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Stability and adaptability of early maturing sugarcane clones by AMMI analysis

Edson Perez Guerra[1], Ricardo Augusto de Oliveira[2], Edelclaiton Daros[2], José Luís Camargo Zambon[2], Oswaldo Teruyo Ido[2], and João Carlos Bespalhok Filho[2]*

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ABSTRACT - *Stability and adaptability of 14 early maturing sugarcane clones were evaluated at 11 locations in the State of Paraná, in the plant cane and ratoon cycles, by the AMMI method. By AMMI2, 59.44% cumulative variance was explained in plant cane and 54.22% in ratoon cane by the first two principal components of tons of pol per hectare (TPH). For genotype RB966928 the TPH was medium to high, phenotypic stability high and adaptability general, recommending this early maturing clone with wide adaptability for northern Paraná. The genotype-environment interaction was lowest in Paranavaí and Mandaguaçú (most stable locations), where the ranking of genotypes was more reliable than the means of the environments tested.*

Key words: *Saccharum* spp., principal components, multivariate analysis, genotype x environment.

INTRODUCTION

The genotype-environment (GE) interaction represents the change in the relative performance of genotypes due to environmental variations. It is a major problem for any kind of breeding program, be it during selection or in the recommendation of cultivars. Among the possibilities to minimize this problem is the choice of varieties with wide adaptation and good stability (Cruz and Carneiro 2003).

Different methodologies can be used to assess the adaptability and stability of genotypes. The most important are based on analysis of variance, linear regression, nonlinear regression, multivariate analysis and non-parametric statistics (Bastos et al. 2007). Zeni-Neto et al. (2008) evaluated early maturing sugarcane clones in the State of Paraná by the non-parametric methodology of Lin and Binns (1988). Oliveira et al. (2005) and Bastos et al. (2007) used mixed models to measure the stability and adaptability of sugarcane clones in the final selection stage.

A method that has been highlighted in studies of GE interaction is AMMI (Additive Main Effects and Multiplicative Interaction analysis) which combines a univariate method for the additive effects of genotypes and environments with a method for the multiplicative effects of the GE interaction (Zobel et al. 1988). This method can contribute both to the identification of widely adapted genotypes with high yields, as to the agronomic zoning for regional cultivar recommendation and the choice of test locations (Gauch and Zobel 1996). An advantage of AMMI is that it eliminates the noise from the GE interaction (Bastos et al. 2007, Silva and

[1] Centro de Ciências Agrárias e Ambientais, Pontifícia Universidade Católica do Paraná, BR 376, Km 14, CP 129, 83010-500, São José dos Pinhais, PR, Brazil
[2] Departamento de Fitotecnia e Fitossanitarismo, Universidade Federal do Paraná, Rua Funcionários 1540, 80035-050, Curitiba, PR, Brazil. *E-mail: bespa@ufpr.br

Duarte 2006). Another advantage is the graphical interpretation of the results of statistical analysis using the biplot procedure (Melo et al. 2007). This method was used to study the genotype stability of different crops, but there are few studies for sugarcane, e.g., Bajpai and Kumar (2005).

The purpose of this study was to evaluate the stability and adaptability of promising early maturing sugarcane clones in the State of Paraná by the AMMI method.

MATERIAL AND METHODS

The study of genotype-environment interaction (GE) was applied to clones of the sugarcane breeding program of the Universidade Federal do Paraná (PMGCA/UFPR/RIDESA). Fourteen genotypes were evaluated, 11 early maturing clones of the Series RB94, RB95 and RB96 and three standard varieties, RB855156, RB855453 and RB925211. The tests were conducted in 11 production units in the state of Paraná, in the final testing phase from 2003 to 2005, in plant and ratoon cane.

The altitude above sea level and coordinates of the 11 locations were: E1- São Tomé (23º 32'S, 52º 35'W, alt. 420 m asl); E2- Rondon (23º 23'S, 52º 43'W, 530 m asl); E3- Jandaia do Sul (23º 37'S, 51º 37'W, 760 m asl); E4- Nova Londrina (22º 55'S, 53º 15'W, 480 m asl); E5- Ibaiti (23º 50'S, 50º 11'W, 850 m asl); E6- Bandeirantes (23º 06'S, 50º 22'W, 492 m asl); E7-Jussara (23º 50'S, 52º 27'W, 408 m asl); E8- Mandaguaçú (23º 21'S, 52º 05'W, 580 m asl); E9- Cidade Gaúcha (23º 22'S, 52º 56'W, 550 m asl); E10- Paranavaí (23º 05'S, 52º 27'W, 503 m asl); E11- São Pedro do Ivaí (23º 52'S, 51º 41'W, 400 m asl).

The experiments were conducted in a complete randomized block design with three replications, in plots with four 8.0 m-rows spaced 1.40 m apart, where 18 buds per meter were planted in March 2003. Plant cane was harvested in April 2004 and ratoon cane in April 2005. The following variables were evaluated: number of stalks per plot; mass of 15 stalks (kg) in three random samples, without the tips; pol content of 10 stalks per plot (%) by technological analysis; tons of pol per hectare (TPH) as related to tons of cane per hectare (TCH) by the following formulas (Oliveira et al. 2008):

TCH = NSM x M1S x 7.142

TPH = (TCH x POL)/100

where:

TCH-tons of cane per hectare (t ha^{-1}), TPH-tons of pol per hectare (t ha^{-1}), NSM- number of stalks per linear meter; M1S-mass of one stalk (kg); POL-pol content (%).

Analysis of variance for plant cane and ratoon cane was performed for each location, recording means and variances (data not shown). The combined analysis was performed for cane plant and ratoon cane data separately, obtaining individual information for interpretations. Firstly, the homogeneity of residual variances of the experiments was tested (MSr), verified by the ratio of the greatest by the lowest mean square, considered homogeneous due to the ratio below seven.

After verifying the existence of GE interaction (F test significant) by the combined analysis of variance, the analysis of adaptability and phenotypic stability was performed by the AMMI method (Zobel et al. 1988). The model is uni-multivariate, consisting of the analysis of variance of main effects, genotypes and environments, and of the multivariate analysis of the effects of GE interaction (analysis of principal components and decomposition of singular values) (Gauch 1992). The AMMI model was described by Duarte and Vencowsky (1999) as follows:

$$Y_{ij} = \mu + g_i + a_j + \sum_{k=1}^{n} \lambda_k \alpha_{ik} \gamma_{jk} + r_{ij} + \bar{\varepsilon}_{ij}$$

where:

Y_{ij}: the mean response of genotype i in environment j; μ: is the overall mean of the test; g_i is the fixed effect of genotype i (i = 1, 2, ... g); a_j is the fixed effect of environment j (j = 1, 2, ... a); ε_{ij} is the mean experimental error, assumed independently; the GE interaction is controlled by the factors: λk: singular value of the k^{th} Interaction Principal Component Axis (IPCA), (k = 1, 2, ... p, where p is the maximum number of estimatable principal components); α_{ik}: singular value of the i^{th} genotype in the k^{th} IPCA; y_{jk}: singular value of j^{th} environment in the k^{th} IPCA; r_{ij}: residue of the GE interaction or AMMI residue (data noise); k: characteristic non-zero roots, k= [1, 2,... min(g-1, e-1)].

The SS_{GxE} was partitioned into n individual axes or principal components of the interaction (IPCA-Interaction Principal Component Axis) that described the standard portion; each axis corresponded to an AMMI model. The choice of the model that describes the interaction best was based on the F test of Gollob (1968), by the significance of each IPCA related to the $MS_{mean\ error}$ of the axes to be retained in the model.

After selecting the AMMI model, stability and adaptability were studied by the biplot graph, obtained by combinations of the orthogonal axes IPCA. The data were analyzed using software Genes (Cruz 1997) for Anova and Estabilidade (Universidade Federal de Lavras 2000) for AMMI analysis.

RESULTS AND DISCUSSION

The combined analysis of 11 trials with plant and ratoon cane indicated highly significant differences (P <0.01) for genotypes and environments (Table 1). The genotype x environment interaction was also significant (P <0.01), indicating that the best clones in one environment are not necessarily the best in another. This justifies the need to take stability and adaptability into account for selection and for the recommendation of promising early sugarcane clones.

The AMMI model seeks to recover a portion of the SS_{GxE} that determines what is in fact caused by the GE interaction, which is called a standard portion (effects of genotypes and environments) and a noise portion, which is the additional residue of unpredictable and not interpretable responses (Crossa et al. 1990). To choose the AMMI model, the cutting point would be the n^{th} significant IPCA. The models may be: AMMI0, when no y axis or interaction term is included; AMMI1, when only the first axis of the interaction is included; and AMMI2, the first two axes and so on (Cornelius et al. 1996). The partitioning of SS_{GxE}, indicated the first three principal components (IPCA1 to IPCA3) with significant differences (P <0.01) for plant cane and ratoon cane (Table 1). The non-significant deviation for IPCA3 indicates that only three axes could be used to explain the GE interaction.

In the AMMI2 model in the explanation of the cumulative variance by the axes IPCA1 and IPCA2 added up to 59.44% and 54.22% for plant cane and ratoon cane, respectively, using only 42 degrees of freedom (32.3% of the 130 DF the SS_{GxE} contains) (Table 1). The cumulative percentage of explanation on each axis of the main components is important because there should be greater concentration of the GE interaction pattern on the first axis; as the number of selected axes increases, the noise percentage increases as well, reducing the predictive power of AMMI analysis (Oliveira et al. 2003). Although the values obtained are relatively low, according to Gauch (1988), the first axis captures the greatest standard portion of the GE interaction, while the subsequent axes show pattern reduction and noise increase. The evaluation of graphical interaction using a two-dimensional AMMI2 biplot is therefore acceptable. The environments and genotypes can be detected that contributed least to the interaction (most stable) as well as the desirable combinations of genotypes and environments in terms of specific adaptability (Morais et al. 2003). Once the AMMI2 model was defined, the predicted TPH means were calculated from the second principal component, IPCA2 (Table 2).

Table 1. Summary of the analysis of variance of tons of pol per hectare (TPH) of 14 early maturing sugarcane clones in plant cane (2003/2004) and ratoon cane (2004/2005), at 11 locations in the state of Paraná and the partitioning of the EG interaction, with percentage of variance explanation and accumulated value

Source of		TPH – Plant cane			TPH – Ratoon cane		
variation	df	MS	Explained (%)	Accumulated (%)	MS	Explained (%)	Accumulated (%)
Genotype	13	39.34 **			49.70 **		
Environment	10	380.13 **			337.70 **		
GxE	130	16.95 **			8.57 **		
IPCA 1	22	40.03 **	39.95	39.95	16.42 **	32.40	32.40
IPCA 2	20	21.17 **	19.48	59.44	12.16 **	21.81	54.22
IPCA 3	18	17.50 **	14.29	73.73	11.43 **	18.45	72.67
Deviations	70	8.27 *			4.35		
Residue	286	5.68			4.21		

* significant at 5% probability by the F test; ** significant at 1% probability by the F test

Tabela 2. Means of tons of pol per hectare predicted by AMMI2, of 14 early maturing sugarcane clones in plant cane (2003/2004) and ratoon cane (2004/2005), at 11 locations in the State of Paraná

		Tons of pol per hectare (t ha^{-1})											
		Environments (in plant cane)**											
Clone	**Genotype**	**E1**	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	**E8**	**E9**	**E10**	**E11**	**Mean**
G1	RB855046	13.3	12.9	15.1	9.6	17.3	22.3	15.3	14.1	12.4	20.2	20.2	15.7
G2*	RB855156	12.6	15.5	13.5	13.7	14.9	19.0	17.3	13.6	12.0	19.5	22.4	15.8
G3*	RB855453	12.0	14.7	14.5	21.7	14.4	19.5	16.3	14.4	12.9	18.8	18.7	16.2
G4*	RB925211	14.8	16.3	15.7	11.8	17.8	22.1	18.4	15.3	13.6	21.6	24.0	17.4
G5	RB925345	12.7	16.9	14.0	20.4	14.3	18.5	18.4	14.5	13.0	19.5	22.2	16.8
G6	RB945961	12.1	14.1	14.5	18.9	14.9	19.9	15.9	14.1	12.6	18.9	18.8	15.9
G7	RB946903	14.3	18.6	16.1	24.7	15.9	20.4	20.0	16.6	15.1	21.2	23.0	18.7
G8	RB955970	11.4	14.6	13.6	20.6	13.6	18.4	16.2	13.7	12.2	18.2	19.0	15.6
G9	RB956911	12.6	18.3	13.3	21.3	13.4	17.1	19.5	14.3	12.8	19.4	23.9	16.9
G10	RB965902	13.6	17.5	14.2	15.8	15.4	19.2	19.2	14.6	13.0	20.5	24.5	17.0
G11	RB965911	14.5	20.0	14.0	15.2	15.5	18.5	21.5	15.0	13.4	21.5	28.1	17.9
G12	RB966925	12.3	12.5	14.3	12.1	15.9	21.0	14.7	13.5	11.8	19.1	18.9	15.1
G13	RB966927	12.3	15.4	12.8	11.6	14.5	18.3	17.2	12.9	11.3	19.2	23.1	15.3
G14	RB966928	14.0	17.2	15.4	19.0	16.2	20.5	18.9	15.5	14.0	20.8	23.0	17.7
	Mean	13.0	16.0	14.4	16.9	15.3	19.6	17.8	14.4	12.9	19.9	22.1	16.6
Clone	**Genotype**	**Environments (in ratoon cane)**											**Mean**
G1	RB855046	9.8	9.0	13.4	11.9	7.7	13.7	11.1	12.9	13.4	12.8	18.8	12.2
G2*	RB855156	13.3	12.5	14.7	13.7	9.1	11.3	16.4	15.2	17.7	14.8	19.2	14.4
G3*	RB855453	11.0	8.7	13.3	16.4	8.2	13.4	10.1	12.6	13.5	13.5	18.9	12.7
G4*	RB925211	13.7	11.5	14.9	18.0	9.9	13.1	13.9	14.7	16.6	15.5	20.1	14.7
G5	RB925345	14.5	11.8	14.5	19.4	9.7	11.4	14.4	14.6	17.3	15.6	19.4	14.8
G6	RB945961	12.0	10.7	15.5	15.4	10.0	16.3	12.4	14.8	15.2	15.1	21.1	14.4
G7	RB946903	14.9	12.3	15.8	20.3	10.9	14.0	14.4	15.5	17.5	16.6	21.0	15.8
G8	RB955970	11.3	9.3	14.9	16.9	9.6	16.8	10.0	13.8	13.7	14.6	20.9	13.8
G9	RB956911	12.5	10.8	14.5	16.0	9.2	13.2	13.1	14.2	15.7	14.6	19.6	14.0
G10	RB965902	13.0	10.9	14.3	17.0	9.2	12.5	13.4	14.1	16.0	14.8	19.4	14.1
G11	RB965911	15.1	11.3	14.8	23.2	10.4	12.5	12.8	14.3	16.8	16.4	20.1	15.3
G12	RB966925	10.7	10.6	14.5	10.6	8.5	14.2	13.6	14.3	15.0	13.5	19.6	13.2
G13	RB966927	10.1	8.3	12.5	14.0	7.2	12.2	10.3	12.0	13.1	12.5	17.9	11.8
G14	RB966928	14.2	12.2	16.3	18.7	11.1	15.7	14.1	15.8	17.1	16.5	21.7	15.8
	Mean	12.6	10.7	14.6	16.5	9.3	13.6	12.9	14.2	15.6	14.8	19.9	14.1

*standard variety; **E1: São Tomé; E2: Rondon; E3: Jandaia do Sul; E4: Nova Londrina; E5: Ibaiti; E6: Bandeirantes; E7: Jussara; E8: Mandaguaçú; E9: Cidade Gaúcha; E10: Paranavaí; E11: São Pedro do Ivaí

The graphic interpretation of the biplot was initially based on the variation due to additive main effects of genotypes and environments and on the multiplicative effect of the GE interaction (AMMI1) (Figures 1a and 1b). The abscissa represents the main effects (the overall TPH mean of the tested genotypes) and the ordinate the first axis of interaction (IPCA1). The lower the value of IPCA1 (in absolute values), the lower is the contribution to the GE interaction and the more stable the plant material. The ideal genotype has high yields and IPCA1 values near zero. An undesirable genotype has low stability as well as low yields (Ferreira et al. 2006).

In plant cane (Figure 1a), clone RB946903 (G7) had the highest TPH values, but low stability. The yield of the clones RB965911 (G11), RB966928 (G14) and RB965902 (G10) however exceeded the overall mean and agronomic stability was high. The yield of control RB855156 (G2) was below-mean and stability intermediate. The genotypes that contributed most to the GE interaction in plant cane were RB855046 (G1), RB925211 (G4) and RB946903 (G7), and those who contributed least (most stable) were RB965911 (G11), RB966928 (G14) and RB965902 (G10) since the coordinates on the axis were the lowest IPCA1 (Figure 1a). Of these, the clones RB965911 and RB966928 had highest yields, exceeding the overall mean.

In ratoon cane (Figure 1b), the promising clones RB966928 (G14) and RB946903 (G7) had the highest TPH values, high stability and moderate stability, respectively. Those with highest yields and stability were RB966928 (G14), followed by RB925211 (G4), RB965902 (G10), RB956911 (G9) and RB855156 (G2).

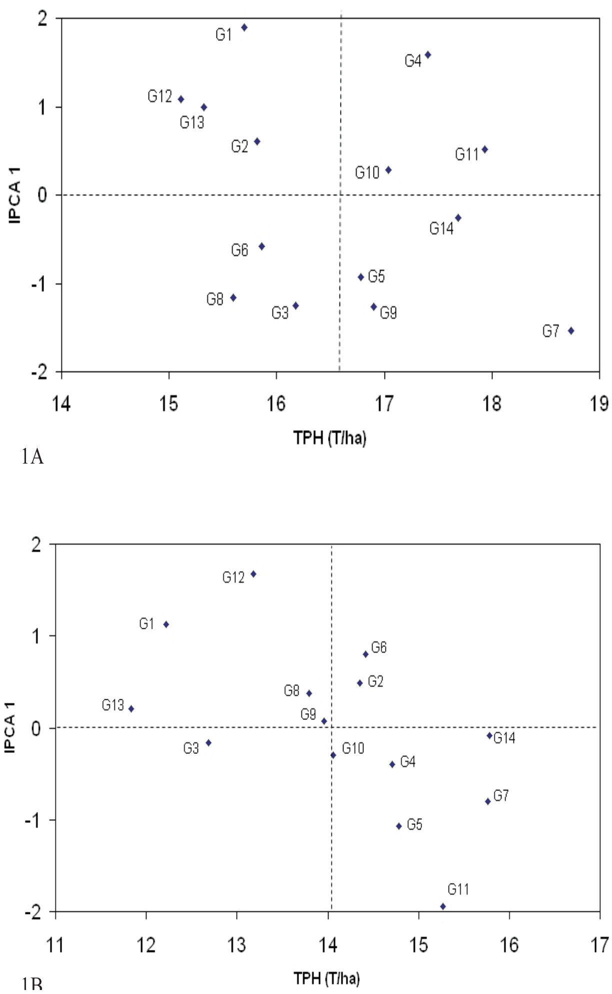

Figure 1. AMMI1 biplot with the first principal axis of interaction (IPCA1) x mean yield of tons of pol per hectare (TPH) of 14 sugarcane genotypes, in plant cane (2003/2004) **(1A)** and ratoon cane (2004/2005) **(1B),** at 11 locations in Paraná. The vertical line in the center represents the general mean of 16.6 t ha^{-1} (1A) and 14.1 t ha^{-1} (1B)

For some clones a change in performance was observed between cycles. For example, the performance of control RB855156 (G2) improved, from the tenth place in the combined analysis of the environments in plant cane to the seventh place in ratoon cane. An explanation for this could be the low germination in the first year of cultivation, which was offset by good sprouting from ratoons. This type of instability observed for some clones between the cycles in this study justifies the analysis of the GE interaction in separate cycles.

The analysis AMMI2 was graphically interpreted based on the multiplicative effect of the GE interaction. Figures 2a and 2b show the AMMI2 biplot for plant cane and ratoon cane, respectively. Based on these figures an agronomic zoning is possible choosing groups of genotypes and environments that are located near and in the same region in the graph (Ferreira et al. 2006). The graphics capture the pattern portion of the GE interaction, show the genotypes and environments that least contributed to the interaction (lower scores in absolute values and more stable) and the desirable genotype-environment combinations in terms of specific adaptability. The AMMI2 can identify genotypes with wide adaptation or identify homogeneous macro-environments (Gauch and Zobel 1996). The statistically stable genotypes and environments are represented by points near the origin in the AMMI2 biplot, with values near zero for the two axes of interaction (IPCA1 and IPCA2).

The stability of the genotypes RB966928 (G14) and RB965902 (G10) was considered high for TPH in cane plant (Figure 2a) and they contributed least to the GE interaction. GE interaction was highest in RB855046 (G1) and RB965911 (G11) and they were the least stable.

In ratoon cane, the genotypes RB966928 (G14), RB956911 (G9) and RB966927 (G13) were considered highly stable for TPH, according to the AMMI2 biplot (Figure 2b), followed by RB965902 (G10), RB925211 (G4) RB855453 and (G3), which contributed least to the GE interaction. In contrast, the stability of RB965911 (G11) and RB966925 (G12) was lowest, followed by RB955970 (G8) and RB855156 (G2), directly influencing the GE interaction in ratoon cane. In general, the stability of genotypes and environments was higher in ratoon than in plant cane.

With regard to the locations, Paranavaí (E10) and Mandaguaçú (E8) can be considered highly stable, while Nova Londrina (E4) and Bandeirantes (E6) were less stable for plant and ratoon cane.

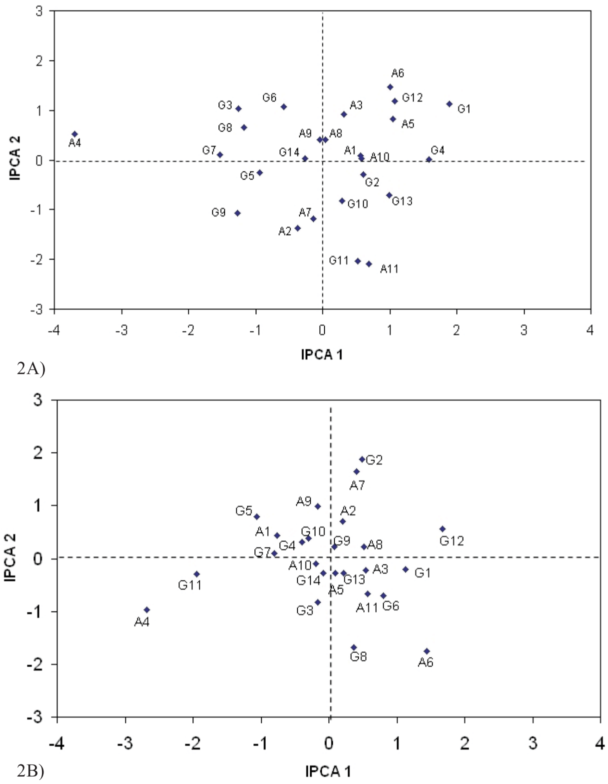

Figure 2. AMMI2 biplot with the two first principal axes of interaction (IPCA1 and IPCA2) of tons of pol per hectare of 14 genotypes of sugarcane (G1 to G14), in plant cane (2003/2004) **(2A)** and ratoon cane (2004/2005) **(2B),** at 11 locations in the state of Paraná (E1 to E11)

The adaptive relations can be easily understood in an AMMI biplot, by observing the signs of the scores for each pair of genotypes and environments. If the sign is the same, they should interact positively and if the sign is opposite, negatively (Duarte and Vencovsky 1999). Melo et al. (2007) identified genotypes and environments with IPCA scores with the same sign, which had specific positive interactions in common bean. Maia et al. (2006) observed positive interactions between genotypes and environments and classified the genotype groups in: adapted and most stable; ability to adapt easily to the environmental conditions; responsive behavior; positive exploitation of the interactive effect of the environment; or adaptive synergism in the environmental conditions.

Specific adaptation of RB956911 (G9) was observed to the location Rondon (E2); of RB965911 (G11) to São Pedro do Ivaí (E11) and of RB946903 (G7) to Nova Londrina (E4) in plant cane. In ratoon cane, genotype RB855156 (G2) was specifically adapted to location Jussara (E7) as well as RB965911 (G11) to Nova Londrina (E4); and RB925345 (G5) and RB946903 (G7) to São Tomé (E1).

In future evaluations and for recommendations, when an experiment cannot be conducted at a highly stable location, or when the crop is even lost due to adversities, the data from another environment with high stability could be considered, e.g., Paranavaí (E10) and Mandaguaçú (E8). Due to the low GE interaction these test locations can be considered adequate for the development of preliminary stages of sugarcane selection. In environments with high stability, genotypes with general adaptability tend to perform well and can be selected with greater safety. On the other hand, environments with high GE interaction (high instability) such as Nova Londrina (E4) and Bandeirantes (E6) should be avoided in the preliminary stages, because the tendency is to select genotypes with specific adaptability to these sites. The order of the genotypes in a stable environment is more reliable, because the classification is determined by genotypic effects (where the GE interaction is zero) (Duarte and Vencovsky 1999).

Combining estimates of the main effects with the estimates of the interaction revealed by standard AMMI2, it was possible to estimate the final phenotypic responses (Table 2) of each genotype in a given environment for plant and ratoon cane. The data confirm the specific adaptation, as discussed, such as of clone RB965911 (G11) to Nova Londrina (E4) with 23.2 t ha^{-1} of pol in sugarcane ratoon.

CONCLUSIONS

The mean TPH, the high phenotypic stability and general adaptability in plant and ratoon cane of genotype RB966928 recommend this early maturing clone with wide adaptability for northern Paraná.

The locations Paranavaí and Mandaguaçú had the lowest GE interaction (most stable locations), where the genotype ranking was more reliable to the mean of the environments tested.

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Estabilidade e adaptabilidade de clones precoces de cana-de-açúcar por análise AMMI

RESUMO - *Avaliou-se a estabilidade e adaptabilidade de 14 clones precoces de cana-de-açúcar, em 11 localidades no Estado do Paraná, nos ciclos de cana planta e cana soca pelo método AMMI. O modelo utilizado foi AMMI2, com explicação acumulada da variância de 59,44% em cana planta e 54,22% em cana soca, nos dois primeiros componentes principais de tonelada pol por hectare (TPH). O genótipo RB966928 apresentou médias elevadas de TPH, alta estabilidade fenotípica e adaptabilidade geral, podendo ser recomendado como clone precoce de ampla adaptabilidade para a região Norte do Paraná. As localidades Paranavaí e Mandaguaçú apresentaram a menor interação genótipo x ambiente (locais mais estáveis), onde o ordenamento dos genótipos apresentaram maior confiabilidade em relação à média dos ambientes testados.*

Palavras-chave: *Saccharum* spp., componentes principais, análise multivariada, genótipo x ambiente.

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