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Adaptability and Stability in Maize Populations

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Abstract

Maize plays an important role in the national and global economy, continuously increasing its total production due to advances in technology and access to new land areas. Thus, new sources of germplasm are fundamental to generate cultivars more adapted to the diversity of environments and planting times. The objective of this study was to evaluate 36 populations of maize in three environments, aiming to identify the existence of genotype-by-environment interaction, classify populations based on adaptability and stability using the methods of regression and mixed models, indicate the best populations, and compare the two methodologies. The environments evaluated were: E1-second crop (safrinha) season of 2016 in an experimental area of latosol, with incidence of water stress; E2-crop season 2016/2017 in sandy soil, in family farm area; and E3-crop season 2016/2017 in an experimental area of latosol, no incidence of water stress. Grain yield was evaluated, adaptability and stability analysis was performed. Population 36 achieved high productivity, adaptability and general stability in three tested environments. Both methodologies showed similar results regarding adaptability and stability of some populations in three environments, but mixed models were more suitable for providing better selective accuracy.

Keywords: genotype × environment interaction, germplasm, mixed models, plant breeding, *Zea mays*

1. Introduction

In plant breeding, effects of genotype-by-environment interaction (G×E), adaptability and stability parameters are very important because each cultivar has an inherent capacity with response to changes in environments (Scapim et al., 2010). Therefore, identification of genotypes with high productive potential and wide adaptability and stability is one of the main targets in maize breeding programs (Faria et al., 2017).

In the maize breeding program, the breeder must plan actions that, in the presence of complex interactions, allow the development of specific cultivars for a specific environment. Thus, it is important to know the type of interaction and genotypes generated due to changes in the environment.

However, the existence of G×E interaction is a great disadvantage in the selection of genotypes with high production capacity across different environments, since a strong interaction makes selection difficult. This is because genotypes that perform well in an environment may not perform so well in other environments or even the occurrence of change in the population order due to change in the study environment in the presence of complex interaction. Thus, performance of genotypes across breeding stages should be evaluated in different environments to reduce the chance of misleading recommendations. Therefore, besides high productivity, the new cultivars should have yield stability and adaptability, or suitability for the target regions. Studies of adaptability and stability parameters contribute greatly as they provide information on the behavior of each genotype under different environmental conditions (Mendes et al., 2012). Different conditions of soil and climate, site of cultivation, crop year, technology level (Scapim et al., 2000), and other factors can be considered as distinct environments.

Several methods have been developed to evaluate adaptability and stability, and it is worth mentioning the methodology of mixed models proposed by Resende (2002). The method takes into account errors correlated within each environment, provides genetic values already penalized by instability and capitalized by adaptability, and allows selection by three attributes at the same time (productivity, stability, and adaptability) (Faria et al., 2017). Because of the soil variability in the municipality of Jataí, with great predominance of Latosol, Cambisols and Argisols, which together exceed 90% of the total area of the municipality (Hermuche, Guimarães, & Castro, 2009); the variability of planting times (crop and second crop) of maize; and production systems with small, medium, and large farms, it is necessary to implement breeding programs that focus on the peculiarities of these areas.

Therefore, the objectives of this study were to evaluate the behavior of different populations of maize in three contrasting environments, aiming to identify the existence of genotype by environments interaction for grain production, classify the populations for adaptability and stability using regression and mixed models, indicate the best populations to form a composite variety, and compare the two methodologies.

2. Method

2.1 Experimental Conditions and Experimental Design

Planting was carried out in three contrasting environments: Environment 1 (E1): Latosol with 22.09% of sand, 16.86% of silt, and 61.06% of clay, planting on February 18, 2016 (second crop), with severe water stress during the crop cycle (Figure 1); Environment 2 (E2): Sandy soil with 86.82% of sand, 3.47% of silt, and 9.71% of clay, planting on November 26, 2016; and Environment 3 (E3): Latosol with 22.09% of sand, 16.86% of silt, and 61.06% of clay, planting on November 23, 2016 (Table 1). The crops in E2 and E3 were conducted in crop year with normal water regime (Figure 2). The experiments were arranged in a randomized block design with four replicates. The plots consisted of two rows of five meters with plants spaced 0.90 m between rows and 0.20 m within rows.

Table 1. Characterization of the environments (E1, E2, E3) used for evaluation of 36 populations of maize (*Zea mays*) in Jataí, Goiás, BR

Environments	Planting Time	Soil	Sand%	Silt%	Clay%
E1	18 February 2016-Second crop season 2016	Latosol	22.09	16.86	61.06
E2	26 November 2016-Crop season 2016/17	Sandy	86.82	3.47	9.71
E3	23 November 2016-Crop season 2016/17	Latosol	22.09	16.86	61.06

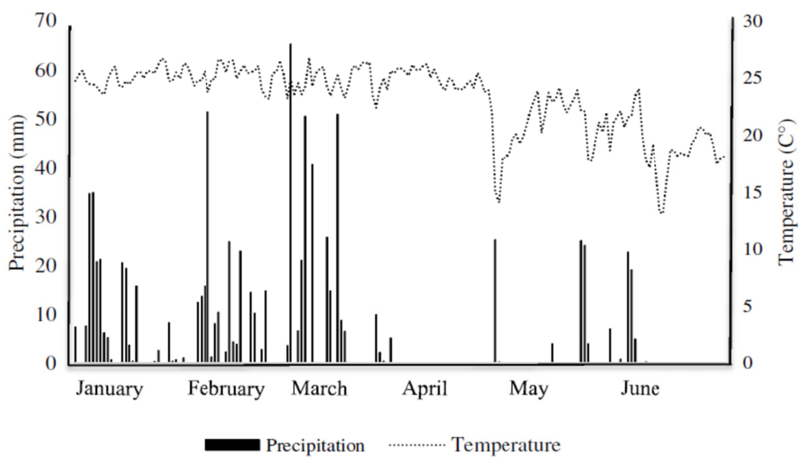

Figure 1. Precipitation and temperature data in Jataí-Goiás, January to June 2016 (environments E1). Jataí/GO

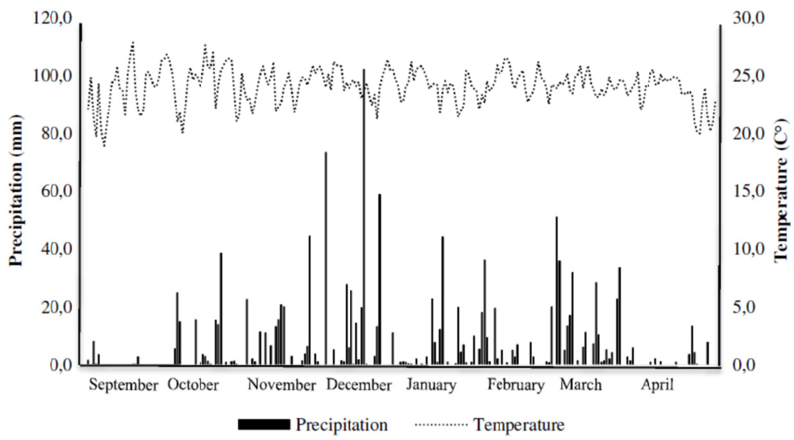

Figure 2. Precipitation and temperature data in Jataí-Goiás, September to April 2016 (environments E2 and E3). Jataí/GO

2.2 Plant Materials and Treatments

Thirty-six populations of maize were evaluated, including: 17 populations derived from the assessment of partly self-fertilized progenies in a top cross 1 to 14: Top-cross hybrids (1to5: selected for higher grain yield; 6 to10: selected for lower relative spike height; 5 and 11to14: selected for greater multiple disease tolerance); synthetics produced by the three selection strategies (29: recombination of 5 best-performing S_2 families for leaf disease tolerance; 30: recombination of 5 best-performing S_2 families for grain production; 31: recombination of 5 S_2 families for low relative spike height); 14 populations derived from composites formed by partial diallel between commercial hybrids and semiexotic populations (15 to 23: composite under usual crop season; 19 to 22 and 24 to 28: composite under second crop; the populations CRE-01 (35) and TGMV (36) from the UFG-Jataí breeding program; and 3 controls: a modified commercial hybrid; a conventional commercial hybrid; and an open-pollinated variety (32: Modified Hybrid-30S31H; 33: Conventional Hybrid-AG1051; 34: Commercial Variety-Al-Bandeirantes).

2.3 Conduction of Study and Traits Measured

Fertilization was applied in topdressing, according to soil analysis, using the NPK formula 04-20-18. Two fertilizer applications were carried out: the first, at V4, with NPK formula 20-00-20; and the second, a week later, with ammonium sulphate. For pest control, seeds were treated with the insecticide fipronil and two applications of Diflubenzuron at 20 and 35 days after sowing. Weed control was done with two applications of 240 mL tembotrione and 3 L ha^{-1} atrazine during post emergence of maize and weeds at 20 and 35 days after sowing.

At harvest, plants per plot (stand) were counted and grain yield was obtained from the total yield of each plot and corrected to kg ha^{-1} with 13% moisture. Grain weight was adjusted to optimum stand of 50 plants according to the covariance method of Vencosvsky and Barriga (1992).

2.4 Statistical Anlysis

Maize grain yield was examined by analyses of variance performed for each of the three environments followed by the analysis of joint variance and the F-test at 1% of probability.

The adaptability and stability parameters were estimated according to the methodology of Eberhart and Russell (1966), using the Genes program (Cruz, 2013) and the Selegen-REML/BLUP (model 54) software (Resende, 2016).

The harmonic mean of the relative performance of the genotypic values (HMRPGV) model mistos was used for the evaluation of stability, adaptability, and yield, was calculated for all genotypes according to the following expressions (Resende, 2002):

$$\text{MHPRVG} = \frac{\text{I}}{\sum_{i=1}^{I} \frac{1}{\text{PRVGj}}} \quad (1)$$

$$\text{PRVG} = \frac{1}{\text{I}}\left(\frac{\sum \text{VGj}}{\text{Mj}}\right) \quad (2)$$

where, I is the number of environments; VG is the genotypic value; and j represent the genotypes.

3. Results and Discussion

3.1 Analysis of Variance

The analysis of variance showed significant effects of the genotype and environment interaction for grain yield (Table 2), indicating different responses of the genotypes to the studied environments. Similar results for maize grain yield were reported by Cargnelutti Filho, Storck, Riboldi, and Guadagnin, (2009); Faria, Viana, Mundim, Silva, and Câmara (2010); Scapim et al. (2010); Mendes et al. (2012); Oliveira, Moreira, and Ferreira, (2013) and Faria et al. (2017), confirming the importance of adaptability and stability analysis. The method of Eberhart and Russell (1966) classified the environments 1 and 2 as unfavorable (negative environmental index) for grain production, the environment 3 as favorable (positive environmental index) (Table 3).

Table 2. Joint analyses of variance of 36 populations of maize (*Zea mays*) evaluated for grain yield in three environments (E1, E2 and E3), Jataí, Goiás, BR

SV	Grain yield	
	Df	SM
Block/Environment	9	2.03
Population (G)	35	1.576**
Environment (E)	2	401.302**
G×E	70	2.718**
Error	315	0.265
Mean	3.706	
CV%	13.898	

Note. ** Significant at 1% probability by the F test. Df: Degrees of freedom; SM: Square Middle;, SV: Source of Variation.

Table 3. Environment classification, using the environmental index method of Eberhart and Russell (1966), of the 36 populations of maize (*Zea mays*) evaluated for grain yield (kg ha^{-1}) in three environments, in Jataí-GO, in the second crop 2015/2016 and in the crop year 2016/2017

Environment *	Mean	Index (I_j)	Maximum	Minimum
Environment 1	2.714	-0.993	3.083	2.218
Environment 2	2.771	-0.935	3.860	1.753
Environment 3	5.633	1.927	7.730	3.970

Note. * Environment 1: second crop 2015/2016-occurrence of water stress; Environment 2: crop year 2016/2017-soil with 86.82% sand; Environment 3: crop year 2016/2017-soil of medium texture.

3.2 Method of Eberhart and Russell (Adaptability and Stability)

The method of Eberhart and Russell (1966) uses the parameters "regression coefficient" (β_{1i}) to evaluate genotype adaptability and "regression deviation" (σ^2_{di}) to evaluate the stability, which indicates the predictability of the genotypes to changes in the environment (Rios et al., 2009).

The genotypes 16, 24 (Table 4) had regression coefficient greater than unity (β_{1i}) and non-significant regression deviation, showing adaptation to favorable environments and predictability of behavior (Scapim et al., 2010). The control genotypes 33 and 34 had the same classification, however, the genotype 34 (a commercial variety) showed significant regression deviation, indicating low predictability. These genotypes are among the best behavior *per se* for productivity. Genotypes 6, 9, 10, 11 and 31 had regression coefficient lesser than unity (β_{1i}) and non-significant regression deviation, demonstrating their adaptation to unfavorable environments and predictability of behavior, however, as shown by the productivity mean (Table 4), they are genotypes of inferior behavior *per se*. The other genotypes showed regression coefficient equal to unity (non-significant (β_{1i})), which characterizes adaptability to all environments (Scapim et al., 2010) and non-significant regression deviation, indicating predictability of behavior in the environments, except for the commercial hybrid (genotype 31), with low predictability. According to Cardoso et al. (2012), these analyses aim to identify genotypes that are adapted, stable, and productive, allowing recommendation according to the environment of interest.

Table 4. Estimates of adaptability and stability parameters according to the method of Eberhart and Russell (1966) and stability and adaptability of genotypic values (MHPRVG) for grain yield in 36 populations of maize (*Zea mays* L.) evaluated in three environments, in Jataí-GO, second crop season 2015/2016 and crop season 2016/2017

Population order[1/]	Mean	β_1	σ^2_{di}	R² (%)	Population order[2/]	MHPRVG	MHPRVG·MG
34	4.703	1.578**	0.719 **	94.642	34	1.191	4.414
36	4.270	1.112	-0.042^{ns}	99.649	36	1.132	4.195
16	4.260	1.244*	0.099^{ns}	98.119	16	1.118	4.144
33	4.220	1.330**	-0.066^{ns}	99.996	33	1.103	4.088
24	4.127	1.230*	-0.005^{ns}	99.273	24	1.088	4.032
18	4.027	1.033	0.088^{ns}	97.475	18	1.074	3.983
30	3.997	1.204	0.021^{ns}	98.932	25	1.060	3.931
25	3.953	1.025	-0.064^{ns}	99.958	30	1.055	3.912
22	3.927	1.045	-0.009^{ns}	99.063	22	1.051	3.895
4	3.897	1.035	-0.077^{ns}	99.028	4	1.043	3.867
26	3.880	1.048	-0.066^{ns}	99.999	26	1.038	3.849
17	3.840	1.132	-0.055^{ns}	99.835	7	1.030	3.819
7	3.833	1.025	-0.065^{ns}	99.978	1	1.023	3.791
1	3.817	1.047	-0.038^{ns}	99.544	17	1.021	3.786
35	3.797	1.154	-0.063^{ns}	99.958	35	1.010	3.444
27	3.757	1.043	-0.055^{ns}	99.808	27	1.008	3.738
15	3.753	1.180	-0.053^{ns}	99.827	2	1.006	3.730
2	3.733	0.975	-0.006^{ns}	98.868	28	1.004	3.722
28	3.703	0.902	-0.017^{ns}	98.918	15	0.997	3.694
8	3.697	1.069	-0.036^{ns}	99.532	8	0.991	3.673
32	3.613	1.073	0.316 *	94.373	3	0.978	3.624
3	3.610	0.961	-0.022^{ns}	99.145	13	0.972	3.605
20	3.553	1.156	-0.061^{ns}	99.924	32	0.964	3.573
13	3.550	0.821	-0.062^{ns}	99.878	11	0.960	3.558
12	3.547	1.041	-0.050^{ns}	99.713	14	0.958	3.552
21	3.540	1.022	-0.051^{ns}	99.736	12	0.956	3.543
14	3.507	0.852	-0.009^{ns}	98.594	21	0.955	3.539
11	3.457	0.677**	-0.036^{ns}	98.832	20	0.946	3.508
19	3.370	1.095	-0.066^{ns}	99.992	31	0.943	3.494
31	3.370	0.567*	-0.050^{ns}	99.080	10	0.910	3.373
23	3.303	0.879	-0.017^{ns}	98.871	19	0.906	3.361
5	3.270	0.798	-0.053^{ns}	99.635	23	0.906	3.360
10	3.207	0.395*	-0.025^{ns}	95.462	5	0.905	3.355
6	3.187	0.614**	-0.052^{ns}	99.326	9	0.896	3.323
9	3.183	0.603**	-0.065^{ns}	99.921	6	0.896	3.322
29	2.983	1.034	0.072^{ns}	97.739	29	0.808	2.997

Note. β_0 = regression constant, β_1 = regression coefficient, σ^2_{di} = regression deviation, R^2 = coefficient of determination. **, *: significantly different from 1, by t test, at 1% and 5% probability, respectively. **, *: significantly different from 0, by F test, at 1% and 5% probability, respectively. ^{ns}: non significant.

[1/]: Order based on the average of the three environments.

[2/]: Order based on the method of mixed models.

3.3 Mixed Model Methodology to Test Genotype's Adaptability and Stability

The mixed model methodology (Resende, 2016) was used for the simultaneous selection of genotypes based on productivity, adaptability, and stability. The harmonic mean of the relative performance of the genotypic value (MHPRVG) (Table 4), which infers about the expected productivity, adaptability, and stability of genotypes, was estimated (Silva, Carvalho, Vieira, & Benin, 2011; Rosado, Rosado, Alves, Laviola, & Bhering, 2012). This estimate (MHPRVG) can be used when considering planting in several locations with different G×E interactions. Therefore, we should seek genotypes with the MHPRVG greater than or equal to 1 (Torres, Teodoro, Sagrilo, Ceccon, & Correa, 2015; Carvalho, Farias, Moewllo, & Teodoro, 2016). We found that among the five genotypes with the highest MHPRVG (34, 36, 16, 33, 24), four are indicated by the Eberhart and Russell method for favorable environments and good predictability of behavior (Table 4). Genotype 36 is the only one that appears among those indicated for favorable environments and with good predictability, all with good behavior *per se*.

The MHPRVG method was applied separately for the favorable and unfavorable environments. To do so, we divided the three environments into two groups, based on the grain yield of each environment. Environments with yield above the overall mean (3,710 kg ha^{-1}) were classified as favorable and those with mean yields below the overall mean were classified as unfavorable. Mendes et al. (2012), and Oliveira, Atroch, Dias, Guimarães, and Guimarães (2017) evaluated maize adaptability and stability in favorable and unfavorable environments and showed that this classification is important in the selection of genotypes with adaptability to specific environments. Of the three environments evaluated, two (environment 1 and environment 2) were classified as unfavorable, and one (environment 3) as favorable.

Figure 3 shows the scatter plot of genotype performance measured by MHPRVG·MG, combining productivity, adaptability, and stability. This allowed the identification of stable materials that are widely adapted to different environments (favorable and unfavorable). Populations were found with good adaptability and yield stability for different environments. The seven populations that had the best MHPRVG·MG in favorable environment were, in descending order: 34, 33, 16, 24, 36, 30, and 15, indicating populations with good productivity, adaptability, and stability for these environments. However, genotypes 36, 34, and 16, showed the best behavior in unfavorable environment. On the other hand, genotypes 20, 32, 15, 8, and 35 showed good productivity in favorable environments, and had low productivity in the unfavorable environment and, thus, they can be classified as having adaptability specific to favorable environments.

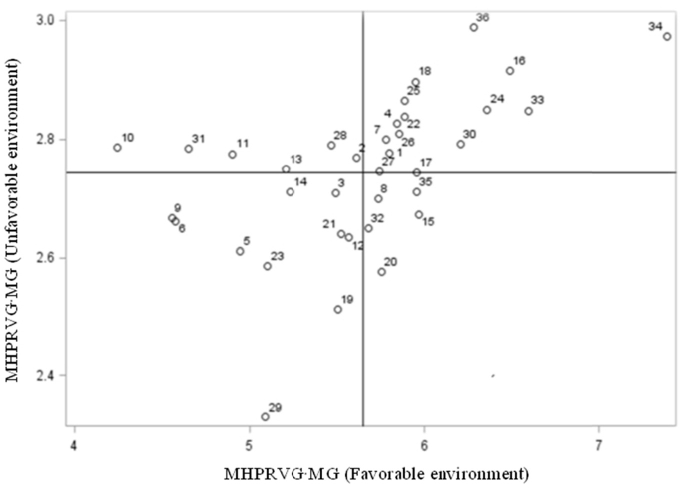

Figure 3. MHPRVG·MG scatter plot for grain yield (kg ha^{-1}) of 36 maize populations in favorable (E3) and unfavorable environments (E1 and E2)

3.4 Estimate the Genetic Parameters

Individual broad-sense heritabilities increased across the unfavorable environments 1 and 2, and the favorable environment 3 (Table 5). The mean heritability of the genotypes across the environments and blocks was higher in the favorable environment. Accuracy, which indicates the experimental precision, was estimated at 64.6% and 61.6% for the favorable and unfavorable environment, respectively, showing that experimental precision increases with improvement of the environment. According to Pimentel et al. (2014), the greater the selective accuracy in the evaluation of an individual, the greater the confidence in the assessment and the genetic value predicted for the individual. Similarly, Mendes et al. (2012), and Oliveira, Atroch, Dias, Guimarães, and Guimarães (2017), studying adaptability and stability of maize cultivars, found that heritability and accuracy increased in the favorable environment compared with the unfavorable environment, corroborating the results of this study.

The genotypic correlation between the performances across the environments was moderate (Table 5). The correlations of 50% for favorable environment and 53.9% for unfavorable environment indicate a coincidence of 50 to 54 % in the selection of genotypes specific for each environment, that is, if we were to select genotypes in each environment, in environment 3, the coincidence of this selection across the environments would be 50%.

These correlations result in the presence of the complex part of the G×E interaction and complicate the selection of genotypes with larger adaptation, as it is observed by Mendes et al. (2012), Faria et al. (2017), and Oliveira, Atroch, Dias, L. J. Guimarães, and P. E. O. Guimarães (2017).

Table 5. Estimates of variance components (individual REML) for comparison of unfavorable environments (E1 and E2) with favorable environment (E3)

Variance components (individual REML)			
Unfavorable environment		Favorable environment	
V_g	0.022	V_g	0.237
V_{int}	0.019	V_{int}	0.237
V_e	0.211	V_e	0.373
V_f	0.252	V_f	0.848
h_g^2	0.087; 0.049	h_g^2	0.279; 0.125
h_{mg}^2	0.379	h_{mg}^2	0.418
A_{cgen}	0.616	A_{cgen}	0.646
c_{int}^2	0.074	c_{int}^2	0.280
r_{gloc}	0.539	r_{gloc}	0.500
$CV_{gi}\%$	5.386	$CV_{gi}\%$	8.648
$CV_e\%$	16.761	$CV_e\%$	10.846
Overall mean	2,740	Overall mean	5,630

Note. (V_g): genotypic variance; (V_{int}): variance of genotype × environment interaction; (V_e): residual variance; (V_f): individual phenotypic variance; ($h_g^2 = h^2$): broad sense heritability of individual plots, *i.e.*, total genotypic effects; ($c_{int}^2 = c^2$): coefficient of determination of the effects of genotype × environment interaction; (h_{mg}^2): heritability of the genotype mean, assuming complete survival; (A_{cgen}): accuracy of genotype selection, assuming complete survival; (r_{gloc}): genotypic correlation between performance in the environments; ($CV_{gi}\%$): genotypic coefficient of variation.; ($CV_e\%$): coefficient of residual variation.

3.5 Favorable and Unfavorable Environments

The overall mean grain yield of the 36 populations in the favorable and unfavorable environments were 5,630 and 2,740 kg ha^{-1}, respectively, showing a 100% increase in the yield of the favorable environment in relation to the unfavorable environment. The lower yield in the unfavorable environments can be explained by the long-term water deficit during the experiment in environment 1, in the second crop 2016, and the sandy soil in environment 2, which is a limiting factor of productivity. Thus, the average yield of unfavorable environments is approximately 50% lower than the national average yield of maize in the crop season 2015/16, which was 4,928 kg ha^{-1} (IBGE, 2016). The yield of environment 3 was approximately 14% higher than the national average yield. These results demonstrate the importance of performing experiments in specific environments for selection of superior populations for specific environment conditions.

3.6 Comparison of the Two Methodologies of Adaptability and Stability

The MHPRVG method was suitable for the identification of maize genotypes with high productivity and wide adaptability and yield stability. There was similarity in the selection of some populations by the methodologies used in the three environments evaluated. The most productive, stable, and widely adaptable populations recommended by the method of Eberhart and Russell for environment 1 are 24, 36, 30, 25, and 7. These populations were also indicated as superior by the method of mixed models for the same environment. However, these methods disagree as to the selection of two populations: the method of Eberhart and Russell also selected populations 10 and 31, and the method of mixed models selected populations 16 and 26.

For environment 2, the most productive, stable, and widely adaptable populations selected by the method of Eberhart and Russell are 16, 36, 18, 22, 4, and 28. These populations were also indicated as superior by the method of mixed models for this environment. Again, these methods disagree regarding the selection of one population: the method of Eberhart and Russell also selected population 2, and the method of mixed models selected the population 25.

The method of Eberhart and Russell recommended for the environment 3 the populations 16, 24, 36, 30, 35, and 17, as the most productive, stable and widely adaptable. The method of mixed models also indicated them as superior for this environment. The methods disagree on the selection of one population: the method of Eberhart and Russell selected the population 15, and the method of mixed models selected the population 18.

Vasconcelos et al. (2015) points out that the use of more than one method to estimate the genetic parameters is a strategy that allows greater reliability in the interpretation of the data for later recommendation of cultivars.

4. Conclusions

The methods of Eberhart and Russell and Mixed Models showed similar classification of some populations regarding adaptability and stability in the three environments, but the method of mixed models is recommended for the indication of the best populations for providing better selective accuracy.

G×E interaction exists for the populations evaluated, with predominance of the complex type.

Population 36 is promising for breeding programs aimed at cultivars with greater adaptability and stability, since it was selected as superior in all environments.

The populations selected by the method of mixed models to form a composite to obtain new populations for future breeding actions for each environment are: environment E1: 36, 24, 30, 25, 16, 7, and 26; environment E2: 16, 36, 18, 22, 4, 25, and 28; and environment E3: 16, 24, 36, 30, 18, 17, and 35.

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