM2C and EIH) (Tab. I). In turn, for 3X and 4X hybrids there seems to be a highly significant discrimination with respect to EIH and, in the case of double hybrids, also to PH.

The multivariate data analysis allowed the reduction of the multidimensional array of points to a tri-, uni- and univariate distribution for the 2X, 3X, and 4X hybrids, respectively (Tab. II) using a χ^2 probability criterion (i.e. $p < 0.01$): 3 significant canonical roots were extracted for the 2X group, and only 1 root for 3X and 4X hybrids.

The composition of those canonical roots in terms of the original variables is shown in Table III. In all the 3 groups it was clear that the main component of the first canonical root (the most important in all cases) was EIH with an explanatory power greater than 61% in the case of 2X hybrids, greater than 90% for 3X hybrids, and

greater than 84% in the case of double hybrids. In agreement with what was explained when commenting in Table II, only 1 canonical variate is nec-

Table I. Discriminant analysis with λ Wilks tests corresponding to measurements taken on the whole plant*.

Hybrid Type	Variable	Wilks λ	$p <$
2X	PH	0.311	0.0040
	DIAM1C	0.287	0.0931
	DIAM2C	0.327	0.0005
	DIAM1L	0.292	0.0516
	DIAM2L	0.272	0.5299
	EIH	0.440	0.0001
3X	PH	0.201	0.2593
	DIAM1C	0.198	0.4694
	DIAM2C	0.195	0.7190
	DIAM1L	0.203	0.1736
	DIAM2L	0.207	0.0813
	EIH	0.385	0.0001
4X	PH	0.371	0.0002
	DIAM1C	0.285	0.9028
	DIAM2C	0.286	0.7994
	DIAM1L	0.287	0.7484
	DIAM2L	0.290	0.5763
	EIH	0.574	0.0001

* PH: plant height, DIAM1C: upper minor stalk diameter, DIAM2C: lower minor stalk diameter, DIAM1L: upper major stalk diameter, DIAM2L: lower major stalk diameter, EIH: ear insertion height.

Table II. Canonical roots extracted and χ^2 tests corresponding to measurements taken on plants.

Hybrid type	Roots	Eigenvalue	χ^2	D. F.	$p <$
2X	1	1.091	124.869	24	0.0001
	2	0.404	55.894	15	0.0001
	3	0.191	24.188	8	0.0021
	4	0.088	7.849	3	0.0493
3X	1	2.991	187.884	30	0.0001
	2	0.219	31.480	20	0.0493
	3	0.079	9.109	12	0.6936
	4	0.004	0.504	6	0.9978
	5	0.001	0.103	2	0.9500
4X	1	1.634	93.361	18	0.0001
	2	0.229	21.320	10	0.0190
	3	0.085	6.071	4	0.1940

essary to account for the discrimination for 3X and 4X hybrids and 2 (84.29%) or 3 (95.06%) for 2X ones. The second canonical variate corresponding to 2X hybrids is constituted mainly by DIAM2C.

The great explanatory power of the 2 first canonical roots is clearly shown. We have included the second canonical root in the case of 2X hybrids because it explains almost 23% of the total variation, but it is worth taking into account its low eigenvalue (0.404, less than half of the recommended value of 1). Hence, EIH seems to be the main reason why groups are different regarding the whole plant traits analyzed in this experiment.

3.2. Ear architecture traits

Table IV shows the discriminant analysis abstract corresponding to ear architecture traits. Clearly, EBD does not contribute to much of the discrimination, among 2X hybrids and among 4X ones. In the case of the 2X hybrids EL and EMD determine a highly significant discrimination among hybrids while in the case of 3X groups, EL and EBD do. Also for the 4X hybrids EL and EMD are the main discriminatory variables but to a lesser significance level.

As in the case of plant traits, 2 of the extracted roots were highly significant ($p[\chi^2] < 0.01$) in the case of 2X hybrids but only one in the other cases (Tab. V). The composition of the canonical variables shows a clear picture for single hybrids in which case the first canonical root explains more than 92% of total variation, this root being constituted mainly by EMD. Discrimination among 3X hybrids is explained mainly by a sort of “ear shape” coefficient ($-0.739 \cdot EL + 0.898 \cdot EBD$). Among 4X hybrids, discrimination is accounted for by an “ear size” coefficient ($0.634 \cdot EBD + 0.800 \cdot EMD$) (Tab. VI).

3.3. Ear measurements associated with yield

The overall discriminant analysis shows a complex pattern in terms of the original variables (Tab. VII). In order to summarize it, it may be said that there are no statistically significant differences

Table III. Standardized coefficients for each canonical variate corresponding to measurements taken on plants*.

Hybrid type	Variable	λ_1	λ_2	λ_3	λ_4	λ_5
2X	PH	0.351	0.050	-0.683	-0.502	—
	DIAM1C	-0.165	0.451	0.281	0.262	—
	DIAM2C	-0.053	0.930	-0.352	0.260	—
	DIAM1L	-0.189	-0.357	0.556	-0.595	—
	DIAM2L	-0.104	-0.012	0.247	-0.585	—
	EIH	0.839	0.095	0.560	-0.050	—
	Eigenvalue	1.091	0.404	0.191	0.088	—
	Cumul. Perc.	61.52	84.29	95.06	100.00	—
3X	PH	0.151	-0.228	0.700	0.289	0.569
	DIAM1C	0.176	0.189	-0.555	-0.681	0.327
	DIAM2C	0.021	-0.065	-0.634	0.942	0.041
	DIAM1L	0.234	-0.430	0.207	-0.236	-0.809
	DIAM2L	0.242	-0.635	0.146	-0.175	0.272
	EIH	0.800	0.567	0.021	-0.062	-0.221
	Eigenvalue	2.991	0.219	0.079	0.004	0.001
	Cumul. Perc.	90.81	97.46	99.86	99.97	100.00
4X	PH	-0.417	0.851	-0.415	—	—
	DIAM1C	0.150	0.003	0.041	—	—
	DIAM2C	0.095	-0.280	-0.406	—	—
	DIAM1L	-0.001	-0.212	-0.478	—	—
	DIAM2L	-0.127	-0.332	-0.138	—	—
	EIH	-0.879	-0.400	0.241	—	—
	Eigenvalue	1.654	0.229	0.085	—	—
	Cumul. Perc.	84.03	95.66	100.00	—	—

* PH: plant height, DIAM1C: upper minor stalk diameter, DIAM2C: lower minor stalk diameter, DIAM1L: upper major stalk diameter, DIAM2L: lower major stalk diameter, EIH: ear insertion height.

Table IV. Discriminant analysis with λ Wilks tests corresponding to ear architecture traits*.

Hybrid type	Variable	Wilks λ	$p <$
2X	EL	0.393	0.0001
	EBD	0.279	0.1383
	EMD	0.778	0.0001
3X	EL	0.776	0.0099
	EBD	0.818	0.0008
	EMD	0.764	0.0208
4X	EL	0.813	0.0133
	EBD	0.760	0.1257
	EMD	0.800	0.0226

* EL: ear length, EBD: ear basal diameter, EMD: ear medium diameter.

Table V. Canonical roots extracted and χ^2 tests corresponding to ear architecture traits.

Hybrid type	Roots	Eigenvalue	χ^2	D. F.	$p <$
2X	1	2.225	128.205	12	0.0001
	2	0.115	16.966	6	0.0094
	3	0.072	6.631	2	0.0363
3X	1	0.242	44.262	15	0.0001
	2	0.124	19.440	8	0.0127
	3	0.054	6.003	3	0.1115
4X	1	0.227	26.297	9	0.0018
	2	0.158	11.037	4	0.0262
	3	0.002	0.128	1	0.7201

Table VI. Standardized coefficients for each canonical variate corresponding to ear architecture traits*.

Hybrid type	Variable	λ_1	λ_2	λ_3
2X	EL	0.839	-1.017	-0.0019
	EBD	0.080	-0.089	1.035
	EMD	-1.334	0.044	-0.260
	Eigenvalue	2.225	0.115	0.072
	Cumul. Perc.	92.24	97.00	100.00
3X	EL	-0.739	0.633	0.666
	EBD	0.898	0.439	0.278
	EMD	0.280	-1.083	0.340
	Eigenvalue	0.242	0.125	0.054
	Cumul. Perc.	58.58	87.20	100.00
4X	EL	-0.043	-1.096	-0.059
	EBD	0.634	0.015	0.778
	EMD	0.800	0.449	-0.599
	Eigenvalue	0.227	0.158	0.002
	Cumul. Perc.	58.78	99.55	100.00

* EL: ear length, EBD: ear basal diameter, EMD: ear medium diameter.

among 2X and 3X hybrids with regard to NKR and NK and that, with the exception of NH and NK, all variables show differences among 4X hybrids. 3X hybrids show a lesser degree of discrimination among them. The χ^2 tests shown in Table VIII and the canonical variates constitution in Table IX indicate that at least 2 of the roots should be taken in mind in order to explain most of the variation. In the case of 2X hybrids they explain 88.7% of the total variation, while for 3X hybrids almost 80% is explained. In the case of double hybrids the first 2 canonical roots explain 94%. With respect to the root components, KW (1st root) and NK (2nd root) are the main components in the case of 2X hybrids. HW (1st root) and a linear combination of the kernel numbers ($-2.798 \cdot \text{NKR} + 2.523 \cdot \text{NK}$) are the main components in the case of 3X hybrids. Finally, NKR and NK are the principal root components in the case of 4X hybrids.

3.4. Kernel traits

The main character is KL while KT seems to make little or no contribution in all three groups

Table VII. Discriminant analysis with λ Wilks tests and corresponding to ear measurements associated with yield*.

Hybrid type	Variable	Wilks λ	$p <$
2X	HW	0.060	0.0005
	NKR	0.050	0.2767
	KW	0.091	0.0001
	NH	0.081	0.0001
	NR	0.056	0.0079
	NK	0.052	0.0670
3X	CW	0.059	0.0010
	HW	0.289	0.0001
	NKR	0.185	0.4373
	KW	0.195	0.0586
	NH	0.245	0.0001
	NR	0.190	0.1825
4X	NK	0.186	0.3813
	CW	0.214	0.0010
	HW	0.3108	0.1231
	NKR	0.3956	0.0001
	KW	0.4017	0.0001
	NH	0.2929	0.6630
	NR	0.3651	0.0007
	NK	0.4266	0.0001
	CW	0.3313	0.0163

* HW: husk weight, NKR: mean number of kernels per row, KW: kernels weight, NH: number of husks, NR: number of rows, NK: total number of kernels, CW: cob weight.

Table VIII. Canonical roots extracted and χ^2 tests corresponding to ear measurements associated with yield.

Hybrid type	Roots	Eigenvalue	χ^2	D. F.	$p <$
2X	1	4.260	282.960	28	0.0001
	2	1.226	128.576	18	0.0001
	3	0.528	54.146	10	0.0001
	4	0.172	14.743	4	0.0053
3X	1	1.623	194.892	35	0.0001
	2	0.365	86.418	24	0.0001
	3	0.293	51.374	15	0.0001
	4	0.180	22.439	8	0.0042
	5	0.035	3.816	3	0.282
4X	1	1.271	91.914	21	0.0001
	2	0.391	31.624	12	0.0016
	3	0.106	7.390	5	0.1933

Table IX. Standardized coefficients for each canonical variate corresponding to ear measurements associated with yield*.

Hybrid type	Variable	λ_1	λ_2	λ_3	λ_4	λ_5
2X	HW	0.273	0.601	-0.035	-1.237	—
	NKR	-0.244	0.167	-2.229	-1.951	—
	KW	2.022	1.849	0.511	1.859	—
	NH	-0.473	-0.364	0.900	-0.103	—
	NR	-0.642	0.895	-1.244	-0.712	—
	NK	-0.851	-2.171	2.150	1.415	—
	CW	-1.092	-0.294	-0.185	0.152	—
	Eigenvalue	4.260	1.226	0.328	0.172	—
	Cumul. Perc.	68.87	88.70	97.22	100.00	—
3X	HW	1.023	0.724	-0.451	-0.651	0.002
	NKR	-0.661	-2.798	1.342	-2.441	-1.545
	KW	-0.574	0.122	-0.117	-1.282	2.142
	NH	0.389	-0.772	0.660	0.202	0.044
	NR	-0.718	-1.155	1.493	-2.238	-1.092
	NK	0.788	2.523	-2.977	3.527	0.578
	CW	-0.102	0.679	1.430	1.278	-0.755
	Eigenvalue	1.623	0.365	0.293	0.180	0.035
	Cumul. Perc.	65.01	79.63	91.41	98.62	100.00
4X	HW	-0.269	0.635	0.039	—	—
	NKR	-0.899	0.063	0.592	—	—
	KW	-2.086	-0.788	-0.656	—	—
	NH	-0.063	-0.281	-0.199	—	—
	NR	-1.193	0.490	0.431	—	—
	NK	2.289	0.721	-0.595	—	—
	CW	1.027	-0.373	-0.086	—	—
	Eigenvalue	1.271	39.06	0.106	—	—
	Cumul. Perc.	0.719	94.02	100.00	—	—

* HW: husk weight, NKR: mean number of kernels per row, KW: kernels weight, NH: number of husks, NR: number of rows, NK: total number of kernels, CW: cob weight.

(Tab. X). Two canonical roots must be entered to take account of a significant part of the variation in the 3 groups (Tabs. XI and XII). In the case of 2X's a sort of "kernel shape" coefficient appears to be the meaning of the 1st canonical root: 0.731-KL-0.855-KB while a predominant variable appears in the constitution of the 2 first canonical roots in the case of 3X (KL and KT) and 4X (KB and KL) hybrids.

3.5. Genetic variance

The group of 2X hybrids is also especially interesting because the variance among individual

Table X. Discriminant analysis with λ Wilks tests and corresponding to measurements taken in kernels*.

Hybrid type	Variable	Wilks λ	$p <$
2X	KT	0.466	0.0310
	KL	0.619	0.0001
	KB	0.630	0.0001
3X	KT	0.789	0.0225
	KL	0.855	0.0005
	KB	0.752	0.1808
4X	KT	0.663	0.0781
	KL	0.741	0.0018
	KB	0.727	0.0035

* KT: kernel thickness, KL: kernel length, KB: kernel breadth.

Table XI. Canonical roots extracted and χ^2 tests corresponding to measurements taken in kernels.

Hybrid type	Roots	Eigenvalue	χ^2	D. F.	$p <$
2X	1	0.792	83.192	12	0.0001
	2	0.315	27.757	6	0.0001
	3	0.019	1.753	2	0.4162
3X	1	0.240	40.298	15	0.0004
	2	0.107	15.711	8	0.0467
	3	0.036	4.022	3	0.2591
4X	1	0.328	37.885	9	0.0001
	2	0.244	16.475	4	0.0024

Table XII. Standardized coefficients for each canonical variate corresponding to measurements taken in kernels*.

Hybrid type	Variable	λ_1	λ_2	λ_3
2X	KT	-0.159	0.649	0.851
	KL	0.731	0.841	0.005
	KB	-0.855	0.411	-0.427
	Eigenvalue	0.792	0.315	0.019
	Cumul. Perc.	70.38	98.35	100.00
3X	KT	-0.378	-0.951	-0.130
	KL	-0.966	0.193	0.293
	KB	0.347	-0.459	0.861
	Eigenvalue	0.240	0.107	0.036
	Cumul. Perc.	62.58	90.66	100.00
4X	KT	-0.595	-0.012	—
	KL	0.363	0.902	—
	KB	-0.805	0.277	—
	Eigenvalue	0.327	0.244	—
	Cumul. Perc.	57.34	100.00	—

* KT: kernel thickness, KL: kernel length, KB: kernel breadth.

plants within each hybrid is almost completely of an environmental nature. Assuming the construction has been properly performed, simple hybrids arise as a result of the intercrossing of 2 inbred lines. Thus, their genetic makeup is uniform.

In order to gain some help in the interpretation of multivariate results we have computed some values of variance components to assess the amount of the genetic component in these groups.

By means of an ANOVA Mixed Model [7] we have estimated the parameter σ_H^2 , i.e. the variance among single-cross hybrids. We have employed a mixed model because the HYBRID factor is random but the BLOCK factor is fixed. The mean square between simple hybrids estimate both components, σ_e^2 (the error component) and $nb \cdot \sigma_H^2$, n being the number of plants per block and b , the number of blocks. In the cases of 3X and 4X hybrids, in turn, the “Within Hybrids” component includes also a certain amount of genetic variation. In Table XIII the estimation of both components as well as the percentage of σ_H^2 with respect to σ_{TOT}^2 is presented. The BLOCK X TREATMENT interaction term was included in the TOTAL variance.

Table XIII. Estimation of the percentage of σ_H^2 – the variance between simple hybrids – with respect to the total variance, σ_{TOT}^2 , corresponding to each trait*.

	σ_H^2	σ_{TOT}^2	%
PH	80.25	419.1	20
DIAM1C	0.029	0.197	15
DIAM2C	0.040	0.170	24
DIAM1L	0.030	0.230	13
DIAM2L	0.020	0.340	6
EIH	94.90	198.6	48
EL	0.964	11.99	8
EBD	0.098	0.239	41
EMD	0.180	0.308	58
HW	6.376	19.77	32
NKR	0.001	64.96	0
KW	750.3	3270.4	23
NH	1.610	3.258	49
NR	5.930	7.820	76
NK	11256	30196	37
CW	28.34	70.68	40
KT	33×10^{-5}	373×10^{-5}	9
KL	56×10^{-4}	195×10^{-4}	29
KB	185×10^{-5}	655×10^{-5}	28

* PH: plant height, DIAM1C: upper minor stalk diameter, DIAM2C: lower minor stalk diameter, DIAM1L: upper major stalk diameter, DIAM2L: lower major stalk diameter, EIH: ear insertion height, EL: ear length, EBD: ear basal diameter, EMD: ear medium diameter, HW: husk weight, NKR: mean number of kernels per row, KW: kernels weight, NH: number of husks, NR: number of rows, NK: total number of kernels, CW: cob weight, KT: kernel thickness, KL: kernel length, KB: kernel breadth.

4. Discussion and conclusions

4.1. Plant architecture characteristics

There is a decrease in discrimination from 2X hybrids toward 3X's and 4X; single hybrids show a greater magnitude of overall differences and to a greater extent. This may be observed in the decrease of significance of Wilks' tests for the most of the variables. Only EIH keeps its significance across the 3 groups and the differences among the stalk diameters nearly disappears. This may well be the consequence of many years of struggle against a very common problem in early materials: lodging. So, breeders have tended to rely on homogeneous materials with respect to stalk architecture traits. This is especially important because of the breeders' tendency to start breeding programs upon the base of hybrid populations, extracting from them the allelic background that may determine their high performances, and recombining to obtain new higher performances in the field. Breeders generally do not use landraces or wild relatives in their programs [13]. Double and three way hybrids merge the genetic makeup of the simple hybrids and lines they are based on, thus decreasing the magnitude of the differences among them. Also the number and the statistical significance of the roots removed are by far greater for 2X hybrids (Tab. II). Moreover, the variances among simple hybrids with respect to total variance (which may give a good idea of the amount of genetic variance) is not very high (Tab. XIII). Only EIH presented a relatively high value (48%).

It would be worth remembering that canonical variables are absolutely correlation-free in the experiment. Thus, the inner variability partition calculated is much more than mere calculations of variances for further comparison with other populations. Indeed, we obtained discriminant functions explaining what the output of (maybe) years of genetic manipulation is. Canonical variates may be analyzed without any reference to other components and may be the starting point to take account of when considering the choice of selection variables.

4.2. Ear architecture characteristics

Given the results obtained for these traits, it may be said, – although the picture is not so clear – the situation here is not as threatening with respect to variation as in the plant architecture characteristics. The overall discrimination is not too low (Tab. IV) and the percentage of σ_H^2 with respect to σ_{TOT}^2 for the main variable (EMD) in the 2X group is high (58%). There still seems to be room for selection without regard for reduction in variability. Anyway, it would be interesting to take measurements of more characteristics with respect to ear architecture in order to draw a more general conclusion.

4.3. Ear measurements related to yield

The discriminatory power diminishes, going from 2X's to 3X and 4X as observed in the case of plant traits. The distances between single-cross hybrids are greater than distances observed among the hybrids of the other groups¹. There is an interesting degree of variation among simple hybrids and the percentages of σ_H^2 with respect to σ_{TOT}^2 are relatively high (Tab. XIII) – around 40% – and this is especially interesting taking into account the great manipulation these traits have undergone through years of breeding towards the highest possible yield: it seems that variability is still high.

4.4. Kernel measurements

With the exception of KB in the 3X group, the general discrimination is at the same statistical level of the characteristics associated with yield. Especially for KL the distances between hybrids within each group are statistically significant and this variable is also relevant as canonical root component in all three groups.

¹ We have computed and statistically tested squared Mahalanobis distances [Seber, 1984] among hybrids but we have not included them here, for the sake of brevity.

5. Concluding remarks

This survey may be extended to many different characteristics other than the morphological ones. Metabolic as well as chemical-composition or even molecular characteristics would be worth analyzing. Considering more inclusive levels of complexity, populational or ecological characteristics must be included especially addressing the ecological impact that the ever-increasing-uniformity breeding programs and the insertion of foreign genes can have on agro-ecosystems.

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Appendix

Canonical variates can be obtained from the original data matrix Y ($n \cdot p$, where n is the number of plants measured and p is the number of variables) through a linear transformation [Seber, 1984] that maximizes the differences among populations and minimize the variation within them. The linear transformation:

$$Z = Y \cdot T$$

(where T is the $p \cdot p$ transformation matrix) can be found by solving the characteristic equation:

$$|B - \alpha \cdot W| = 0$$

where B and W are between-groups and the within-groups sum of squares and products matrices, respectively. This equation has p eigenvalues ($\alpha_1, \alpha_2, \dots, \alpha_p$) given p is the number of original variables measured. Hence, the eigenvectors t_i corresponding to each of the canonical roots α_i , can be extracted.

Thus Z is an $n \cdot p$ matrix of fully orthogonal transformed variables maximizing the variation among the populations.

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