Genetics and Molecular Biology, 23, 2, 387-393 (2000)

Yield stability in maize (*Zea mays* L.) and correlations among the parameters of the Eberhart and Russell, Lin and Binns and Huehn models

Carlos Alberto Scapim[1], Valter Rodrigues Oliveira[2], Alessandro de Lucca e Braccini[1], Cosme Damião Cruz[3], Carlos Alberto de Bastos Andrade[1] and Maria Celeste Gonçalves Vidigal[1]

Abstract

Assessment of the stability and adaptability of a genotype to different environments is useful for recommending cultivars for known conditions of cultivation and should be a requirement in breeding programs. Twenty maize (*Zea mays* L.) cultivars were tested at eight locations in Minas Gerais by the National Center for Maize and Sorghum Research (CNPMS) of the Brazilian Enterprise for Agricultural Research (EMBRAPA) for two years. The experiments involved a randomized complete block design in which three procedures were used to analyze cultivar stability and adaptability. The level of association among the parameters obtained by the three methods was assessed using Spearman's rank correlation. Hybrids 'DINA 170', 'G-96C', 'C 505', 'DINA 70' and 'C 435' had a mean yield greater than 6,000 kg/ha. Eberhart and Russell's regression coefficient (β_i) was negative and correlated significantly ($P < 0.01$) with Lin and Binn's superiority index (P_i), indicating that the most responsive cultivars tended to have smaller P_i. P_i did not correlate with Huehn's nonparametric measurements $S_i^{(2)}$ and $S_i^{(3)}$ nor with Eberhart and Russell's σ_{di}^2 ($P \geq 0.05$), but correlated positively with $S_i^{(1)}$ ($P < 0.05$), indicating that superior genotypes (with lower P_i) could also be stable, a finding not commonly reported in the literature. The stability parameters, $S_i^{(1)}$, $S_i^{(2)}$, $S_i^{(3)}$ and σ_{di}^2, correlated positively among each other ($P < 0.01$), indicating that the stability estimates of the Huehn's nonparametric model did not add important information to those obtained by the Eberhart and Russell's method. Estimates from the Huehn's method, however, showed that stability estimates from nonparametric models are useful alternatives to parametric models. 'DINA 170', which had a greater general mean, was characterized as a cultivar adapted to favorable environments, and was among the most productive in the different environments assessed. The cultivar 'G-96C' showed medium adaptation to all environments (ideal cultivar) and had good stability. Cultivars 'C 505' and 'C435' were alternatives for 'G-96C'. 'DINA 70' showed good adaptability but had low stability.

INTRODUCTION

Cultivar interaction with environmental factors (location, year of planting, soil type, level of technology used, etc.) is an important consideration for plant breeders. The effects that cultivars and environments exert on cultivar-environment interactions (G x E) are statistically nonadditive, indicating that differences in yields among cultivars will depend on the environment (Yue *et al.*, 1997). Consequently, selection procedures based on the mean yield of cultivars in a given environment are less efficient (Hopkins *et al*., 1995).

There are two possible strategies for developing cultivars with low G x E interaction. The first is subdivision or stratification of a heterogeneous area into smaller, more homogeneous sub-regions, with breeding programs aimed at developing cultivars for specific sub-regions. However, even with this refinement, the level of interaction can remain high because breeding area does not reduce the interaction of cultivars with locations on years (Eberhart and Russell, 1966; Tai, 1971). This approach is also costly. Allard and Bradshaw (1964) classified the environmental variations for which stratification is not effective as unpredictable.

The second strategy for reducing G x E interaction involves selecting cultivars with a better stability across a wide range of environments in order to better predict behavior (Eberhart and Russell, 1966; Tai, 1971). Various methods use the G x E interaction to facilitate genotype characterization and as a selection index together with the mean yield of the cultivars. Parametric models based on simple linear regression analysis are among the most widely used to identify superior cultivars, and include the method proposed by Eberhart and Russell (1966), which interprets the variance of the regression deviations (σ_{di}^2) as a measure of cultivar stability and the linear regression coefficient (β_i) as a measure of the cultivar adaptability. Although regression is widely applied, the fact that the mean of all the cultivars in each environment is taken as a measure of the environmental index and is used as an independent variable in the regression may be considered a serious limitation to this procedure because there cannot be independence among the variables, especially when the number of cultivars is less than 15 (Becker and Léon, 1988; Crossa, 1990). Furthermore, the variation of the estimates of the regression coefficient is usually so small that classification of the genotype for stability and adapt-

[1]*Departamento de Agronomia, Universidade Estadual de Maringá, Av. Colombo, 5790, 87020-900 Maringá, PR, Brasil.*
Send correspondence to C.A.S. E-mail: scapim@cca.uem.br
[2]*Empresa de Pesquisa Agropecuária de Minas Gerais, Centro Tecnológico do Centro-Oeste, Caixa Postal 295, 35701-970 Sete Lagoas, MG, Brasil.*
[3]*Departamento de Biologia Geral, Universidade Federal deViçosa, 36571-000 Viçosa, MG, Brasil.*

ability is difficult (Farias *et al*., 1995). Yue *et al*. (1997) considered the need to satisfy the assumptions of normality, the homogeneity of variance, and the additivity or linearity of the effects of genotypes and environment as further limitations of parametric models.

Lin and Binns' (1988) methodology, although infrequently quoted in the literature, is a good alternative for the assessment of cultivar performance in the G x E interactions. Their method does not have limitations inherent to the use of regression. It characterizes the genotypes with a single parameter (P_i) by associating stability and productivity, and defines a superior cultivar as one with a performance near the maximum in various environments (Lin and Binns, 1988; Helgadóttir and Kristjánsdóttir, 1991). This definition of superiority is similar to the breeder's objective, since a superior cultivar should be among the most productive in the greatest possible number of environments (Farias *et al*., 1995, 1997).

Stability estimates from nonparametric models based on the relative classification of the cultivars in a given set of environments do not require previous assumptions and are good alternatives for parametric measurements (Nassar and Hühn, 1987; Hühn and Nassar, 1989). Huehn (1990a) proposed as stability measures the nonparametric statistics $S_i^{(1)}$, $S_i^{(2)}$, and $S_i^{(3)}$ based on the classification of the genotypes in each environment, and defined stable cultivars as those whose position in relation to the others remained unaltered in the set of environments assessed. In addition to not having the limitations of the parametric models, this model reduces or avoids the biases caused by points outside the adjusted regression equation (outliers), and the stability parameters are easy to use and interpret. The addition or removal of one or a few genotypes probably causes less variation in estimates of the stability parameters than in parametric models. Finally, this approach can be used for other purposes, such as selection in competition and breeding programs, when the order of genotype classification is of fundamental importance (Huehn, 1990a).

The level of association among the adaptability or stability estimates of different models is indicative of whether one or more estimates should be obtained for reliable predictions of cultivar behavior, and also helps the breeder to choose the best adjusted and most informative stability parameter(s) to fit his concept of stability (Duarte and Zimmermann, 1995).

The objective of our study was to determine phenotypic stability of grain yield in maize cultivars and evaluate the level of association among the stability parameters derived using the models suggested by Eberhart and Russell (1966), Lin and Binns (1988) and Huehn (1990a).

MATERIAL AND METHODS

Data from a group of experiments from the Early Genotypes National Maize Experiment carried out in 1989/90 and 1990/91 were used. Twenty maize (*Zea mays* L.) cultivars with an early maturity and normal height from research companies and public and private universities were assessed. The National Maize Experiment is coordinated by the National Center for Maize and Sorghum Research (CNPMS) of the Brazilian Enterprise for Agricultural Research (EMBRAPA).

Five of the 10 experiments were carried out in 1989/90 and the remaining five were carried out in 1990/91. In 1989/90, the experiments were conducted in Rio Paranaíba, Uberlândia, Sete Lagoas, Capinópolis, and Viçosa and, in 1990/91, they were conducted in Uberlândia, Capinópolis (at two locations in the same county), Coimbra, and Lavras. All locations are counties in the State of Minas Gerais, Brazil. Since the experiments were carried out in different places and under different soil and climatic conditions, each was considered as a distinct environment. Each trial was laid out in a randomized complete-block design with three replications. The characteristic assessed was grain yield (kg/ha) standardized for 14.5% moisture.

The statistical procedures adopted for the adaptability and stability analysis of the genotypes were those proposed by Eberhart and Russell (1966), Lin and Binns (1988), and Huehn (1990a).

As described by Eberhart and Russell (1966), the behavior of the cultivars was assessed by the model $Y_{ij} = m + \beta_i I_j + \delta_{ij} + \bar{\varepsilon}_{ij}$, where Y_{ij} = observation of the i-th (i = 1, 2, ..., g) cultivar in the j-th (j = 1, 2, ...n) environment, m = general mean, β_i = regression coefficient, I_j = environmental index obtained by the difference among the mean of each environment and the general mean ($\sum_{j=1}^{n} I_j = 0$), δ_{ij} = the regression deviation of the i-th cultivar in the j-th environment and $\bar{\varepsilon}_{ij}$ = effect of the mean experimental error.

The Lin and Binns' (1988) model uses the P_i parameters obtained by the expression $P_i = \sum_{j=1}^{n} (X_{ij} - M_j)^2/2n$ to assess the superiority of the cultivar, where P_i = superiority index of the i-th cultivar, X_{ij} = yield of the i-th cultivar in the j-th environment, M_j = maximum response obtained among all the cultivars in the j-th environment, and n = number of environments. This expression was further partitioned into $P_i = [n(\bar{X}_{i.} - \bar{M})^2 + \sum_{j=1}^{n} (X_{ij} - M_j + \bar{M})^2]/2n$, where $\bar{X}_i = \sum_{j=1}^{n} X_{ij}/n$ and $\bar{M} = \sum_{j=1}^{n} M_j/n$, $\bar{X}_i$ = yield mean of the i-th cultivar in the n environments and $\bar{M}$ = mean of the maximum response in the n environments. According to Lin and Binns (1988), the first part of the P_i expression quantifies the genetic deviation and the second quantifies the G x E interaction.

Huehn (1990a) proposed the use of the parameters $S_i^{(1)}$, $S_i^{(2)}$, and $S_i^{(3)}$ as stability measurements based on the classification of genotypes in various environments, where $S_i^{(1)} \sum_{j<j'} \left| r_{ij} - r_{ij'} \right| /[n(n-1)/2]$, $S_i^{(2)} = \sum_{j=1}^{n} (r_{ij} - \bar{r}_{i.})^2 /n\text{-}1$ and $S_i^{(3)} = \sum_{j=1}^{n} \left| r_{ij} - \bar{r}_{i.} \right| / \bar{r}_{i.}$, where $S_i^{(1)}$, = mean of the absolute differences among the classification of the i-th cultivar in the n environments, r_{ij} = classification of the i-th cultivar in the j-th environment, n = number of environments, $S_i^{(2)}$ = variance of the classifications of the i-th cultivar in the environments, $\bar{r}_{i.} = \sum_{j=1}^{n} r_{ij}/n$ and $S_i^{(3)}$ = sum of absolute deviations in yield units of each classification relative to the mean classification.

The significance tests for the $S_i^{(1)}$ and $S_i^{(2)}$ statistics were determined as suggested by Nassar and Hühn (1987) and Hühn and Nassar (1989). The χ^2 values associated with $S_i^{(1)}$ and $S_i^{(2)}$ were obtained by the expression $\chi^2_s = \sum_{i=1}^{g} Z_i^{(m)}$, where m = 1, 2, $Z_i^{(m)} = [S_i^{(m)} - E(S_i^{m})]^2 / V(S_i^{m})$, $E(S_i^{(m)})$ = expected value (= mean) of $S_i^{(m)}$, and $V(S_i^{(m)}) = S_i^{(m)}$ variance. The significance test for the null hypothesis that all the genotypes are equally stable was done using a chi-square distribution with g degrees of freedom. The stability parameters were compared using Spearman's rank correlation (Steel and Torrie, 1980).

RESULTS AND DISCUSSION

The differences in the classification of the cultivars in the various environments indicated the presence of G x E interactions (Table I). This was confirmed by the significant effect of the cultivar x environment interaction in the joint analysis of variance (Table II) and indicated the need to assess the response of the cultivars to environmental variation. Taking the mean general yield as the first parameter for the assessment of the cultivars, 'DINA 170', 'G-96C', 'C 505', 'DINA 70' and 'C 435' gave the best yields, with mean yields greater than 6,000 kg/ha (Table I). 'DINA 170' had the lowest yield variation among the environments.

The adaptability and stability of a genotype are useful parameters for recommending cultivars for known cropping conditions. Eberhart and Russell (1966) proposed an assessment of cultivar response to environmental changes using a linear regression coefficient and the variance of the regression deviations. The cultivars are grouped according to the size of their regression coefficients, less than, equal to, or greater than one and according to the size of the variance of the regression deviations (equal to or different from zero). Those cultivars with regression coefficients greater than one would be more adapted to favorable growth conditions, those with regression coefficients less than one would be adapted to unfavorable environmental conditions, and those with regression coefficients equal to one would have an average adaptation to all environments. Thus, genotypes with variances in regression deviations equal to zero would have highly predictable behavior, whereas with a regression deviation greater than zero, they would have low predictability because of the environmental stimulus.

'DINA 170' had a high general mean (Table I) and a regression coefficient greater than one (Table III), thus characterizing it as a cultivar adapted to environments with a high level of technology. In environments with a low level of technology, the yield potential of this cultivar would not be fully exploited. The level of variance in the stability regression deviations was greater than zero, indicating low predictability. This fact, however, should not adversely influence decisions regarding the use of this genotype because it had a high determination coefficient (r^2 = 90%).

The 'G-96C', 'C 505', 'C 435' cultivars had regression coefficients equal to one, regression deviation variances equal to zero and high determination coefficients (Table III). Therefore, they had an average capacity for adaptation to all the environments and were highly predictable. According to Eberhart and Russell (1966), they could be considered ideal cultivars, since they maintained good performance in environments with low yields. This concept of an ideal genotype has been questioned by Hildebrand (1990), who suggests that breeders should find genotypes capable of maintaining good yield in unfavorable environments or those excellent in variable environments, rather than select materials with a regression coefficient equal to one. Hildebrand (1990) stated that these genotypes may yield less in unfavorable environments than those with low regression coefficients, and less in favorable environments than those with higher regression coefficients.

The cultivar 'DINA 70' had a regression coefficient equal to one, but had a regression deviation variance greater than zero and a relatively low determination coefficient (r^2 = 79.0%). In view of its low predictability, care should be taken when recommending it for general adaptability.

Genotypes with high mean yields and a specific adaptability to unfavorable environments were not identified by the regression analysis (Tables I and III). The only cultivar with a regression coefficient lower than one was 'DINA 556', which had the lowest mean yield, the greatest variance in the regression deviations and the lowest determination coefficient of all the cultivars assessed. Cultivars 'C 425', 'C 411', 'BR 201', 'HATÃ 1000' and 'AG 303' had yields similar to or above the general mean of the experiments (5,748 kg/ha) and had adaptability and stability parameters defined as ideal by Eberhart and Russell (1966).

In an alternative procedure for assessing the behavior of genotypes in genotype-environment interactions proposed by Lin and Binns (1988), the superiority of a genotype may be assessed by the superiority index (P_i), defined as the deviation of the i-th cultivar relative to the genotype with maximum performance in each environment. The superior genotype would be that one with the lowest P_i

Table I - Mean yield (kg/ha) of maize cultivars evaluated in five environments for two seasons.

Cultivar	Environments (1989/90)					Environments (1990/91)					
	Rio Paranaíba	Uberlândia	Sete Lagoas	Capinópolis	Viçosa	Uberlândia	Capinópolis[1]	Capinópolis[1]	Coimbra	Lavras	Mean
C 505	5710 (4) a	5473 (1) a	7427 (12) a	5424 (5) a	4392 (9) a	5421 (6) b	7833 (3) a	5893 (7) b	6803 (3) a	8616 (4) b	6299 (3)
BR 201	4075 (19) b	4216 (12) a	7337 (15) a	4742 (15) a	4295 (14) a	4530 (14) c	7385 (8) a	6164 (4) a	6174 (10) a	8527 (5) b	5745 (12)
U 502	4073 (20) b	3750 (19) a	9093 (3) a	4841 (13) a	4245 (15) a	3844 (18) d	7344 (9) a	5406 (14) b	5697 (17) a	6843 (16) c	5514 (15)
HATÃ 1000	4508 (18) b	4114 (13) a	7436 (11) a	4865 (12) a	4785 (3) a	4712 (12) c	7622 (7) a	5585 (13) b	5967 (15) a	8131 (8) b	5773 (9)
AGROMEN 2010	4801 (13) b	4325 (10) a	9338 (2) a	4532 (18) a	4477 (8) a	4718 (11) c	6626 (15) b	5638 (12) b	6556 (5) a	6664 (17) c	5768 (10)
C 425	5691 (5) a	4474 (7) a	7474 (9) a	5021 (10) a	3594 (20) a	5688 (3) b	7722 (13) b	5639 (11) b	6507 (6) a	8073 (10) b	5988 (7)
C 431	4628 (15) b	4606 (6) a	7873 (7) a	5198 (7) a	4358 (11) a	4076 (16) d	7666 (6) a	6243 (3) a	5979 (14) a	5874 (19) c	5650 (13)
AGROMEN 2012	4603 (17) b	3648 (20) a	6067 (18) a	4777 (14) a	4304 (12) a	5555 (4) b	5779 (19) b	5695 (9) b	5885 (16) a	8147 (7) b	5446 (17)
DINA 70	5314 (9) a	4332 (9) a	8431 (4) a	4628 (17) a	4623 (5) a	6553 (2) a	6838 (12) b	4940 (16) c	7622 (1) a	8694 (3) b	6198 (4)
DINA 556	5638 (6) a	4094 (14) a	7757 (8) a	5500 (4) a	4631 (4) a	3203 (20) d	4730 (20) c	3656 (20) d	4632 (20) a	4380 (20) d	4822 (20)
GO 873	5376 (7) a	4045 (15) a	5730 (20) a	5168 (8) a	4242 (16) a	4226 (15) c	7084 (11) a	5791 (8) b	6229 (8) a	7647 (13) b	5554 (14)
C 411	4620 (16) b	4385 (8) a	7464 (10) a	5399 (6) a	4520 (7) a	5021 (10) b	7748 (5) a	5676 (10) b	6599 (4) a	7848 (12) b	5928 (6)
G-96C	5829 (3) a	4789 (4) a	7884 (6) a	5631 (3) a	5095 (2) a	5354 (7) b	7781 (4) a	6833 (1) a	6068 (12) a	8817 (2) b	6408 (2)
IR-31	4815 (12) b	4899 (3) a	8211 (5) a	4519 (19) a	4303 (13) a	7135 (1) a	6700 (19) d	4240 (19) d	5351 (19) a	8022 (11) b	5820 (8)
DINA 170	5882 (2) a	5231 (2) a	9488 (1) a	5743 (2) a	5627 (1) a	5447 (5) b	8787 (1) a	5962 (5) b	6478 (7) a	10974 (1) a	6962 (1)
C 435	5282 (10) a	4722 (5) a	7207 (16) a	5915 (1) a	4361 (10) a	5229 (9) b	8039 (2) a	6405 (2) a	6108 (11) a	8518 (6) b	6179 (5)
AGROMEN 2005	4940 (11) b	4223 (11) a	7352 (14) a	5037 (9) a	3854 (19) a	4676 (13) c	6561 (16) b	4749 (17) c	5660 (18) a	6219 (18) c	5327 (18)
AG 303	5984 (1) a	3790 (18) a	7105 (17) a	4726 (16) a	4536 (6) a	5231 (8) b	7181 (10) a	5125 (15) c	6923 (2) a	7098 (15) c	5770 (11)
IAC 100B	5337 (8) a	3974 (16) a	5800 (19) a	4439 (20) a	3920 (18) a	3382 (19) d	6061 (18) b	4638 (18) c	5997 (13) a	8099 (9) b	5165 (19)
AG 405	4712 (14) b	3887 (17) a	7408 (13) a	4916 (11) a	4186 (17) a	3951 (17) d	6281 (17) b	5929 (6) b	6223 (9) a	7104 (14) c	5460 (16)
F-test	2.73**	1.70ns	2.32*	1.42ns	1.86ns	11.41**	4.44**	8.85**	1.24ns	5.67**	
Means	5091	4349	7597	5051	4417	4898	7039	5510	6173	7715	5784
CV (%)	12.2	14.9	15.3	12.4	12.5	10.3	10.7	8.0	15.6	12.8	

*P < 0.05, **P < 0.01 (F-test). ns, Nonsignificant (P > 0.05). Measurements followed by the same letter in each column belong to a homogeneous group at the 5% probability level (Scott-Knott (1974) grouping test). Values in parentheses refer to the order of classification of measurements for the genotypes in a given environment. [1]Two locations in the same county.

value, that one which remained among the most productive in a given set of environments. The estimate of P_i could be partitioned into a portion attributed to genetic deviation, that is, the sum of the squares of the genotypes. This would be troublesome to breeder's since it does not necessarily imply alteration in the genotypes ranking or in the portion attributed to genotype x environment interactions. In this case, the cultivars of greatest interest would be those with the lowest P_i values, most of which would be attributed to genetic deviation (Lin and Binns, 1988).

Cultivars 'DINA 170', 'G-96C', 'C 505', 'DINA 70' and 'C 435' had the greatest mean general yields (Table I) and the lowest P_i values, with its most part attributed to the genetic component. The exception was 'DINA 170', which had the greatest part of P_i , that was attributed to the interaction (Table III). However, this genotype contributed only 1.8% of the total value of the interaction (Table III).

Huehn (1990a) proposed that the stability of a cultivar in response to environmental changes could be assessed based on its classification in various environments. Three nonparametric stability measurements ($S_i^{(1)}$, $S_i^{(2)}$ and $S_i^{(3)}$) were proposed such that the i-th cultivar could be considered stable in n environments under analysis if its classifications were similar in all environments, i.e., it would correspond to maximum stability. For a cultivar with maximum stability $S_i^{(1)} = S_i^{(2)} = S_i^{(3)} = 0$.

The χ_s^2 value for the $S_i^{(1)}$ statistic is a measure of the homogeneity of the $S_i^{(1)}$ values of all the cultivars. It was not significant (P = 7.1%), indicating that there was no difference in stability among the genotypes (Table III). The cultivar with the lowest $S_i^{(1)}$ value was 'C 411', followed by 'G-96C', 'C 505', 'C 425' and 'AG 405'; all except 'AG 405' had mean yields above the general mean for the experiment (Tables I and III). On the other hand, 'DINA 170', 'DINA 70', 'C435' and 'IR-31' had mean yields above the general mean but relatively high $S_i^{(1)}$ values and, consequently, showed low stability.

The genotypes $S_i^{(2)}$ were significantly different (P < 0.01). The cultivar stability evaluated by these $S_i^{(2)}$ values coincided with the classification of the cultivar stability given by $S_i^{(1)}$ (Table III). The stability of genotypes based on the estimates of $S_i^{(3)}$ was similar to that estimated by the two previous measures (Table III). According to Huehn

Table II - Joint analysis of variance for the yield (kg/ha) of 20 maize cultivars in 10 environments.

Source of variation	Degrees of freedom	Mean squares
Block/environments	20	1,643,639
Cultivars	19	6,764,587 **
Environments	9	96,971,800 **
Cultivars x environments	171	1,455,783 **
Error	380	577,628

**P < 0.01 (F-test).

Table III - Estimates of the stability parameters proposed by Eberhart and Russell (1966), Lin and Binns (1988) and Huehn (1990a) for grain yield (kg/ha) of 20 maize hybrids evaluated in 10 environments.

Cultivar	Eberhart and Russell (1966)			Lin and Binns (1988)				Huehn (1990a)		
					Deviation		Contribution to interaction (%)			
	β_i	r^2(%)	σ^2_{di}/1000	P_i/10000	Genetic	Interaction		$S_i^{(1)}$	$S_i^{(2)}$	$S_i^{(3)}$
C 505	0.99	91	-15.15	85.26	58.82	26.44	2.95	5.69 (3)	24.04 (4)	3.66 (6)
BR 201	1.20	92	51.31	151.43	134.37	17.06	1.90	6.02 (7)	26.54 (8)	3.70 (7)
U 502	1.28*	86	306.95^^	227.80	174.88	52.92	5.92	7.56 (12)	40.27 (11)	5.83 (16)
HATÃ 1000	1.11	95	-68.78	148.27	129.81	18.46	2.06	5.96 (6)	25.60 (6)	3.77 (8)
AGROMEN 2010	1.09	78	412.90^^	188.14	130.62	57.52	6.44	6.49 (9)	29.82 (9)	4.04 (10)
C 425	1.08	90	50.30	121.92	97.37	24.55	2.74	5.73 (4)	24.04 (4)	3.54 (5)
C 431	0.87	69	431.10^^	234.98	150.29	84.69	9.48	7.87 (15)	43.33 (14)	4.67 (12)
AGROMEN 2012	0.82	71	293.33^	219.17	187.75	31.42	3.51	7.62 (13)	43.21 (13)	4.77 (13)
DINA 70	1.15	79	439.46^^	92.26	70.37	21.89	2.44	8.93 (18)	58.84 (18)	7.39 (19)
DINA 556	0.43**	18	1284.70^^	503.09	328.12	174.97	19.61	10.09 (19)	83.33 (19)	7.82 (20)
GO 873	0.82	76	210.25^	222.33	167.45	54.88	6.14	5.78 (5)	24.93 (5)	3.33 (3)
C 411	1.05	95	-84.29	131.69	105.97	25.72	2.87	4.49 (1)	15.29 (1)	3.18 (2)
G-96C	1.02	91	-11.15	73.40	47.60	25.80	2.88	5.09 (2)	18.94 (2)	3.05 (1)
IR-31	0.95	61	870.66^^	159.90	122.35	37.55	4.19	8.24 (17)	48.99 (17)	6.61 (18)
DINA 170	1.51**	90	246.45^	25.08	8.90	16.18	1.80	7.42 (11)	43.82 (15)	6.42 (17)
C 435	1.02	88	66.73	102.82	72.63	30.19	3.37	6.80 (10)	32.89 (10)	4.18 (11)
AGROMEN 2005	0.81	89	-42.43	264.67	211.50	53.17	5.95	6.04 (8)	25.78 (7)	4.00 (9)
AG 303	0.89	82	123.50	178.74	130.23	48.51	5.43	7.96 (16)	46.49 (16)	5.77 (15)
IAC 100B	0.94	75	353.97^^	293.00	246.22	46.78	5.23	7.78 (14)	43.16 (12)	4.83 (14)
AG 405	0.97	90	-14.51	228.52	185.11	43.41	4.86	5.73 (4)	23.07 (3)	3.53 (4)
Total								29.93ns	45.28+	

*P < 0.05, **P < 0.01 (*t*-test) for the hypothesis $\beta_i = 1$. $^+$P < 0.01 and ns, nonsignificant (χ^2 test). ^P < 0.05, ^^P < 0.01 (F-test).

(1990a,b) $S_i^{(1)}$ and $S_i^{(2)}$ are functions only of the stability measurements whereas the numerical value of $S_i^{(3)}$ is determined by yield and stability simultaneously.

The correlation among the adaptability or stability estimates of the different models may indicate if more estimates should be obtained to improve confidence in the prediction of cultivar behavior. The Spearman's rank correlation between the β_i regression coefficient and the superiority index (P_i) was negative and significant ($P < 0.01$). This estimate indicates that more responsive genotypes tended to have lower P_i values. Similar results were obtained in barley (*Hordeum vulgare*) (Lin and Binns, 1988), timothy (*Phleum pratense* L.) (Helgadóttir and Kristjánsdóttir, 1991) and cotton (*Gossypium hirsutum*) (Farias *et al*., 1995, 1997). P_i did not correlate with $S_i^{(2)}$, $S_i^{(3)}$ or σ^2_{di}, but P_i did correlate positively and significantly with $S_i^{(1)}$ (Table IV). The presence of a correlation between P_i and $S_i^{(1)}$ seems to indicate that superior genotypes (with lower P_i) could also be stable (with lower $S_i^{(1)}$). According to Huehn (1990a,b), $S_i^{(1)}$ is a function only of the stability measurement using corrected data, i.e., if one wants to estimate the phenotypic stability independent from yield level effects.

The stability parameters $S_i^{(1)}$, $S_i^{(2)}$, $S_i^{(3)}$ and σ^2_{di} were positively and significantly correlated ($P < 0.01$), indicating that the four measures were similar in classifying the genotypes according to their stability under different environmental conditions (Table IV). Consequently, only one of these parameters would be sufficient to select the stable genotypes in a breeding program. Similar results were obtained in the common bean (*Phaseolus vulgaris* L.) (Miranda 1993), corn (*Zea mays* L.) (Veronesi, 1995), soybean (*Glycine max* (L.) Merrill) (Yue *et al*., 1997) and popcorn (*Zea mays* L.) (Vendrúscolo, 1998). Parameters $S_i^{(1)}$ and $S_i^{(2)}$ are measurements of stability alone. They are strongly intercorrelated with each other even in the case of using the uncorrected yield data x_{ij}. But, if one adjusts the x_{ij} by the genotype effects, i.e., using the corrected values x_{ij}^*, then all the nonparametric measures $S_i^{(1)}$ - $S_i^{(3)}$ are nearly perfectly correlated among each other - including $S_i^{(3)}$ (Huehn, 1990a).

The nonparametric stability measurements $S_i^{(1)}$, $S_i^{(2)}$ and $S_i^{(3)}$ do not require any assumptions about the normality of the distribution and variance homogeneity. The interaction concepts of the classification they represent are strongly related to that of selection in which breeders are interested, i.e., whether the best cultivar in one environment is also the best in other environments. In conclusion, nonparametric stability measurements seem to be useful alternatives to parametric measurements (Yue *et al*., 1997), although they do not supply information about genotype adaptability. Miranda (1993) suggested that $S_i^{(1)}$ and $S_i^{(2)}$ are easier to apply and interpret than $S_i^{(3)}$.

Table IV - Spearman's coefficients of linear correlation among parameters of the Eberhart and Russell's (1966), Lin and Binns' (1988), and Huehn's (1990a) models, for 20 maize hybrids evaluated in 10 environments.

	β_i(ER)[1]	$S_i^{(1)}$(H)[1]	$S_i^{(2)}$(H)	$S_i^{(3)}$(H)	σ^2_{di}(ER)
P_i (LB)[1]	-0.63**	0.37*	0.23	0.22	0.33
$S_i^{(1)}$(H)			0.98**	0.94**	0.85**
$S_i^{(2)}$(H)				0.96**	0.83**
$S_i^{(3)}$(H)					0.78**

[1]ER = Eberhart and Russell; LB = Lin and Binns; H = Huehn. *$P < 0.05$, **$P < 0.01$.

ACKNOWLEDGMENTS

The authors thank Embrapa - CNPMS for allowing the use of the experimental data.

RESUMO

O conhecimento sobre a estabilidade e adaptabilidade de comportamento de genótipos contém informações muito úteis para a recomendação de cultivares para condições de cultivo conhecidas *a priori*, de modo que a avaliação da resposta dos genótipos às variações ambientais deve ser etapa obrigatória em programas de melhoramento. Para caracterizar 20 cultivares de milho, foram realizados dez ensaios (oito localidades do Estado de Minas Gerais, em dois anos) no delineamento de blocos ao acaso, pelo Centro Nacional de Pesquisa de Milho e Sorgo (CNPMS) da Empresa Brasileira de Pesquisa Agropecuária (Embrapa). Três procedimentos estatísticos foram adotados para a análise da estabilidade e adaptabilidade dos cultivares e avaliou-se o grau de associação entre os parâmetros dos três métodos por meio da correlação classificatória de Spearman. 'DINA 170', 'G-96C', 'C 505', 'DINA 70' e 'C 435' destacaram-se com produtividades médias superiores a 6.000 kg/ha. O coeficiente de regressão (β_i) de Eberhart e Russell foi negativo e significativamente correlacionado ($P < 0,01$) com o índice de superioridade (P_i) de Lin e Binns, indicando que os cultivares mais responsivos tenderam a apresentar menor P_i. P_i não se correlacionou com as medidas não-paramétricas $S_i^{(2)}$ e $S_i^{(3)}$ de Huehn e com σ^2_{di} de Eberhart e Russell ($P \geq 0,05$), mas correlacionou-se positiva e significativamente com $S_i^{(1)}$ ($P < 0,05$), indicando que genótipos mais produtivos e responsivos (com menor P_i) também podem ser estáveis (com menor $S_i^{(1)}$), embora tal situação não seja comumente observada na literatura. Huehn afirma que as estimativas de $S_i^{(1)}$ indicam somente estabilidade, quando os dados são corrigidos. Os parâmetros de estabilidade $S_i^{(1)}$, $S_i^{(2)}$, $S_i^{(3)}$ e σ^2_{di} correlacionaram-se positiva e significativamente entre si ($P < 0,01$), indicando que as estimativas de estabilidade do modelo não-paramétrico de Huehn não acrescentaram maiores informações, além das obtidas pelo método de Eberhart e Russell, ao mesmo tempo que mostram que estimativas de estabilidade de modelos não-paramétricos são alternativas úteis às estimativas de modelos paramétricos. 'DINA 170', com maior média geral, caracterizou-se como um cultivar adaptado para ambientes favoráveis e permaneceu entre os mais produtivos no conjunto de ambientes avaliados. 'G-96C' comportou-se como um cultivar de média adaptação a todos os ambientes (cultivar ideal) e estável, enquanto 'C 505' e 'C 435' podem ser considerados alternativos para a 'G-96C'. 'DINA 70', também de adaptabilidade geral, caracterizou-se como de baixa estabilidade.

REFERENCES

Allard, R.W. and **Bradshaw, A.D.** (1964). Implications of genotype-environmental interactions in applied plant breeding. *Crop Sci. 4*: 503-507.

Becker, H.C. and **Léon, J.** (1988). Stability analysis in plant breeding. *Plant Breed. 101*: 1-23.

Crossa, J. (1990). Statistical analysis of multilocation trials. *Adv. Agron. 44*: 55-85.

Duarte, J.B. and **Zimmermann, M.J.** (1995). Correlation among yield stability parameters in common bean. *Crop Sci. 35*: 905-912.

Eberhart, S.A. and **Russell, W.A.** (1966). Stability parameters for comparing varieties. *Crop Sci. 6*: 36-40.

Farias, F.J.C., Ramalho, M.A.P., Carvalho, L.P., Moreira, J.A.N. and **Costa, J.N.** (1995). Comparação entre métodos de avaliação de estabilidade para rendimento em cultivares de algodoeiro herbáceo. *Ciênc. Prát. 19*: 252-255.

Farias, F.J.C., Ramalho, M.A.P., Carvalho, L.P., Moreira, J.A.N. and **Costa, J.N.** (1997). Parâmetros de estabilidade propostos por Lin e Binns (1988) comparados com o método da regressão. *Pesqui. Agropecu. Bras. 32*: 407-414.

Helgadóttir, A. and **Kristjánsdóttir, T.** (1991). Simple approach to the analysis of G x E interactions in a multilocational spaced plant trial with timothy. *Euphytica 54*: 65-73.

Hildebrand, P.E. (1990). Modified stability analysis and on-farm research to breed specific adaptability for ecological diversity. In: *Genotype-By-Environment Interaction and Plant Breeding* (Kang, M.S., ed.). Louisana State, Baton Rouge, pp. 169-180.

Hopkins, A.A., Vogel, K.P., Moore, K.J., Johnson, K.D. and **Carlson, I.T.** (1995). Genotype effects and genotype by environment interactions for traits of elite switchgrass populations. *Crop Sci. 35*: 125-132.

Huehn, M. (1990a). Nonparametric measures of phenotypic stability. Part 1: Theory. *Euphytica 47*: 189-194.

Huehn, M. (1990b). Nonparametric measures of phenotypic stability. Part 2: Applications. *Euphytica 47*: 195-201.

Hühn, M. and **Nassar, R.** (1989). On tests of significance for nonparametric measures of phenotypic stability. *Biometrics 45*: 997-1000.

Lin, C.S. and **Binns, M.R.** (1988). A superiority measure of cultivar performance for cultivar x location data. *Can. J. Plant Sci. 68*: 193-198.

Miranda, G.V. (1993). Comparação de avaliação da adaptabilidade e estabilidade de comportamento de cultivares: exemplo com a cultura do feijão (*Phaseolus vulgaris* L.). Master's thesis, UFV, Viçosa, MG.

Nassar, R. and **Hühn, M.** (1987). Studies on estimation of phenotypic stability: tests of significance for nonparametric measures of phenotypic stability. *Biometrics 43*: 45-53.

Scott, A.J. and **Knott, M.** (1974). A cluster analysis methods for grouping means in the analysis of variance. *Biometrics 30*: 507-512.

Steel, R.G.D. and **Torrie, J.H.** (1980). *Principles and Procedures of Statistics*. McGraw Hill Book Company, New York.

Tai, G.C.C. (1971). Genotypic stability analysis and its application to potato regional trials. *Crop Sci. 11*: 184-190.

Vendrúsculo, E. (1998). Comparação de métodos e avaliação da adaptabilidade e estabilidade de genótipos de milho pipoca na região Centro-Sul do Brasil. Master's thesis, UEM, Maringá, PR.

Veronesi, J.A. (1995). Comparação de métodos e avaliação da adaptabilidade e estabilidade de comportamento de vinte genótipos de milho (*Zea mays* L.) em dez ambientes do Estado de Minas Gerais. Master's thesis, UFV, Viçosa, MG.

Yue, G.L., Roozeboom, K.L., Schapaugh Jr., W.T. and **Liang, G.H.** (1997). Evaluation of soybean cultivars using parametric and nonparametric stability estimates. *Plant Breed. 116*: 271-275.

(Received March 16, 1999)