

Effect of *genotype x environment* interactions in popcorn maize yield and grain quality

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Abstract

Fourteen commercial popcorn maize hybrids were evaluated in a randomised block design in three locations for two years with the aim of introducing this crop into a region of the Buenos Aires province, Argentina, an area characterized by changing environmental conditions. The traits evaluated were grain yield, expansion volume, kernel width, kernel length, caryopsis roundness index, ear diameter, ear length, kernel density before expansion, expanded kernel density and prolificacy index. The interaction *genotype x environment* revealed environments favourable towards yield but which were simultaneously unfavourable towards expansion capacity, as well as genotypes stable for one of these variables but unstable for the other. However, some environments and genotypes were simultaneously favourable to both. Only a weak negative correlation was found between grain yield and expansion capacity, suggesting this relationship may not be very strong in these modern hybrids. Rounded grains showed higher expansion capacities, but this characteristic was negatively correlated to yield; roundness is therefore not recommended as a selection criterion. The prolificacy index correlated positively with yield but not with expansion volume, and is therefore a potential selection criterion.

Key words: *Zea mays* L., genotype x environment interaction, expansion capacity.

Resumen

Interacción genético-ambiental en cultivos de maíz reventón para rendimiento y calidad del grano

Se evaluaron 14 híbridos simples de maíz reventón, siguiendo un diseño de bloques al azar con tres repeticiones, en tres localidades de la provincia de Buenos Aires, Argentina, de condiciones variables en precipitación y tipo de suelo: Luján, Esteban Echeverría y Chascomús, durante dos años. Se analizaron las relaciones entre variables morfológicas, su influencia sobre rendimiento y capacidad de expansión: ancho y largo de grano, índice de redondez del cariopse, diámetro y largo de la espiga, densidad del grano sin expandir y del grano expandido e índice de prolificidad. El estudio de la interacción genético-ambiental mediante método AMMI mostró grupos de ambientes favorables para rendimiento y desfavorables para capacidad de expansión. En el caso de los genotipos se observó estabilidad para una variable e inestabilidad para la otra. No obstante, ciertos ambientes y genotipos resultaron con elevados valores para ambas variables. Se corroboró una débil correlación negativa ($r = -0.16^*$) entre rendimiento y capacidad de expansión, sugiriendo que en los híbridos modernos tal tendencia no es tan marcada. La influencia de la forma del grano sobre la capacidad de expansión fue muy importante. Los granos de forma redondeada tuvieron mayor capacidad de expansión que los alargados, pero menor rendimiento. El carácter planta con dos espigas influyó positivamente sobre el rendimiento y sin afectar la capacidad de expansión. De las tres localidades no tradicionales para el cultivo, Chascomús resultó la menos recomendable.

Palabras clave: *Zea mays* L., interacción genotipo x ambiente, capacidad de expansión.

Introduction

The cultivation of popcorn in Argentina has increased greatly in the last ten years: demand by the

MERCOSUR countries is high, as is profitability. Nearly all Argentine production is exported since internal consumption is tiny – less than 5% of total production.

«Popped corn» is produced by the explosion of the caryopsis due to the cooking temperature. Maize kernels, which are small and hard, are composed of three structural units: the pericarp, the endosperm, and the

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Table 1. Monthly rainfall (mm) at trial locations: E (Esteban Echeverría), L (Luján), C. (Chascomús)

Year	Location	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
1997	E									23.4	79.5*	146.0*	197.0*
	L									10.9	93.0*	135.3*	131.7*
	C									27.6	149.2*	124.6*	98.2*
1998	E	162.0*	50.1*	161.0*	133.0*	66.6	12.8	80.1	13.8	54.4	58.4*	58.8*	152.0*
	L	104.0*	101.3*	95.3*	98.8*	44.4	15.2	48.0	10.8	12.7	48.0*	54.7*	83.1*
	C	57.8*	26.5*	73.0*	238.3*	64.1	8.2	49.1	3.3	48.0	46.0*	76.9*	80.0*
1999	E	167.0*	137.0*	125.0*	40.6*	35.6	9.2	76.8	77.2	72.3	20.4	68.6	7.4
	L	158.3*	195.2*	111.7*	17.8*	18.0	6.8	51.9	42.1	64.1	22.5	36.4	29.4
	C	95.0*	63.7*	80.4*	51.2*	63.9	34.0	121.1	81.8	34.8	10.5	70.5	23.9

* Monthly rainfall from sowing until harvest.

embryo. Explosion capacity is determined by the corneous endosperm fraction being larger than the floury fraction, as well as the characteristics of the pericarp. The corneous endosperm, which is glassy in appearance, is composed of compact starch granules embedded in an elastic protein matrix with no air spaces. This resists the vapour pressure generated inside the grain until an explosive force is reached (Hoseney *et al.*, 1983). The pericarp helps the endosperm resist until this threshold pressure is attained. This tissue is thicker than in other maizes and has a negative effect on the quality of the popcorn pieces produced, leaving them with hard pieces of husk. The embryo has the least influence on the explosive qualities of the kernel (Richardson, 1960).

The aim of the present study was to compare the behaviour of different popcorn maize hybrids in a region characterised by its heterogeneous soils and irregular rainfall during the growth cycle (in some years abundant, in others scant, leading to marked water deficits).

The effects of these factors on yield and grain quality were analysed to evaluate the possibilities of introducing this crop into the studied region.

Material and Methods

Random block design assays (three repetitions) were performed at three sites (Luján, Esteban Echeverría and Chascomús) in the province of Buenos Aires, during the 1998 and 1999 growing seasons.

The rainfall recorded for both years (Table 1) was regular and sufficient for the growth of the crops in Esteban Echeverría and Luján; less rain fell in Chascomús. The soil characteristics of these locations are presented according to *Soil Taxonomy* (Soil Survey Staff, 1999) (Table 2). The heterogeneity of the soils influenced the availability of water (depending on their retention capacity). The landscape of Luján and Esteban Echeverría belongs to that known as *Pampa*

Table 2. Soil characteristics at the different trial locations

Location	1998	1999	Landscape	Soil classification*	Solum	Characteristics
Luján	E1	E4	Long, low rolling hills. Short slopes	Typical argiudol	Very deep, silty loam texture. Good supply of organic material	Well drained. No alkalinity. No salinity
Esteban Echeverría	E2	E5	Flat with some rolling country	Hapludol	Very deep silty loam texture. Good supply of organic material	Well drained. No alkalinity. No salinity
Chascomús	E3	E6	Low-lying flat land	Tapto-argic hapludol	Moderately deep, silty loam texture. Good supply of organic material	Imperfectly drained. No alkalinity. No salinity. Hydromorphism after 24 cm

E1, E2, E3, E4, E5 and E6: nomenclature of evaluation environments. * Soil Survey Staff (1990).

ondulada (low rolling grassland), the upland and half slope land providing the best soil for agriculture. The Chascomús landscape, however, belongs to the *Pampa deprimida*, which has low-lying soils (often salty and alkaline) showing signs of water erosion, and which are of limited use for agriculture. In this area, the experimental crops suffered changes in water availability during different phases of their development. This was not the case at the other sites where rainfall was greater and the soils were better.

Fourteen commercially available simple hybrids from North America (Alumni 608, Alumni 612, Alumni 614, Alumni 615, Alumni 618, Alumni 620, Alumni 621, Bahy 05, Bahy 08, Bahy 35, Hexp 1, Hexp 2, Hexp 3 and Hsur – here called G1-G14 respectively) were used in the study. These were provided by five seed companies randomly selected from the 30 operating in the area at the time of the study. The experimental plot consisted of two furrows each 5 m long separated by 70 cm, giving a density of 70,000 plants ha^{-1} . Maturity was reached at a mean of 135 days after sowing (grain humidity 15%).

The variables analysed, all related to grain yield and quality, were: grain yield Y (kg ha^{-1}), expansion volume (EV, $\text{cm}^3 \text{g}^{-1}$), kernel thickness (KT, mm), kernel width (KW, mm), kernel length (KL, mm), caryopsis roundness index (CRI), ear diameter (ED, mm), ear length (EL, cm), kernel density before expansion (KDbe, g cc^{-1}), expanded kernel density (EKD, g cc^{-1}), and prolificacy index (PI).

— Y was determined by removing all the grains from all the ears corresponding to each experimental treatment. The homogenised grains were weighed when they reached a humidity of 13.5% (optimum for adequate expansion).

— EV is defined as the volume of 1 g of popcorn grains expanded under normalised conditions (Dofing *et al.*, 1990). Data were collected using a thermostat-controlled popcorn maker with a temperature sensor below the heating plate. EV is the relationship between the exploded, expanded sample (measured in a 1000 cc flask) and 30 cc of unexploded seed.

— KT, KW and KL were determined using a random 1000 kernels from each treatment; measurements were taken as the largest distances possible for the given dimension. The importance of kernel shape on EV was first suggested by Lyster (1942). This author took into account three dimensions of the kernel and then determined their relationships via a factor he termed the «caryopsis roundness index» (CRI): $\text{CRI} = \text{KT} / \text{KW} + \text{KL}$.

— KDbe and EKD were calculated employing samples taken randomly (as immediately above), and using the following equations:

$\text{KDbe} = \text{Mass of 1000 kernels before expansion} / \text{volume of 1000 kernels before expansion}$.

$\text{EKD} = \text{Mass of 1000 expanded kernels} / \text{volume of 1000 expanded kernels}$.

— PI was determined by counting the number of plants and the number of ears per plant for each treatment, and then applying the following equation: $\text{PI} = \text{number of ears} / \text{number of plants}$.

Joint analysis of variance involved 14 genotypes $\times$ 6 environments $\times$ 3 repetitions for each environment. In agreement with the aims of the study, year and location were considered as the range of environments for the evaluation of the hybrids' phenotypic stability for yield and expansion volume:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha \times \beta)_{ij} + \rho_{k(j)} + \varepsilon_{ijk}$$

where:

Y_{ijk} = Observation corresponding to treatment i in environment j in repetition k .

μ = Overall mean

α_i = Effect (random) of genotype i

β_j = Effect (random) of environment j

$(\alpha \times \beta)_{ij}$ = Effect of interaction *genotype $\times$ environment*

$\rho_{k(j)}$ = Nested effect of repetitions in environment

ε_{ijk} = Error associated with Y_{ijk}

AMMI (additive main effects and multiplicative interaction models) analysis was used to examine the interaction *genotype $\times$ environment* (Crossa, 1990; Gauch, 1992; Gauch and Zobel, 1996).

$$Y_{ge} = \mu + \alpha_g + \beta_e + \sum \lambda_n \tau_{gn} \rho_{en} + \varepsilon_{ge}$$

where:

Y_{ge} = Observation of genotype g in environment e

μ = Overall mean

α_g = Mean genotypic deviation

β_e = Mean environmental variation

λ_n = Eigenvalue of the n axis in principal components analysis (PCA)

τ_{gn}, ρ_{en} = Genotypic and environmental unit vectors associated with λ_n

ε_{ge} = Random variable corresponding to the experimental error

This model was validated by cross checking (Cornelius, 1993; Gauch and Zobel, 1996), which allows the optimum number of axes for PCA to be chosen.

The relationships between variables were calculated using the program «Genes for Windows» (Cruz, 2001), which generates phenotypic, genetic and environmental correlations from the analysis of variance.

Table 3. Mean squares for the joint analysis of variance of the study variables

SV/DF variables	Environments (5 DF)	Rep (Env.) 12	Genotypes 13	Gen × Env. 65	Error 156	CV (%)
Y	4.93×10^7 **	1.97×10^6	1.58×10^6 **	4.7×10^5 **	2.6×10^5	9.97
EV	36.09**	8.36	23.68**	11.02**	5.8	7.77
KT	1.16**	0.047	0.243**	0.072	0.041	5.04
KW	1.89**	0.17	0.394**	0.082	0.087	4.91
KL	3.04**	0.256	1.039**	0.088	0.11	4.26
CRI	5.3×10^{-3} **	7.47×10^{-4}	1.65×10^{-3} **	4.06×10^{-4}	3.22×10^{-4}	4.76
ED	36.34**	2.18	9.97**	1.07	1.51	3.81
EL	34.6**	6.15	4.24**	0.87	0.77	5.51
KDBE	3×10^{-3} **	7.7×10^{-4}	1.3×10^{-3}	7.8×10^{-4}	8.8×10^{-4}	3.89
EKD	4.3×10^{-5} **	9.6×10^{-6}	2.8×10^{-5} *	1.3×10^{-5} **	6.16×10^{-6}	7.62
PI	0.318**	0.091	0.064**	0.019	0.0125	7.79

SV: source of variation, DF: degrees of freedom, CV: coefficient of variation. Variables defined in Material and Methods. ** $p < 0.01$. * $p < 0.05$.

Results

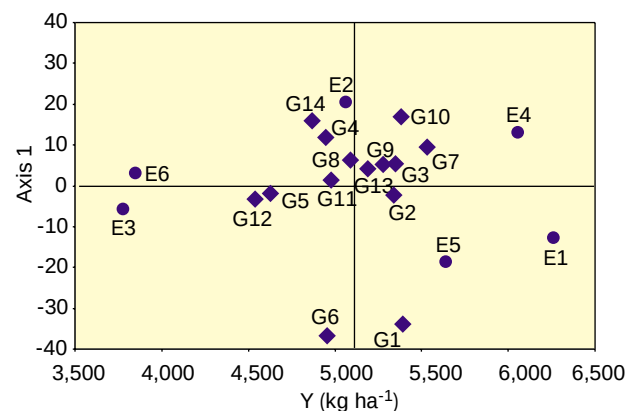
The interaction *genotype × environment* was significant for the two main variables Y and EV (Table 3). Of their component variables, it was only significant for EKD. With respect to the other variables, the effects of environment and genotype were important, except for KDBE, upon which genotype had no influence.

AMMI showed the main significant effects at $P = 0.01$ (Table 4); the interaction *genotype × environment* and PCA axis 1 were also significant at $P = 0.05$. The validation of the model by cross checking indicated a single PCA axis as optimum. AMMI1 includes only the first PCA axis, which in this case covers 80% of the variable Y and 88% of the sum of the total squares.

Figures 1 and 2 show the AMMI1 results for Y and EV. The ordinate axis coincides with PCA axis 1 for genotypes (G1-G14) and environments (E1-E6). The abscissa represents the quantitative variable. The genotypes and environments of axis 1 showing values close to zero contributed little to the sum of the squares of the interaction *genotype × environment*; they were therefore the most stable.

For Y, genotypes G11, G13, G12, G5 and G2 were those that contributed least to the interaction *genotype × environment*. G7 had the highest mean Y and shows an intermediate positive value for its coordinates with axis 1. The genotypes making the greatest contributions to this interaction were G1 and G6. The environment making the greatest contribution was E2; the

res of the interaction *genotype × environment*; they were therefore the most stable.

**Figure 1.** AMMI analysis for the variable «yield» (Y).**Table 4.** Mean squares from the analysis of variance of the AMMI1 model

SV/DF variables	Environment 5 DF	Genotypes 83	Gen × Env. 65	PICA1 17	Residual 48	Error 84	Total 167	Mean gral.
Yield (kg ha ⁻¹)	3.2×10^7 **	2.5×10^6 **	4.9×10^5 *	7.1×10^5 *	4.1×10^5	3.3×10^5	1.4×10^6	5,134.3
Expansion volume (cm ³ g ⁻¹)	29.38**	16.19**	9.41*	12.38*	8.34	6.42	9.03	31.08

SV: source of variation, DF: degrees of freedom, CV: coefficient of variation. Variables defined in Material and Methods. ** $p < 0.01$. * $p < 0.05$.

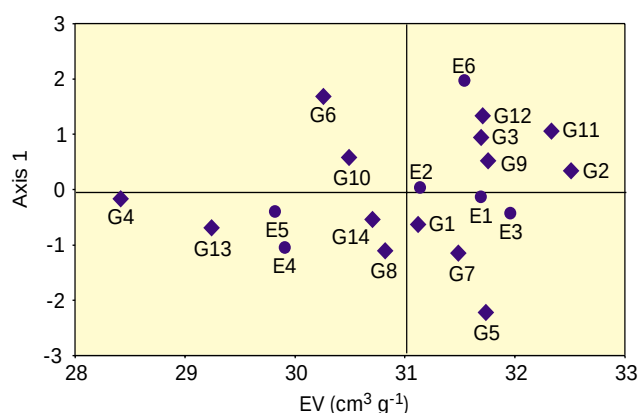


Figure 2. AMMI analysis for the variable «expansion volume» (EV).

smallest contributions were made by E3 and E6, which provided mean yields well below those of the other environments. The most favourable environments were E1 followed by E4, with intermediate values and opposite signs on axis 1. E1 showed a positive interaction with G1 and a negative interaction with G6. E4 showed a positive interaction with G7 and G10, two of the genotypes with the greatest yields.

Figure 2 shows the results for EV, which showed less environmental variability. E6 made the greatest contribution to the interaction *genotype $\times$ environment* while E1 and E2 were the most stable. The most favourable environments for this trait were E3 followed by E1, which showed a positive interaction with G5 and G7 and a negative interaction with G6 and G10. G5 and G6 made the greatest contributions;

G4 was the most stable, with a lower mean capacity for expansion than the rest. The most important genotypes for this trait were G2 followed by G11 (which made a greater contribution to the interaction than G2).

A comparison of Figures 1 and 2 shows that E3 and E6 had the lowest values for Y but the highest for expansion capacity, while E4 and E5 were favourable for Y but unfavourable towards expansion capacity. A third group, represented by E1, was favourable for both characteristics.

Table 5 shows the relationships between the variables. For Y, positive correlations were found with KL ($r = 0.52^{**}$), EL ($r = 0.55^{**}$), ED ($r = 0.51^{**}$) and PI ($r = 0.32^{**}$), KDbc ($r = 0.21^{**}$), and EKD ($r = 0.15^{**}$). There was a weak negative correlation between Y and EV ($r = -0.16^{*}$). Positive correlations were also found between EV and KT ($r = 0.46^{**}$) and CRI ($r = 0.81^{**}$). KT could be taken as a morphological variable with influence on EV. KL showed a certain negative influence on expansion capacity ($r = -0.18^{**}$). The strong correlation between EV and EKD ($r = -0.98^{**}$) is clear since the capacity to expand is directly proportional to volume, and inversely proportional to density. CRI correlated negatively with Y ($r = -0.32^{**}$), and with its components KL and ED ($r = -0.52^{**}$ and -0.25^{**} respectively). EKD showed a weak positive correlation with Y ($r = 0.15^{*}$) and with its components KL ($r = 0.19^{**}$) and ED ($r = 0.16$), and a stronger negative correlation with KT ($r = -0.46^{**}$) and CRI ($r = -0.47^{**}$). KDbc correlated positively with Y and its components ED and EL ($r = 0.21^{**}$, 0.19^{**} and

Table 5. Phenotypic correlations between characteristics related to grain yield and quality

	EV	Y	KT	KW	KL	CRI	ED	EL	KDbc	EKD
Y	-0.16*	—	—	—	—	—	—	—	—	—
KT	0.46**	-0.11	—	—	—	—	—	—	—	—
KW	0.09	-0.02	0.32**	—	—	—	—	—	—	—
KL	-0.18**	0.52**	-0.03	0.18**	—	—	—	—	—	—
CRI	0.47**	-0.32**	0.81**	-0.14	-0.52**	—	—	—	—	—
ED	-0.15*	0.51**	-0.01	-0.02	0.57**	-0.25**	—	—	—	—
EL	-0.01	0.55**	0.23**	0.17**	0.37**	-0.003	0.48**	—	—	—
KDbc	0.02	0.21**	-0.08	-0.09	0.12	-0.09	0.19**	0.21**	—	—
EKD	-0.98**	0.15*	-0.46**	-0.11	0.19**	-0.47**	0.16*	0.01	-0.014	—
PI	0.03	0.32**	0.19**	0.17*	0.11	0.07	0.011	0.28**	0.004	-0.04

** $p < 0.01$. * $p < 0.05$. Variables defined in Material and Methods.

0.21** respectively). No significant correlation was found between EV and KDbc.

Discussion

The AMMI results and the significant but low negative correlations observed for yield and expansion capacity confirms the disagreement between productivity and quality reported by several authors [Alexander and Greech (1977), Pajic and Babic (1991), Babic and Pajic (1992) and Da Silva *et al.* (1993)].

Analysis of the interaction *genotype x environment* detected environments favourable towards grain yields but unfavourable towards expansion volume. Similarly, the main group of genotypes showed stability for one variable but simultaneous instability for the other. The remainder showed differential behaviour from an agricultural point of view, with high simultaneous stability for both variables. The present results agree, at least partly, with those of Pajic and Babic (1991) and Babic and Pajic (1992) who performed their work in Europe.

The significant correlations between KL (negative), KT, and CRI (positive) confirm the importance of kernel shape with respect to expansion as reported by Lysterly (1942). This author concluded that the most rounded grains had greater expansion capacity than elongated grains. However, selecting KT or CRI as criteria for improving expansion capacity has quite a serious negative effect on yield. Both variables were found to be associated with soils with water deficits which provoked problems in plant growth and led to poor pollination. This gave rise to deficient grain filling, with some lines containing rounded seeds and irregular grain distribution on the cob. Similar field observations were reported from Venezuela by Vidal-Martínez *et al.* (2001). Pajic and Babic (1991) assert that the shape and size of the grain depends exclusively on the environment, but in the present work genotype was found to influence these variables.

The KDbc of the sample did not determine greater expansion capacity as reported by Robles and Covarrubias (1966) who worked on native Mexican maize populations. Taking this variable as a selection criterion, they increased expansion volume through successive crosses. The difference in results may be due to the different methodology used to measure KDbc. Further, unlike these populations, the commercial hybrids used have a uniform grain size.

The results suggest that Chacomús is not a good place for raising popcorn maize. True, high expansion capacity was recorded for this location, but so too was low yield. Luján and Esteban Echeverría, however, would seem to be reasonable locations. Cultivation could be undertaken on the rolling hillsides where horticultural activity is currently concentrated. However, the water deficits that occur in these places need to be taken into account: artificial irrigation would have to be available. However, the cost could be offset by the price the crop demands.

The relationships between the variables measured suggest that the best strategy for simultaneously improving yield and expansion capacity would be to use material with good expansion capacity and then select plants with more than one ear; the results showed PI to be an important component of yield but to have no significant influence on EV.

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