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P_i statistics underlying the evaluation of stability, adaptability and relation between the genetic structure and homeostasis in popcorn

Thiago Otávio Mendes de Paula[1], Antonio Teixeira do Amaral Júnior[2*], Leandro Simões Azeredo Gonçalves[3], Carlos Alberto Scapim[4], Luiz Alexandre Peternelli[5] and Vanessa Quitete Ribeiro da Silva[6]

*[1]Programa de Pós-graduação em Genética e Melhoramento, Universidade Federal de Viçosa, Av. Peter Henry Rolfs, s/n, 36570-000, Viçosa, Minas Gerais, Brazil. [2]Laboratório de Melhoramento Genético Vegetal, Universidade Estadual do Norte Fluminense "Darcy Ribeiro", Campos dos Goytacazes, Rio de Janeiro, Brazil. [3]Programa de Pós-graduação em Melhoramento de Plantas, Laboratório de Melhoramento Genético Vegetal, Universidade Estadual do Norte Fluminense "Darcy Ribeiro", Campos dos Goytacazes, Rio de Janeiro, Brazil. [4]Departamento de Agronomia, Pós-graduação em Agronomia e Genética e Melhoramento, Universidade Estadual de Maringá, Maringá, Paraná, Brazil. [5]Departamento de Informática, Universidade Federal de Viçosa, Viçosa, Minas Gerais, Brazil. [6]Programa de Pós-graduação em Produção Vegetal, Laboratório de Melhoramento Genético Vegetal, Universidade Estadual do Norte Fluminense "Darcy Ribeiro", Campos dos Goytacazes, Rio de Janeiro, Brazil. *Author for correspondence. E-mail: amaraljr@uenf.br*

ABSTRACT. The purpose of this study was to evaluate the interaction between genotypes and environments, evaluate adaptability and stability, and study the relationship between genetic structure and homeostasis. In addition to landrace, the study evaluated recommended genotypes or genotypes in experimental recommendation stages (varieties and hybrids) in three environments in northern and northwestern Rio de Janeiro State. Eight traits were measured, including grain yield and popping expansion. The individual analysis of variance revealed significant differences for all traits at 1% probability. In the combined analysis of variance, the genotype by environment interaction was significant at 1% probability for all traits except ear height. The interaction was simple for all traits except mean number of ears. The method of Lin and Binns detected the most suitable and stable genotypes, and also the most productive. UNB2U-C4 and IAC112 contained the lowest values of general P_i. Of those, UNB2U-C4 contributed least to the interaction, and IAC112 ranked fourth in interaction. UNB2U-C4 stood out with the best adaptation to favorable and unfavorable environments. No association between the genetic structure and stability degree in popcorn was observed.

Key words: *Zea mays*, genotype interaction by environment, phenotypic stability.

RESUMO. Estatística P_i na avaliação da adaptabilidade, estabilidade e relação da estrutura genética e homeostasia em milho pipoca. Objetivou-se avaliar interação entre genótipos por ambientes, avaliar adaptabilidade e estabilidade, bem como estudar a relação entre estrutura genética e homeostasia. Além de raças, foram avaliados genótipos recomendados ou em fase de recomendação no Brasil (variedades e híbridos) em três ambientes no Norte e Noroeste Fluminense. Foram quantificadas oito características, incluindo rendimento de grãos e capacidade de expansão. A análise de variância individual revelou diferenças significativas, a 1% de probabilidade de erro, para todas as características avaliadas. Pela análise de variância conjunta, com exceção da variável altura de espiga, houve interação significativa, a 1% de probabilidade, entre genótipos e ambientes. Excetuando-se número médio de espigas, as demais características expressaram interação do tipo simples. O método de Lin e Binns revelou os genótipos mais adaptados e estáveis, os quais foram também, os mais produtivos. UNB2U-C4 e IAC112 contiveram os menores valores de P_i geral. Desses, UNB2U-C4 conteve o menor percentual de contribuição para a interação e IAC112 foi o quarto genótipo a contribuir para a interação. UNB2U-C4 sobressaiu-se com a melhor adaptação a ambientes favoráveis e desfavoráveis. Houve ausência de associação entre estrutura genética e grau de estabilidade em milho pipoca.

Palavras-chave: *Zea mays*, interação genótipos por ambiente, estabilidade fenotípica.

Introduction

As a crop of considerable economic value, popcorn has gained increasing attention from researchers in Brazil, in view of the growing number of publications on popcorn breeding and management, as well as increasing consumption of the product (FARIA et al., 2008; SANTOS et al., 2008; VILELA et al., 2008; FREITAS JÚNIOR et al., 2009). However, intensive studies on the crop are still needed, especially on adaptability and stability, since most cultivars grown in Brazil come from North America (DAROS et al., 2004; FREITAS JÚNIOR et al., 2006; DANDOLINI et al., 2008; MIRANDA et al., 2008; VIEIRA et al., 2009). In addition, only few cultivars are available in the domestic market, for the small producer as well as for large-scale production (SANTOS et al., 2007; RANGEL et al., 2008; SILVA et al., 2009).

The presence of interaction between cultivar and environment influences selection gain and interferes with the indication of cultivars with wide adaptability. The interaction of genotypes by environment is one of the bottlenecks in breeding programs, since it restricts the progress to selection and recommendations of superior genotypes. However, specific cultivars can be developed for each environment, or the region can be subdivided into smaller areas to obtain cultivars with greater stability, minimizing alterations in the performance of genotypes in different environments (RAMALHO et al., 1993; CRUZ et al., 2004).

Kang and Gauch Júnior (1996) cite that the occurrence of interaction is related to cultivar-specific biochemical and physiological factors. The interaction is detected: i) when the expression of genes that control a trait is differential, or ii) when there is no coincidence of gene expression between environments. In both situations, the environment influences or regulates gene expression.

Investigations on the relationships between genetic structure and stability and adaptability in common maize have shown that, despite the greater heterogeneity of open-pollinated populations compared to simple hybrids, the heterozygosity of a panmitic population, for example, may be lower, resulting in a greater individual homeostasis of the simple hybrid, whereas varietal homeostasis is prevalent in open-pollinated populations (CRUZ; CARNEIRO, 2003, LEE et al., 2003). According to Adams and Shank (1959), the intrinsic heterozygosity is not sufficient to explain the stability of *Zea mays*, in agreement with Allard and Bradshaw (1964). The statement of Schnell and Becker (1986) that the stability of double hybrids is greater than of crosses between lines is contradictory to results from other authors, such as Carvalho et al. (2000), who identified simple hybrids with similar stability to double hybrids. Therefore, great care must be taken when dealing with stability related to the population structure in maize. The technique of estimation of stability and adaptability should therefore be appropriate and consistent to allow a clear identification of superior genotypes in different environments.

In an attempt to minimize the effects of the interaction, Tai (1971) suggested two strategies, namely: i) the subdivision of heterogeneous areas in homogeneous sub-areas, each with specific cultivars, and ii) the use of cultivars with high yield stability in a variable environment.

Based on these options, environmental stratification would be an alternative for the identification of superior genotypes in specific conditions; to quantify adaptability and stability, the choice of the methods depends essentially on the number of environments. For assessments in which fewer than five environments are used, methodologies based on regression analysis are not recommended, but rather methods such as: traditional Yates and Cochran, (1938), Plaisted and Peterson (1959), Wricke (1965), Lin and Binns (1988), and Kang and Pham (1991).

Considering the few studies on stability and adaptability in popcorn (VENDRUSCOLO et al., 2001; NUNES et al., 2002; VON PINHO et al., 2003; CARPENTIERI-PÍPOLO et al., 2005), and the lack of research on the relationship between genetic structure and stability, this study was conducted in an attempt to investigate the existence and nature of the interaction between genotypes and environments in northern and northwestern state of Rio de Janeiro, and to estimate the parameter P_i proposed by Lin and Binns (1988), in tests with a very high number of replications, with base populations, improved genotypes and genotypes in experimental recommendation stages in Brazil.

Material and methods

The experiments were conducted in the growing season 2007/2008, at the Colégio Estadual Agrícola Antônio Sarlo, in Campos dos Goytacazes, in the northern region of Rio de Janeiro State; at the experimental station of the Empresa de Pesquisa Agropecuária do Estado do Rio de Janeiro (PESAGRO-RIO) in Itaocara, in the northwestern region of Rio de Janeiro State; and at the experimental station of PESAGRO-RIO, in Campos dos Goytacazes, northern region of Rio de Janeiro State. The Colégio Agrícola is about 8 km away from PESAGRO-RIO in Campos dos Goytacazes, and about 110 km away from PESAGRO-RIO in Itaocara.

Ten popcorn genotypes were evaluated, including two base populations of the Universidade Federal de Viçosa (UFV) Minas Gerais State, improved cultivars and hybrids, as well as cultivars in experimental stages prior to release in Brazil, as follows: i) BRS Angela, an open-pollinated variety recommended by Embrapa Maize and Sorghum, with white grains; ii) IAC 112, a modified simple hybrid recommended by the Instituto Agronômico de Campinas (IAC) Sao Paulo State, orange grains;

iii) IAC 125, a three-way hybrid, recommended by IAC, orange grains; iv) Jade, a three-way Pioneer hybrid, orange grains; v) Zélia, a three-way Pioneer hybrid, orange grains; vi) UFVM2 Barão Viçosa, an open-pollinated variety recommended by UFV, orange grains; vii) UNB2U-C3 and C4, respectively, populations of the third and fourth cycles of recurrent selection of UNB-2U in experimental recommendation stages; and viii) Beija-Flor and Viçosa, both open-pollinated landrace varieties with yellow grains, provided by the UFV gene bank.

The randomized block design was used with seven replications. The plots consisted of one 5-m row spaced 0.90 m and plants spaced 0.02 m apart, totaling 25 plants per plot. The following traits were evaluated: i) plant height, in cm (PH); ii) mean insertion height of the first ear, in cm (IH); iii) mean number of ears (NE); iv) grain yield in kg ha^{-1} (GY); v) mean number of days to flowering (FLOW); vi) mean weight of 100 grains in g (W100); vii) popping expansion of popcorn grains, in mL g^{-1} (PE); and viii) popcorn grain volume per area, in m^3 ha^{-1} (PV).

The combined analysis of variance was performed according to the criteria of homogeneity of the residual mean squares, where the ratio between the highest and lowest residual mean square was not more than seven (CRUZ et al., 2004), based on the genetic-statistical model $Y_{ijk} = \mu + R/E_{jk} + G_i + E_j + GE_{ij} + \xi_{ijk}$, where μ is the mean, R/E_{jk} is the effect of the k^{th} replication in the j^{th} environment, G_i is the fixed effect of the i^{th} genotype, E_j is the fixed effect of the j^{th} environment, GE_{ij} is the interaction effect of the i^{th} genotype in the j^{th} environment; and ξ_{ijk} is the experimental error.

For all evaluated traits, the partitions of the interaction were estimated in complex parts in pairs of environments, by the algorithm proposed by Cruz and Castoldi (1991), in which the complex part was expressed as:

$$C = \sqrt{(1-r)^3}\sqrt{Q_1Q_2}$$

where:

Q_1 and Q_2 are the mean squares of genotypes in the environments 1 and 2, respectively, and r is the mean correlation between genotypes in both environments. Lin and Binns (1988) used the following estimator of phenotypic stability:

$$P_i = \sum_{j=1}^{n} (X_{ij} - M_j) \Big/ 2n$$

where:

P_i is the index of superiority of the i^{th} cultivar, X_{ij} is the yield of the i^{th} cultivar at environmental j, M_j expresses the maximum response obtained among all cultivars at environmental j, and n represents the number of environments. This expression was partitioned in:

$$P_i = \left[n\left(\bar{X}_{i.} - \bar{M}\right)^2 + \sum_{j=1}^{n}\left(X_{ij} - \bar{X}_{i.} - M_j + \bar{M}\right)^2 \right] \Big/ 2n$$

where:

$\bar{X}_i$ is the mean yield of cultivar i obtained in n environments and $\bar{M}$ is the mean of the maximum responses of all cultivars in all environments. The first term of the equation represents the sum of squares related to the genetic effect, and the second the sum of squares of the genotype by environment interaction. The data were analyzed using GENES software (CRUZ, 2006).

Results and discussion

Significant differences for the source of genotypic variation were observed at 1% of the signification for all traits, which confirms the variability detected by the individual analyses. The environment was also significant at 1% of probability for evaluated traits, indicating the existence of variability among locations (Table 1). These significant differences among the locations can be explained by discrepancies in soil and climate conditions in the environments evaluated.

In relation to popping expansion, the significance for environment is in line with results reported by Vendruscolo et al. (2001), based on the evaluation of 15 popcorn genotypes (varieties and inter-varietal hybrids) in 15 environments in south-central Brazil. It is noteworthy that innovative studies on popcorn indicated quantitative inheritance for popping expansion (BRUNSON, 1937). The influence of environment on the popping expansion of popcorn seems clear, which is justified by the fact that not all genes that contribute to the hardness of the endosperm also contribute to popping expansion of the grains, as suggested by Robbins Júnior and Ashman (1984). Research results of Pereira and Amaral Júnior (2001) are helpful in the concept of qualitative inheritance for popping expansion. Theses authors reported high heritability of the trait, based on the evaluation of 92 progenies of half- and full-sibs derived from crosses according to Design I of Comstock and Robinson (1948).

Estimates of the coefficient of experimental variation (CVe) have been widely used due to the experimental accuracy of the results. In this respect, based on results of Gomes (1990), the estimated CVe of the traits PH, IH, FLOW, W100, and PE was low in this study, with less than 10.00%. For number of ears and grain yield, on the other hand, the values were intermediate, ranging from 10 to 20% (Table 1). Values between 20 and 30% are considered high, and were not detected for any trait studied. These results agree with the classification proposed by Scapim et al. (1995) for common corn, since the CVe of the traits evaluated in this study was low to medium (%), with estimates ranging from 2.87% for FLOW to 15.35% for GY (Table 1).

For popcorn, Miranda et al. (2003) found low CVe (%) values for the traits plant and ear height, flowering, final stand and weight of 100 grains. For yield and popping expansion the values were intermediate. Scapim et al. (2002), however, reported moderate CVe (%) values for plant height, ear height, grain yield and popping expansion in popcorn.

For all traits except mean insertion height of the first ear, significant differences were observed at 1% probability by the F test for genotype-environment (GE) interaction (Table 1). This is an indication that more specifically-adapted genotypes in specific environments should be identified. Based on the algorithm of Cruz and Castoldi (1991), a complex interaction was only identified for the mean number of ears per plot, with estimates exceeding 50% for the three pairs of possible comparisons among the evaluated environments. Since almost all genotypes are already recommended in Brazil or in the process of improvement for recommendation in northern and northwestern Rio de Janeiro State, it is possible to recommend genotypes derived from the progenies of superior cultivars tested in this study for a wide area in the State of Rio de Janeiro.

The yield performance of genotypes based on the estimates of phenotypic means and Scott-Knott grouping (STEEL; TORRIE, 1980) was best for UNB2U-C4 and IAC 112, with respective values of 2456.61 and 2257.14 kg ha^{-1} (Table 2). These values confirm that hybrids recommended by the IAC and Pioneer perform poorly in northern and northwestern Rio de Janeiro State, compared with progenies of the population UNB-2U from the third cycle of recurrent selection onwards, as shown in studies by Freitas Júnior et al. (2006) and Rangel et al. (2007; 2008).

It must however be emphasized that IAC 112 is a highly productive hybrid in São Paulo, and contributed to the reduction in the importation of popcorn grains in Brazil (SAWAZAKI et al., 2000). Vieira et al. (2009) confirmed the productive value of IAC 112 in northwestern Paraná State. They found that the grain yield of this hybrid, with a value of 3175.90 kg ha^{-1} was the second highest of 27 simple hybrids bred in a breeding program of specialty corns at the State University of Maringá (UEM), State of Paraná, Brazil.

Considerably differing grain yields of the hybrid Zélia, from Pioneer, were observed in studies in the States of São Paulo (SAWAZAKI et al., 2000) and Paraná (PINTO et al., 2007), with estimates of 3691.00 and 1.096.00 kg ha^{-1}, respectively.

This display of research results confirms the influence of the environment on the response capacity of genotypes bred in improvement programs, and reinforces the importance of the generation of genotypes for regional soil-climate conditions and management. Moreover, the results show the expectation of success of the program of recurrent selection of Northern Fluminense State University in the new cycles, by concentrating favorable alleles for grain yield.

Based on the procedure of Scott-Knott (STEEL; TORRIE, 1980), for the two main popcorn traits – grain yield and popping expansion – two and four groups were formed, respectively (Table 2).

Table 1. Mean squares, means and coefficient of experimental variation of eight traits evaluated in three environments and in ten popcorn genotypes (base populations, improved genotypes and experimentally recommended genotypes in Brazil). Colégio Agrícola and PESAGRO–RIO in Campos dos Goytacazes; and PESAGRO–RIO in Itaocara, Rio de Janeiro State, Brazil. 2008.

SV(2)	DF(3)	MS(1)							
		PH	IH	NE	GY	FLOW	W100	PE	PV
R/E	18	636.34	28.1	35.1	551393.21	11.03	0.954	2.03	435.41
G	9	2030.00**	972.33**	150.40**	1054396.14**	77.38**	27.13**	448.46**	3254.81**
E	2	44449.47**	11425.26**	2293.12**	6233734.27**	118.66**	339.57**	37.63*	5576.01**
G x E	18	139.65**	77.54ns	61.54**	370937.83**	10.51**	3.17**	34.64**	457.03**
Error	162	70.21	60.27	16.43	98655.58	2.8	0.52	2.58	73.04
Mean		177.53	102.3	28.05	2045.08	58.29	10.93	26.14	53.81
CVe (%)		4.71	7.58	14.44	15.35	2.87	6.61	6.14	15.88
MSr^{+}/MSr^{-} (4)		2.47	2.39	2.32	3.56	2.39	1.81	2.21	2.97

(1)PH = mean plant height, IH = mean height of insertion of the first ear, NE = mean number of ears per plot, GY = grain yield, FLOW = mean number of days until flowering, W100 = mean weight of 100 grains, PE = popping expansion, and PV = popcorn grain volume per area (m^3 ha^{-1}). ns = non-significant at 5% and 1% probability by the F test; *significant at 5% probability by the F test; and **significant at 1% probability by the F test. (2)SV = Source of variation. (3)DF = Degrees of freedom. (4)Relation between the largest and the smallest mean square.

For popping expansion (PE), the ranking (in decreasing order) of the genotypes was IAC 125, BRS Angela, Zélia and UNB2U-C4. The inclusion of UNB2U-C4 among the four genotypes with best PE performance and an estimate of 29.41 mL g^{-1} – near the limit of 30 mL g^{-1} indicated for recommendation – confirms the possibility that the producers in northern and northwestern Rio de Janeiro State will in the near future benefit economically from the genetic value of popcorn grains of progenies in advanced cycles of recurrent selection. This expectation is represented by UNB2U-C4, with the highest value for the trait popcorn grain volume (amount of popcorn expanded per hectare) (Table 2).

Mean number of days to flowering is an essential trait for popcorn, because the maintenance of the crop in the field for a long period is undesirable due to the greater fragility in the corn market. The grouping of genotypes based on Scott-Knott (STEEL; TORRIE, 1980) for this trait formed three groups, indicating 112 IAC as the earliest, followed by IAC 125 and UNB2U-C4. A promising level of earliness was also detected in UNB2U-C4; it was concluded that in the next cycles of recurrent selection the desirability of reducing the mean number of days to flowering should be considered to avoid undesirable effects on grain yield and its components.

For size, there was a reduction in the mean height of population UNB2U, from cycle C3 to C4. The mean insertion height of the first ear was reduced as well, but to a lesser degree. Anyway, even lower values may be obtained from the cycles following UNB2U-C4, avoiding vulnerability to plant breaking and lodging, in view of the strong winds blowing in north and northwestern of Rio de Janeiro State.

By the estimates of P_i statistics for grain yield (Table 3) of UNB2U-C4 and IAC 112 the values of general P_i were lowest and therefore, these genotypes tend to be better adapted and more stable. Since the grain yield estimates of these genotypes are the highest while the contributions to the interaction are small, they can be considered superior. According to Cruz and Carneiro (2003), these results can be explained by the way the P_i stability index is estimated, which is the deviation of cultivar i in comparison with the best-performing genotype in all environments, so the lower the value of P_i, the better adapted is the genotype.

This high correlation between mean and stability is characteristic of the method of Lin and Binns (1988), which associates stability with the capacity of genotypes to make the slightest possible deviation from the maximum in all studied environments. This is considered the greatest advantage of this method, since the most stable genotypes can be identified among the most productive, as also observed by Daros et al. (2000) in sweet potato genotypes; by Scapim et al. (2000) in maize; by Carbonell et al. (2001) for common bean genotypes; by Ferreira et al. (2004) and Botrel et al. (2005) in studies with alfalfa; by Cargnelutti Filho et al. (2007) in maize; and by Silva Filho et al. (2008) for cotton.

Table 2. Grouping based on the procedure of Scott-Knott (Steel and Torrie, 1980)[1] for eight traits[2] evaluated in ten popcorn genotypes. Colégio Agrícola and PESAGRO–RIO in Campos dos Goytacazes; and PESAGRO–RIO in Itaocara, Rio de Janeiro state, Brazil, 2008.

Genotypes	Traits															
	PH		IH		NE		GY		FLOW		W100		PE		PV	
UNB2U-C3	186.00	a	109.25	a	24.29	b	1,846.56	b	60.00	a	12.16	a	24.98	c	46.08	c
UNB2U-C4	179.24	b	105.40	a	28.62	a	2,456.61	a	56.38	c	12.45	a	29.41	b	72.30	a
BRS Angela	165.48	d	97.30	b	23.81	b	1,759.26	b	60.43	a	11.05	b	31.56	a	55.30	b
Viçosa	183.77	b	110.95	a	26.57	b	2,151.85	a	57.71	b	12.43	a	20.03	d	43.14	c
Beija-flor	179.92	b	106.83	a	30.95	a	1,942.86	b	58.90	a	11.14	b	20.63	d	40.61	c
IAC 112	193.10	a	103.73	a	31.48	a	2,257.14	a	55.48	c	9.19	c	28.10	b	64.15	b
IAC 125	175.36	b	95.04	b	28.57	a	2,129.63	a	55.67	c	10.68	b	32.13	a	68.76	a
Zélia	172.58	c	103.02	a	31.00	a	2,124.87	a	60.52	a	9.97	c	29.71	b	62.42	b
Jade	159.48	d	88.77	b	28.05	a	2,020.63	b	59.52	a	10.57	b	23.70	c	47.76	c
UFVM2 Barão Viçosa	180.40	b	102.77	a	27.24	b	1,761.38	b	58.33	a	9.76	c	21.16	d	37.62	c

(1)Means followed by the same letter, in each column, belong to the same group, by the procedure of Scott-Knott (STEEL; TORRIE, 1980), at 5% of probability. (2)PH = mean plant height; IH = mean height of insertion of the first ear; NE = mean number of ears per plot; GY = grain yield; FLOW = mean number of days until flowering; W100 = mean weight of 100 grains; CE = popping expansion; and PV = popcorn grain volume per area (m^3 ha^{-1}).

Table 3. Estimates of the stability parameters of Lin and Binns (1988) for the trait grain yield, in kg ha^{-1}, of 10 popcorn genotypes (base populations, improved genotypes and experimentally recommended genotypes in Brazil) evaluated at three locations.

Genotypes[1]	Mean	General P_i	Deviation		% of genetic deviation	Contribution to the interaction (%)
			Genetic	Interaction		
1	1846.56	233285.00	188999.00	44286.60	81.0161	17.701
2	2456.61	34.02	11.34	22.6803.00	33.3333	0.009
3	1759.26	331488.00	246484.00	85003.90	74.3569	33.975
4	2151.85	75539.00	47902.50	27636.40	63.4143	11.045
5	1942.86	140089.00	134431.00	5658.20	95.961	2.261
6	2257.14	29612.00	20855.40	8756.30	70.4296	3.499
7	2129.63	69531.00	55027.60	14503.40	79.1411	5.796
8	2124.87	56945.00	56618.80	325.83	99.4278	0.13
9	2020.63	146870.00	97126.10	49744.10	66.1306	19.882
10	1761.38	259257.00	245000.00	14257.70	94.5006	5.698

(1)1 = UNB2U-C3; 2 = UNB2U-C4; 3 = BRS Angela; 4 = Viçosa; 5 = Beija-flor; 6 = IAC 112; 7 = IAC 125; 8 = Zélia; 9 = Jade; and 10 = UFVM2 Barão de Viçosa.

Ferrão et al. (2008) emphasized that further research should be prioritized in breeding programs, to significantly reduce the temporary interaction, which has caused great insecurity and most damage to producers. Simultaneously, genotypes with appropriate reactions to specific climatic conditions in different soils should be accurately identified for use in breeding programs.

The partitioning of the estimated P_i results in two components: the first is attributed to genetic deviation from the maximum, and the second corresponds to the interaction between genotypes and environments. The first component does not interfere with the breeders' work because it does not necessarily influence the genotype ranking, while the second can affect the classification. Therefore, a genotype with a low P_i, where the genetic deviation accounts most of this value, would be ideal.

A reanalysis of the genotypes with lowest P_i values (UNB2U-C4 and IAC 112) showed a GE interaction of, respectively, 0.009 and 3.499% (Table 3), which are considered low values. UNB2U-C4 prevailed, with the lowest percentage of contribution to the interaction.

Carpentieri-Pípolo et al. (2005) evaluated the adaptability and stability of eight popcorn populations for grain yield and popping expansion at two locations in northern Paraná State, based on the model proposed by Eberhart and Russell (1966). The grain yield of hybrid Zélia and the populations UEL PAPA, UEL PASHA, UEL PO, UEL PAMPGA, and UEL PAPCB were highest, with approximate values of 3,203.00; 3,733.00; 3,512.00; 3,176.00; 2,847.00 and 2,764.00 kg ha^{-1} and popping expansion of 27.68, 25.05, 27.41, 27.17, 27.64, and 28.60 mL g^{-1}, respectively; the stability of performance in the region of interest was high.

In a comparison of the coefficient of adaptability (β_i) of Eberhart and Russell (1966) and the superiority parameter P_i of Lin and Binns (1988), Scapim et al. (2000) used the results of the performance of 20 maize genotypes of Embrapa-Milho and Sorgo at eight locations in the State of Minas Gerais and found negative and significant correlations. This shows that the most responsive cultivars tend to have the lowest P_i values. It is therefore expected that these methods are highly consistent not only in terms of stability, but also in phenotypic adaptability.

In particular for the method of Lin and Binns (1988), the most favorable environment for grain yield was Itaocara, where the means were higher than in the other environments. In turn, the Colégio Agrícola, in Campos dos Goytacazes, Rio de Janeiro State, Brazil, was recognized as an unfavorable environment. When considering only the favorable environment (Table 4), genotype UNB2U-C4 was outstanding, with the lowest P_i and mean grain yield of 2,860.32 kg ha^{-1}. Moreover, when examining the unfavorable environment, the same genotype was also allocated in the first position, with a grain yield reduction of only 25.00% (2,133.33 kg ha^{-1}). It is therefore safe to conclude that the grain yield performance of UNB2U-C4 is superior and that the cultivation of the genotype is less instable and has wide adaptability. UNB2U-C4 is therefore a genotype of interest for technically oriented producers as well as for smallholders, due to the high stability and responsiveness. A recommendation for producers can however only be expected by the sixth recurrent selection cycle, when UNB2U-C6 is established, so that a genotype of unquestionable superiority, with a consequently higher economic return can be provided.

Table 4. Estimates of the parameters stability and adaptability, considering favorable and unfavorable environments by the method of Lin and Binns (1988) for the trait grain yield.

Genotypes(1)	Favorable Pi	Genotypes(1)	Unfavorable P_i
2	51.03	2	0
6	23782.11	4	35980.18
7	34029.55	6	41271.06
8	55482.34	1	56086.18
9	90476.34	8	59869.37
4	95318.26	3	105945.90
5	109352.20	7	140534.10
10	283003.20	5	201561.70
1	321884.70	10	211765.70
3	444259.20	9	259657.90

(1)1 = UNB2U-C3; 2 = UNB2U-C4; 3 = BRS Angela; 4 = Viçosa; 5 = Beija-flor; 6 = IAC 112; 7 = IAC 125; 8 = Zélia; 9 = Jade; and 10 = UFVM2 Barão de Viçosa.

A comparative analysis of the performance of modified simple and recommended three-way hybrids, as well as of improved varieties, variety in improvement and technically so far unimproved varieties led to the following conclusions for the environments tested, using a high number of replications (seven): i) for general P_i, although UNB2U-C4 (variety in improvement) was superior among the 50.00% of the best performing genotypes, 60.00% of these consisted of hybrids (a simple modified hybrid, IAC 112; and two three-way hybrids, Zélia and IAC 125), an unimproved variety (Viçosa), with tendency to greater homeostasis of the variety in comparison to the hybrids, mainly in the simple modified compared to the three-way hybrids; ii) by the general parameter P_i, the least stable genotypes were also two improved varieties (UFVM2 Barão Viçosa and BRS Angela), which shows that it is wrong to expect a better adaptation from genotypes with intrinsic heterozygosity, as also pointed out by Adams and Shank (1959) and Allard and Bradshaw (1964) for

Zea mays; iii) for favorable P_i, there was some consistency with the results of general P_i, since one variety in the process of improvement performed best (UNB2U-C4) and since 80.00% of the 50.00% of genotypes with highest stability consisted of hybrids, with advantage of the simple modified over three-way hybrids; iv) for unfavorable P_i, the five best-performing genotypes were UNB2U-C4 (variety in improvement), Viçosa (so far unimproved variety, can be considered a landrace), IAC 112 (simple modified hybrid), UNB2U-C3 (variety in improvement, precursor of UNB2U-C4) and Zélia (three-way hybrid); and v) for favorable P_i, the improved variety BRS Angela had the worst performance for grain yield stability, while the ranking of three-way hybrid Jade was analogous to unfavorable P_i.

This information indicates that regional breeding may favor adaptation. This hypothesis is based on the fact that successive cycles of UNB2U may have led to greater stability and adaptation of the recombined progenies after their selection in northern and northwestern of Rio de Janeiro State, Brazil.

It is worth mentioning that a simple modified hybrid (IAC 112) was superior to any three-way hybrids tested throughout the experiments for general, favorable and unfavorable P_i. The higher homeostasis in the simple hybrid at the expense of the three-way hybrids is therefore unquestionable, despite a possibly lower intrinsic heterozygosity than of the three-way hybrid.

Based on the lack of association between genetic structure and stability in popcorn, it was concluded that the stability of a variety in the process of improvement (UNB2U-C4) can be high in the environments where it is successively selected in breeding programs; that the stability of modified simple hybrids can be higher than that of three-way hybrids; and that the stability of improved varieties (UFVM2 Barão de Viçosa and BRS Angela), as well as three-way hybrid (Jade) and landrace (Beija-Flor) can be low.

Conclusion

The method of Lin and Binns detected the most suitable and stable genotypes, and also the most productive. UNB2U-C4 and IAC112 contained the lowest values of general P_i; UNB2U-C4 contributed least to the interaction while the contribution of IAC112 to the interaction ranked fourth.

UNB2U-C4 stood out with the best adaptation to favorable and unfavorable environments.

No association between the genetic structure and stability degree in popcorn was observed.

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