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Adaptability and stability of maize hybrids in unreplicated multienvironment trials[1]

Adaptabilidade e estabilidade de híbridos de milho em ensaios multiambientais não-repetidos

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ABSTRACT - In maize breeding programs conducted by private companies, it is common to perform the product advanced trials (PAT) in several cultivation environments in order to better recommend the new hybrids, as well as to provide opportunities for the farmers to evaluate their products. The aim of this study was to describe the adaptability and stability of maize hybrids from unreplicated PATs using a multivariate approach combined with univariate methods. We considered the grain yield data of twelve maize hybrids evaluated in a PATs network conducted by the company DuPont Pioneer in 80 cultivation environments in the states of Minas Gerais and Goias, in second-crop of 2014. The AMMI analysis was employed and additionally we applied the methods based on bisegmented linear regression, Lin and Binns index (1988) and Annicchiarico index (1992). Significant differences were verified among the tested hybrids. The macro-environmental variation and the effect of hybrid by environment (H x E) interaction were expressive. The application of the AMMI method allowed the study of the H x E interaction based on maize PATs. Hybrids 7 and 8 are recommended for higher quality environments, while hybrids 3, 5 and 12 present wide adaptability. The Lin and Binns (1988) and Annicchiarico (1992) indexes highlight the hybrid 8 as the most promising for associating high productivity and lower risk in the tested cultivation environments.

Key words: *Zea mays*. Product Advancement Trials. Genotype by Environment Interaction. AMMI. Reliability Index.

RESUMO - Nos programas de melhoramento de milho das empresas privadas é comum realizar os chamados ensaios avançados de produto (PAT) em vários ambientes de cultivo no intuito de melhor posicionar os novos híbridos, bem como oportunizar a avaliação por parte dos produtores. Neste trabalho objetivou-se descrever a adaptabilidade e estabilidade de híbridos de milho a partir de PATs em multiambientes utilizando a abordagem multivariada AMMI (additive main effects and multiplicative interaction) combinada com métodos univariados. Foram considerados os dados de produtividade de grãos de doze híbridos de milho avaliados numa rede de PATs conduzidos pela empresa DuPont Pioneer em 80 ambientes nos estados de Minas Gerais e Goiás na safrinha de 2014. Foi empregada a análise AMMI e adicionalmente foram aplicados os métodos de regressão linear bissegmentada e os índices de Lin e Binns (1988) e de Annicchiarico (1992). Foram observadas diferenças significativas entre os híbridos sob teste, bem como marcante variação macroambiental. O efeito da interação híbridos por ambientes foi expressivo. A aplicação do método AMMI possibilitou o estudo da interação híbridos por ambientes a partir de PATs de milho. Os híbridos 7 e 8 são recomendados para os ambientes de maior qualidade ambiental, enquanto que os híbridos 3, 5 e 12 apresentam adaptabilidade ampla. Os índices de Lin e Binns (1988) e de Annicchiarico (1992) destacam o híbrido 8 como o mais promissor, por associar elevada produtividade e menor risco de adoção pelos produtores nos ambientes de cultivo testados.

Palavras-chave: *Zea mays*. Ensaios de Avanço de Produto. Interação Genótipo x Ambiente. AMMI. Índice de Confiabilidade.

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INTRODUCTION

The grain yield per area in maize crop in Brazil has grown in the last 40 years at a rate of 75.6 kg ha^{-1} year^{-1}, being at least 50% of this increment attributed to hybrid breeding (RAMALHO *et al.*, 2012). However, the large number of maize growing environments in Brazil combined with fluctuations observed in different locations and agricultural years have pointed the need to intensify the evaluation activities in order to mitigate the genotype by environment interaction and to minimize the recommendation risk of hybrids by companies (VAN EEUWIJK *et al.*, 2016). Thus, in addition to the trials of value for cultivation and use, the companies usually dedicate additional resources to the so-called Product Advancement Trials (PAT), in which new hybrids are compared with commercial hybrids in greater plots.

A peculiarity of the advancement trials is that they are conducted without replication (nonreplicated trials), which brings the difficulty of performing statistical tests because we do not have a direct estimate of the experimental error variance. One way of overcoming this obstacle might be through the use of a multiplicative interaction model, such as the AMMI (Additive Main Effects and Multiplicative Interaction) (JOHANNES; PIEPHO, 2014; MILLIKEN; JOHNSON, 2000). The AMMI analysis has been widely used to study the genotype by environment interaction in maize and provides a more detailed description of the variation due interaction between factors, decomposing it in part attributed to the signal of this interaction effect and another one attributed to noise) (FARIA *et al.*, 2017; GAUCH JUNIOR, 2013; NDHLELA *et al.*, 2014; OLIVEIRA *et al.*, 2010). In this way, the variation attributed to noise has the connotation of the variation attributed to random environmental factors, and, thus, might constitute the residual variance of the model. The application of the AMMI method in nonreplicated multienvironment trials, as in the case of the PATs, might allow a more accurate inference about the properties of the tested hybrids, through complementary methods of study of adaptability and stability.

In this context, the indexes proposed by Lin and Binns (1988) and Annicchiarico (1992) are interesting options, because they inform jointly about the adaptability and stability of hybrids, and associate ease application and interpretation. Besides, the description of the hybrid performance across environments might be complemented using other methods, that detail the response pattern of each hybrid and its predictability under favorable and unfavorable conditions, such as bisegmented linear regression proposed by Cruz, Torres and Vencovsky (1989).

Thus, this work aimed to describe the adaptability and stability of maize hybrids from non-replicated product advanced trials using the AMMI approach and complementary univariate methods.

MATERIAL AND METHODS

The grain yield data from a PAT network conducted by DuPont Pioneer in the second crop (safrinha) of 2014 were considered. Eighty (80) trials were conducted on farms located at 38 sites in the states of Minas Gerais and Goiás, Brazil, as described in Table 1. According to Köppen and Geiger classification the climate is Aw (ALVARES *et al.*, 2013). The sowings of the maize hybrids occurred side by side in the properties of rural farmers in the locations listed (Table 1). The plot consisted of 6 rows of 100 meters in length and the seeding density of 60000 plants/ha. The seeds were previously treated with fungicides and insecticides.

In this network of PATs twelve hybrids were evaluated, among new and commercial ones. The fertilization of the areas was defined based on the soil analyzes. The control of weeds and pests throughout the crop was carried out by chemical control, according to recommended to maize crop.

Harvesting was performed taking into account differences between hybrids regarding precocity and standardizing grain moisture between 18 and 24%. Grain yield data were taken, in kilograms per hectare, corrected for 13% moisture.

The grain yield data of the hybrids in the PATs tests were firstly analyzed by the AMMI method, according to the following model:

$$y_{ij}\mu + g_i + a_j + \sum_{c=1}^{q} \varpi_c \alpha_{ic} y_{jc} + \delta_{ij} \tag{1}$$

where: µ: constant associated with all observations; g_i: main effect associated with hybrid *i*; a_j: main effect associated with the environment *j*; ϖ_c: singular value of the *c*-esimo principal component related to the genotype by environment interaction; α_{ic}: eigenvector of the c-esimo principal component related to the hybrid *i*; γ_{jc}: eigenvector of the *c*-esimo principal component related to the environment *j*; δ_{ij}: noise associated to the AMMI model.

The adjustment adequacy of the AMMI model was inferred from the deviance chi-square test. The degrees of freedom associated with the multiplicative or bilinear terms of the model were obtained by the Gollob approximation (DUARTE; VENCOVSKY, 1999). The chosen AMMI model was that retained

Table 1 - Description of the locations of the maize hybrids advancement trials in relation to altitude (meters a.s.l), latitude and longitude (in decimal form)

Location	State	Altitude	Latitude	Longitude
Araguari	MG	890	-18.54	-48.34
Capinópolis	MG	460	-49.48	-18.61
Indianópolis	MG	971	-18.9	-47.87
Nova Ponte	MG	1.009	-19.29	-47.69
Planura	MG	495	-34.35	-34.4
Romaria	MG	982	-18.97	-47.64
Santa Juliana	MG	842	-47.51	-19.38
Unaí	MG	946	-16.64	-47.2
Bom Jesus de Goiás	GO	607	-18.09	-49.85
Cabeceiras	GO	896	-15.65	-47.16
Caiapônia	GO	779	-30.97	-37.77
Caldas Novas	GO	780	-17.71	-48.65
Chapadão do Céu	GO	819	-18.46	-52.56
Edeia	GO	570	-17.38	-49.93
Gameleira de Goiás	GO	890	-16.4	-48.68
Goiatuba	GO	571	-17.89	-49.51
Itaberaí	GO	696	-15.89	-49.69
Itumbiara	GO	525	-18.42	-49.28
Jatai	GO	867	-22.06	-47.57
Jovânia	GO	790	-17.83	-49.64
Mineiros	GO	944	-17.41	-52.85
Montes Claros de Goiás	GO	370	-15.98	-51.38
Montividiu	GO	897	-17.4	-51.3
Morrinhos	GO	791	-49.13	-17.77
Palestina de Goiás	GO	734	-34.04	-34.07
Palmeiras de Goiás	GO	631	-33.45	-33.37
Paraúna	GO	540	-50.33	-17.45
Perolândia	GO	944	-17.43	-52.31
Piracanjuba	GO	775	-17.3	-49.07
Portelândia	GO	907	-17.39	-52.75
Rialma	GO	600	-49.53	-15.34
Rio Verde	GO	797	-26.07	-42.7
Santa Helena de Goiás	GO	565	-50.58	-17.8
São Joao da Paraúna	GO	645	-16.82	-50.37
São Miguel P. Quatro	GO	896	-17.07	-48.64
Serranópolis	GO	773	-35.18	-35.06
Silvania	GO	894	-32.58	-32.45
Vianópolis	GO	939	-16.9	-48.39

significant bilinear terms. From the choice of the model, the variation attributed to noise was used to make the inference about the main effects and genotype by environment interaction. Clustering of the adjusted phenotypic means of hybrids was done by the Scott-Knott test at 5% probability. All statistical analyzes were performed in R platform (R CORE TEAM, 2016).

The analyzes of adaptability and stability of the hybrids were performed from the adjusted phenotypic means of the chosen AMMI model using the software Estabilidade (FERREIRA, 2000). We applied the univariate methods proposed by Lin and Binns (1988), Annicchiarico (1992), and Cruz, Torres and Vencovsky (1989).

For the method of Lin and Binns (1988), we estimated the adaptability and stability index Pi, which refers to the mean square of the deviations between the means of the hybrid *i* in each environment relative to the maximum reached in the environment, according to the expression:

$$P_i = \frac{\sum_{j=1}^{n} \left(y'_{ij} - M_j \right)^2}{2n} \quad (2)$$

where: y'_{ij}: adjusted mean by the chosen AMMI model of the hybrid *i* in the environment *j; M_j*: maximum yield in the environment *j*; *n*: number of environments.

For the Cruz, Torres and Vencovsky (1989) method, the bissegmented linear regression model was fitted according to the model:

$$y'_{ij} = \beta_{oi} + \beta_{1i} I_j + \beta_{2i}\, T(I_j) + \psi_{ij}, \quad (3)$$

where: y'_{ij}: mean adjusted by the chosen AMMI model of the hybrid *i* in the environment *j*; I_j: environmental index or effect of the environment j; β_{0i}, β_{1i} and β_{2i}: regression coefficients; $T(I_j) = 0$, if $I_j < 0$; otherwise $T(I_j) = I_j - I^+$, where I^+ is the mean of the positive indices I_j; ψ_{ij}: deviation associated with y'_{ij}..

In this method, the ideal hybrid was identified as associating high mean (high β_0), adaptability to unfavorable environments ($\beta_{1i} < 1$), responsiveness to favorable environments ($\beta_{1i} + \beta_{2i}$) > 1 and non-significant deviation. The stability of the hybrids was measured by the F-test of the deviation variance of the model with complementary description by the coefficient of determination (R^2).

For the Annicchiarico (1992), the recommendation or reliability index of each hybrid or risk of presenting the lowest yield was calculated from the following expression: $Ii = p_i - z_{(1-\alpha)}\, s_{pi}$, where: p_i: relative average (%) of the hybrid *i*; s_{pi}: standard deviation of the values of the relative means of the hybrid *i* in the different environments; $z_{(1-\alpha)}$: upper quantile of the standard normal distribution for a confidence coefficient *(1-α)*. In this study, a α = 0,25 was pre-established.

RESULTS AND DISCUSSION

From the joint analysis of PATs tests (Table 2), a significant difference was observed among hybrids at 1% probability. This high significance was also verified for environments, demonstrating wide macro-environmental variation, which corresponded to a largest fraction of the phenotypic variation (69.31%).

The existence of significant variation for hybrids and for environments is important to allow a more reliable estimation of the hybrid by environment interaction. It is worth noting that, in this case of non-replicated trials, the variation attributed to the deviations of the main effects of hybrids and environments corresponds to the variation attributed to the hybrid by environment interaction effect and the microenvironmental variation (experimental error). Using the AMMI method is possible to dissociate these sources of variation. The variation associated with interaction hybrids by environments corresponds to the so-called signal, and the deviation is attributed to noise (GAUCH JUNIOR, 2013; PADEREWSKI *et al*., 2016). From the analysis by different AMMI family models, it was observed that the deviance was then significant from the most parsimonious (AMMI0) to the most parameterized model (AMMI10). Due this situation, we decided to use the AMMI10 model.

According to the results of the Scott-Knott test (Table 3), hybrids 1, 3, 5, 7, 8 and 12 were superior for grain yield, while the hybrids 2, 4, 10 and 11 had, statistically, the lowest productivities. However, as previously mentioned, the more detailed description of a hybrid requires information about its phenotypic stability.

From the results presented in Table 3, it was shown that hybrids 1, 3, 4 and 11 presented a regression coefficient b_2 significantly different from zero, which implies behavior better described by the bissegmented model of Cruz, Torres and Vencovsky (1989). For the other hybrids, which did not have this hypothesis rejected, the use of the simple linear regression model of Eberhart and Russell (1966) would be enough to explain the behavior of the hybrids in the different environments.

According to table 3, the hybrids 1, 3 and 4 presented regression coefficients b_1 statistically equal to 1 (one), while hybrid 11 was less than 1 (one). Hybrids with b_1 equal to 1 show lower phenotypic plasticity in unfavorable environments, i.e., they are expected to show a greater reduction in productivity with a decrease in environmental quality. On the other hand, the hybrid 11 associated higher resilience in lower productivity environments, however, presented, at the average of the environments, a low adaptability.

Table 2 - Summary of the analysis of variance and decomposition by the AMMI method for the grain yield (kg/ha) referring to the evaluation of maize hybrids in product advancement trials conducted in 80 environments in the second crop of 2014

Source of Variation	Degree of Freedom	Mean Square	%Sum of Squares
Hybrid (H)	11	2668453**	1.25
Environment (E)	79	20561838**	69.31
(H x E)	869	396869	14.72
H x E PC1:10	800[1/]	415974**	14.20
Residual AMMI10	69	175362	0.52

** Significant at 1% probability by F-test. [1/]Gollob's approximation

Table 3 - Mean values of grain yield of maize hybrids (kg/ha), with Scott-Knott group test at 5% probability, and summary of the adaptability and stability analysis based on the bissegmented linear regression regarding the product advancement maize trials conducted in 80 environments in the second crop of 2014

Hybrid	Mean	Group	b_1 [1/]	b_2 [2/]	$b_1 + b_2$ [3/]	R^2 (%)[4/]
8	7567.6	A	1.08*	0.08	1.15	85.23*
3	7449.4	A	1.07	-0.24*	0.83	80.37*
12	7410.2	A	1	-0.05	0.94	78.99*
5	7406.6	A	0.93	-0.06	0.88	84.06*
1	7403.5	A	0.99	-0.24*	0.76*	85.07*
7	7348.4	A	1.15*	-0.05	1.1	86.87*
6	7239.5	B	1.04	-0.02	1.01	88.82
9	7236.8	B	1.03	-0.01	1.02	90.02
10	7098.2	C	0.97	0.1	1.07	87.04
4	7070.4	C	0.97	0.36*	1.33*	79.54*
2	7067.7	C	0.96	-0.19	0.78*	83.31*
11	7001.9	C	0.83*	0.32*	1.15	74.13*

[1/] H_0: $b_1 = 1$; [2/] H_0: $b_2 = 0$; [3/] H_0: $b_1 + b_2 = 1$; [4/] H_0: $s^2_{\delta i} = 0$. *Significant at 5% probability level

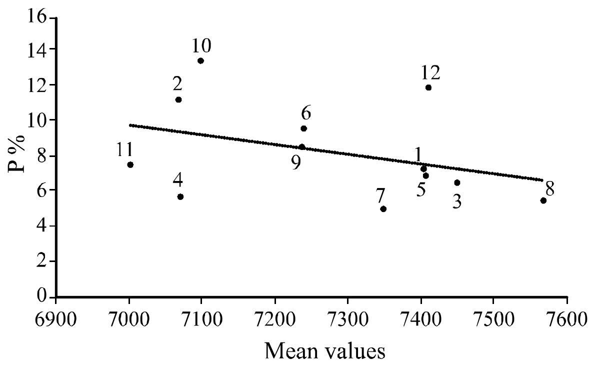
For the hypothesis H_0: $b_1 + b_2 = 1$, the hybrids 3, 4 and 11 were shown to be responsive in favorable environments, and this responsiveness is more evident for hybrid 4 ($b_1 + b_2 > 1$). Hybrids 1 and 2, however, showed low responsiveness in environments with higher environmental quality ($b_1 + b_2 < 1$), but showed high productive performance in the evaluated environments. Hybrids 7 and 8 were adapted to favorable environments ($b_1 > 1$), while the other hybrids presented a broad adaptability ($b_1 = 1$) (Table 3).

According to Cruz, Torres and Vencovsky (1989), among the hybrids tested, none fulfill all the requirements for an ideal genotype (Table 3). However, the hybrids showed a medium to high predictability of behavior, which can be confirmed by the coefficient of determination ($R^2 > 73\%$). Hybrids 6, 9 and 10 were highly stable in that they showed no lack of fit to the regression model. However, when considering the group of hybrids with higher average productivity, hybrids 3, 5, 7, 8 and 12 might be highlighted as the most promising.

Nevertheless, the indication of maize cultivars, in relation to grain yield, might depend on the method of analysis of adaptability and stability employed, because some methods might exploit different concepts of stability. The regression-based method proposed by Cruz, Torres and Vencovsky (1989) assumes that stability means predictability and it is very informative when compared to methods of non-parametric statistics and analysis of variance (CARGNELUTTI FILHO *et al.*, 2007). Thus, the use of other methods might be complementary, because they exploit another concept of stability and therefore might improve the characterization of hybrid performance across environments, such as the Lin and Binns (1988) and Annicchiarico (1992) indexes.

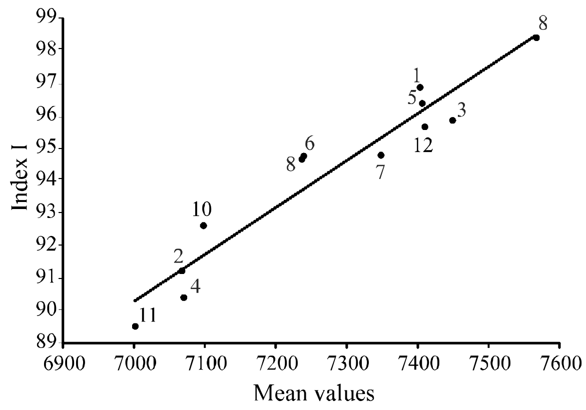
From the index proposed by Lin and Binns (1988), it is possible to identify the hybrids that best approximated the maximum in most environments (Table 3). According to Figure 1, hybrids 1, 3, 4, 5, 7 and 8 were the most adapted and stable, that is, they associated less sum of squares of the deviations with respect to the maximum. In addition, a high negative correlation was observed between the average performance of each hybrid in the different environments and the Lin and Binns (1988), demonstrating the possibility of identifying adapted and stable hybrids. In this case, it is worth highlighting the hybrid 8 that associated high adaptability and smaller deviation in relation to the maximum yields in the tests. However, it was also evidenced that hybrid 12, despite showing a high average productivity, associated a lower phenotypic stability with the estimation of the Lin and Binns (1988). Machado *et al.* (2008) also highlighted the practical use of Lin and Binns (1988) in a study of adaptability and stability of single-cross and double-cross maize hybrids.

Figure 1 - Graphical representation of the grain yield means (kg/ha) of twelve maize hybrids and the values of the Lin and Binns index (1988) (P%) referring to the product advancement trials conducted in 80 environments in the second crop of 2014



According to the proposal of Annicchiarico (1992), it is possible to identify those hybrids that associate lower risk of adoption by the farmers, that is, associate high confidence relative to a minimum possible productivity. Figure 2 shows that hybrid 8 was the most stable, with an index I close to 100% and, consequently, a lower risk of adoption, followed by hybrids 1, 3, 5 and 12. It is also evident that the correlation is high between the hybrid means and their respective values of the reliability index. This result shows that the hybrids with higher average productivity in the environments also had a lower risk of adoption.

Figure 2 - Graphical representation of the grain yield means (kg/ha) of twelve maize hybrids and the Annicchiarico (I) reliability index values for the product advancement trials conducted in 80 environments in the second crop of 2014



To verify the concordances and/or disagreements between the estimates of the adaptability and stability parameters related to grain yield of single-cross maize hybrids ize, Cargnelutti Filho *et al.* (2007) reported that greater stability is bound to be associated with higher productivity. These authors chose to indicate the cultivars based on the method of Eberhart and Russell (1966), considering simultaneously the productivity, the stability and the adaptability to general, favorable and unfavorable environments.

These results corroborate with the interpretation that the hybrids most indicated by the methods proposed by Annicchiarico (1992) and Lin and Binns (1988) are, in general, the most productive ones. This fact occurs, because these indexes taking account the adaptability and stability jointly, what become the interpretation easier. However, despite this ease, the results proportioned by these indexes should be viewed with caution, because they not distinguish adequately the behavior of the genotypes. In the face of the diversity of cultivation environments, the application of regression methods, such as the bissegmented linear regression and non-linear regression (FERREIRA *et al*., 2006) might additionally detail better the response pattern of hybrids. In summary there is not a perfect method to deal with genotype by environment interaction, but the use of complementary methods might help in this task and subside the breeders to make better decisions about the cultivar´s recommendation.

CONCLUSIONS

1. The AMMI method allows the study of the interaction of the hybrids by environments from non-replicated trials of product advancement in maize;

2. The bissegmented linear regression proposed by Cruz, Torres and Vencovsky (1989), and the Lin and Binns (1988) and Annicchiarico (1992) indexes show complementarity in the description of maize hybrids concerned to phenotypic stability. However, the methods of Annicchiarico (1992) and Lin and Binns (1988) result in similar characterization of hybrids;
3. The hybrid 8 is the most promising because it associates high productivity and lower risk of adoption by growers in the tested growing environments.

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