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Statistical methods to study adaptability and stability in breeding lines of food-type soybeans

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ABSTRACT: The grains of food-type soybean cultivars, which are characterized by the absence of lipoxygenases and the presence of high levels of proteins and isoflavones, are regarded as functional foods with high acceptance by consumers. However, few cultivars of food-type soybeans are currently available in the Brazilian market. The aim of this work was to study the adaptability and stability of various genotypes of food-type soybeans and to compare the performance of methods, which are based on analysis of variance, non-parametric, regression, multivariate and mixed models. Ten lines of food-type soybeans obtained from the Breeding Program of Soybeans for Human Consumption of the State University of Londrina (UEL/BPSHC) and two commercial varieties, the food-type cultivar BRS 257 and the cultivar BMX Potência RR, were evaluated in the counties of Londrina, Guarapuava, Ponta Grossa and Pato Branco, Paraná, Brazil, during the two sowing seasons of the harvest of 2014/2015. The characteristic evaluated was grain yield. The adaptability parameters of Eberhart and Russel and Cruz methods showed high correlations with the Wricke model. The parameters provided by the analyses of Lins and Binns and REML/BLUP showed higher grain yield associations and moderated correlations with the Eskridge parameters. The AMMI offered the possibility of use in conjunction with the other methodologies. When yield, adaptability and stability were considered, the genotypes UEL 110, UEL 122, UEL 121 and UEL 123 demonstrated potential for the development of new cultivars of food-type soybeans in which lipoxygenases are absent.

Key words: *Glycine max*, yield, non-parametric, regression, multivariate, mixed models.

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INTRODUCTION

The soybean (*Glycine max* (L.) Merrill) is recognized by the U.S. *Food and Drug Administration* (FDA) as a functional food. Containing approximately 40% protein with a balanced proportion of amino acids that are essential to the human diet, soy protein can reasonably replace protein from meat and dairy products (Day 2013). In addition, soybeans are rich in minerals, vitamins and isoflavones, and the latter are associated with the prevention or reduced incidence of several chronic degenerative diseases (Rimbach et al. 2008) and display oestrogenic and antioxidant activities (Liu et al. 2010).

Despite the clear benefits of soybeans and their derivatives consumption, less than 5% of the soybean crop produced is intended for human consumption (Hirakuri and Lazarotto 2014). This is in part due to its unpleasant flavor, known as *beany flavor*, which results from the action of lipoxygenase enzymes (LOXs) (Silva et al. 2012). Consequently, the genetic elimination of LOXs improves the sensory characteristics of soybean foods due to the lower production of hexanal compounds. Genotypes considered triple null (those that display a total absence of LOXs in grains) can be classified as food type and offer special features for human consumption (Silva et al. 2012).

According to the Ministério da Agricultura, Pecuária e Abastecimento (MAPA) data, only 15 food-type soybean cultivars have been recorded, whereas 1524 grain-type cultivars have been recorded (MAPA 2016). Therefore, the expansion of food-type soybean agribusiness depends on the development of breeding programmes that aim to develop genotypes with high agronomic value (Destro et al. 2013; Freiria et al. 2016).

For the commercial release of new cultivars, it is necessary to study various genotypes performances in different cultivation regions to control the interaction of plant genotype with the environment (GE). To minimize the effects of the GE interaction, it is necessary to analyze the adaptability and stability of each cultivar so as to identify genotypes with predictable behavior that are responsive to environmental variations under both specific and general conditions (Cruz et al. 2004).

Several methods to study the adaptability and stability of plant cultivars have been described. These methods are based on analysis of variance (Plaisted and Peterson 1959; Wricke 1965; Annicchiarico 1992) or on non-parametric (Lin and Binns 1988; Huenh 1990), regression (Finlay and Wilkinson 1963; Eberhart and Russell 1966; Tai 1971; Verma et al. 1978; Cruz et al. 1989; Storck and Vencovsky 1994), multivariate analysis (Zobel et al. 1988; Crossa 1990; Yan et al. 2000; Nascimento et al. 2013) or mixed models (Resende 2004).

The choice of method for assessing adaptability and stability is linked to the number of available environments as well as to the type of information and the level of experimental precision required (Cruz et al. 2004). With this in mind, several studies of soybean crops (Silva and Duarte 2006), beans (Pereira et al. 2009), corn (Scapim et al. 2010) and cotton (Silva Filho et al. 2008) have been conducted to identify the best methods of assessing these parameters, as well as their combinations, with the purpose of increasing the available precision for the selection and/or indication of the best genotypes.

The aim of this work was to study the adaptability and stability of various genotypes of food-type soybeans and to compare the performance of methods, which are based on analysis of variance, non-parametric, regression, multivariate and mixed models.

MATERIAL AND METHODS

Twelve soybean genotypes, including 10 lines from the Breeding Program of Soybeans for Human Consumption of the State University of Londrina (UEL/BPSHC) and two commercial varieties (Table 1), were evaluated. The genotypes were sown in the counties of Londrina, Guarapuava, Ponta Grossa and Pato Branco, Paraná, Brazil, during the harvest of 2014/2015 in two seasons of sowing, totalling eight environments (Table 2).

The experimental plants were installed mechanically using a plot seeder in four lines (with five metres long spaced 0.45 m from each other, with 13 to 16 plants per metre) in a complete random block design with four replications. The seeds were treated with Vitavax-Thiram® (carboxanilide and dimethyldithiocarbamate) at a concentration of 250 mL per 100 kg of seeds and inoculated at the time of sowing with strains of *Bradyhizobium japonicum* and *B. elkanii* at a concentration of 10^9 viable cells per mL. A no-tillage management system was used.

The harvest was performed manually after the R8 stage of development, when 95% of the pods displayed →

Table 1. Morphological and chemical properties of 12 evaluated soybean genotypes.

Lines/Cultivars	Grow type	Seed coat color	Hilum color	Weight of 100 grains*	Oil* (%)	Protein* (%)	Isoflavones[1]* ($mg \cdot 100g^{-1}$)	Lipoxygenases[2]
UEL 101	Indeterminate	Yellow	Black	13.36	19.85	40.88	131.36	Null
UEL 110	Determined	Yellow	Yellow	15.20	22.02	38.76	222.34	Null
UEL 112	Indeterminate	Yellow	Yellow	12.83	20.78	39.64	147.10	Null
UEL 113	Indeterminate	Yellow	Yellow	13.71	20.93	39.19	164.80	Null
UEL 114	Determined	Yellow	Brown	13.50	22.15	38.40	162.76	Null
UEL 115	Indeterminate	Yellow	Brown	13.26	22.49	38.75	168.89	Null
UEL 121	Indeterminate	Yellow	Brown	12.95	21.38	38.79	213.91	Null
UEL 122	Indeterminate	Yellow	Brown	12.92	21.11	39.78	214.04	Null
UEL 123	Indeterminate	Yellow	Brown	14.11	21.86	39.12	184.63	Null
UEL 153	Determined	Yellow	Brown	12.06	19.87	40.32	276.37	Null
BRS 257	Determined	Yellow	Brown	14.66	20.34	41.15	278.61	Null
BMX Potência	Indeterminate	Yellow	Brown	12.06	-----	-----	-----	Presence

[1]Sum of chemical forms aglycones. 7-O-β-D-glycosides. 6 ‘-O- malonyl -7-O-β-D-glycosides and 6 “-O-acetyl-7-O-β-D-glycosides; [2] Null: represents total absence of lipoxygenases enzymes in grains; and Presence: represents lipoxygenases enzymes in the presence; *Mean obtained in two seasons of seeding in the municipality of Londrina in 2013/2014.

Table 2. Location and climatic characterization of eight environments in the State of Paraná.

Environments	Counties	Sowing	Altitude (m)	Latitude (S)	Longitude (W)	Regions[1]	Climate[2]
1	Londrina	07 October	576	23º 21’	51º 09’	201	Cfa
2	Guarapuava	15 October	1120	25º 23’	52º 27’	102	Cfb
3	Ponta Grossa	16 October	880	25º 13’	50º 01’	103	Cfb
4	Pato Branco	14 October	760	26º 11’	52º 42’	102	Cfa
5	Londrina	04 December	576	23º 21’	51º 09’	201	Cfa
6	Guarapuava	05 November	1120	25º 23’	52º 27’	102	Cfb
7	Ponta Grossa	03 November	880	25º 13’	50º 01’	103	Cfb
8	Pato Branco	12 November	760	26º 11’	52º 42’	102	Cfa

[1]Edaphoclimatic regions, second Kaster and Farias (2012);[2]According to Köppen-Geifer.

the typical colouring of mature pods (Fehr and Caviness 1977). The two outer lines of the plot, as well as plants within 0.5 m of each end of the centre line, were removed, yielding a useful area of 3.6 m^2. The evaluated characteristic was grain yield ($t \cdot ha^{-1}$), corrected to 13% humidity.

Initially, an individual analysis of variance was performed. After verifying the magnitudes of the residual mean squares, a joint analysis of variance was performed. The effects of genotypes were considered fixed, and those related to the environment were considered random.

The analysis of adaptability and stability was performed using the methods of Wricke (1965), Eberhart and Russell (1966), Lin and Binns (1988), Cruz et al. (1989), Eskridge (1990), Zobel et al. (1988) and Resende (2007).

The statistical stability of the Wricke (1965) method, called ecovalence (ϖ_i) was estimated according to the equation:

$$\varpi_i = \sum_{j-1}^{n} (Y_{ij} - Y_i - Y_j + Y_{..})^2 \quad (1)$$

where Y_{ij} is the mean of the genotype i in environment j; Y_i is the mean of the genotype i in all environments; Y_j is the mean of the environment j for all genotypes; and $Y_{..}$ is the overall mean. The cultivars with low ϖ_i values are considered stable, which indicates that these cultivars have smaller deviations in relation to the environment.

The method of Lin and Binns (1988) is estimated by:

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

where P_i is the estimation of the stability parameter of the cultivar i; X_{ij} is the grain yield of the ith cultivar in the j^{th} environment; M_j is the maximum response observed among all the cultivars in environment j; n is the number of environments. The decomposition of this estimator (P_i) was performed and divides in favorable (P_{if}) and unfavorable (P_{id}) environments.

The mathematical models for the methods of Cruz et al. (1989) and Eberhart and Russell (1966) are similar. The difference is in the introduction of the regression coefficient in unfavorable environments proposed by the model of Cruz et al. (1989), forming two straight segments. The mathematical model in the bissegmented method of Cruz et al. (1989) is estimated by:

$$Y_{ij} = \beta_{0i} + \beta_{1i} I_j + \beta_{2i} T(I_j) + \delta_{ij} + \varepsilon_{ij} \quad (3)$$

where β_{0i} = general mean of genotype i (i = 1.2, ..., g); β_{1i} = linear response of the genotype i to environmental variation; I_j = environmental index (j = 1.2,...,); δ_{ij} = deviation of regression; ε_{ij} = mean experimental error. $T(I_j)$ = 0, if $I_j < 0$ and equal to $I_j + I$ + If $I_j > 0$, being I+ corresponds to the mean of the indexes I_j positive. The model of Eberhart and Russell (1966) is explained by: $Y_{ij} = \beta_{10i} + \beta_i I_j + \delta_{ij} + \varepsilon_j$. The hypotheses (($H_0$: β_{1i} = 1) and (H_0: $\beta_{1i} + \beta_{2i}$) = 1) were tested by the test $t_{\alpha,\, m}$, where α is the level of significance, and m the degrees of freedom of the residue.

The methodology proposed by Eskridge (1990) is based on the compounds estimation of safety first, as an adaptation of the model proposed by Kataoka (1963) for risks financial operations. The parameters were EV, FW, SH and ER, estimated with the inclusion of the following variance compounds: variance between environments ($\hat{S}^2_{xi}$) in EV; the Finlay and Wilkinson linear regression coefficient ($\hat{\beta}_{1i}$) in FW; the Shukla variance ($\hat{\sigma}_i$) in SH; and the Finlay and Wilkinson linear regression coefficient ($\hat{\beta}_{1i}$) plus the deviations variance of the Eberhart and Russel linear regression ($\hat{\delta}_{ji}$) in ER.

For the use of the method AMMI (Zobel et al. 1988), the model applied was:

$$Y_{ij} = \mu + g_i + a_j + \sum_{k=1}^{n} \lambda_k \, \gamma_{ik} \, \alpha_{jk} + \\ + \rho_{ij} + \varepsilon_{ij} \quad (4)$$

where Y_{ij} is the mean response of genotype i (i = 1, 2, ..., G genotypes) in the environment j (j = 1, 2, ..., E environments); μ is the mean of the treatments; g_i is the fixed effect of genotype i; a_j is the fixed effect of the environment j; λ_k is the k^{th} singular value (scalar) of the original interaction matrix (denoted by GE); γ_{ik} is the element corresponding to the i^{th} genotype, in the k^{th} singular vector of each column in the matrix GE; a_{jk} is the element corresponding to the j^{th} environment in the k^{th} singular vector line of the matrix GE; ρ_{ij} is the residue associated with the term (gEij of the classical interaction of genotype i with the environment j; ε_{ij} is the experimental error.

In the REML/BLUP analysis (Resende 2007) was used the statistical model for genetic evaluation for higher values of the harmonic mean of the genotypic values:

$$Y = Xr + Zg + Wi + e \quad (5)$$

where Y is the vector of observations (phenotypic values), r is the vector of the local-repetition combinations effects added to the general mean, g is the vector of the genotypic effects, i is the vector of the interaction genotypes *vs.* environments effects, being e the error vector. The uppercase letters represent the incidence matrices for these effects.

In the REML/BLUP analysis, the selection by the highest values of the harmonic mean of the genotypic values (MHVG) has a simultaneous effect in the selection for grain yield and stability. The adaptability refers to the relative performance of the genotypic values (PRVG) according to the environment. The simultaneous selection for yield, stability and adaptability can be performed by the method of the harmonic mean of the relative performance of the genetic values (MHPRVG).

Spearman's correlation coefficient was used to verify similarities and differences between the parameters of adaptability and stability estimates obtained using different methods, and the significance of the differences was verified by Student's t-test. For the AMMI analysis was considered the weighted average of the absolute scores (MPEA) of the first two principal components for each genotype, weighted by the percentage of variance explained by each component.

The analyses were performed with the aid of the following programs: Genes (Cruz 2016), Selegen (Resende 2016) and R (R Development Core Team 2012) using the agricolae package.

RESULTS AND DISCUSSION

The joint analysis of variance indicated that the sources of variation (genotype - G, environment - E, and the interaction GE) were significant ($p \leq 0.01$). This allowed us to infer that the environments evaluated were distinct and the genotypes presented differentiated performance in response to environmental variations (Table 3). The general mean grain yield was 2.38 t.ha^{-1}; in the environments tested, the value of this parameter ranged from 1.51 to 3.05 t.ha^{-1}.

In the AMMI analysis, the first principal axis (IPCA 1) accounted for 31.80% of the pattern associated with the GE interaction. In addition to the IPCA 2, the accumulated was 60.70%. When the contribution of the other axes was considered, significance ($p < 0.01$) was observed in the IPCA 3 and IPCA 4.

Maia et al. (2006) and Yokomizo et al. (2013) analysed the adaptability and stability of soybean genotypes and found that the values of the first two axes explained the range of 53 to 58 % of the variance in SS_{GE}. According to Oliveira et al. (2003) and Gauch Jr. (2013), as the number of axes selected increases, the percentage of "noise" also increases, reducing the predictive power of the AMMI analysis, i.e., the excessive inclusion of multiplicative terms can reduce the accuracy of the analysis. Therefore, only the IPCA 1 and IPCA 2 axes were considered in the AMMI analysis.

The genotypes or environments with points near the origin of the coordinate system of the biplot graphic are considered more stable (Duarte and Vencovsky 1999). The AMMI biplot 1 (mean of grain yield *vs.* IPCA 1) (Figure 1) showed that the most stable genotypes were BRS 257, UEL 114, UEL 101, UEL 122 and UEL 123. Among these, the most prominent lines were UEL 122 and UEL 123, both of which showed yields above the overall average. Thus, these lines demonstrated general adaptability in both sowing seasons, but with higher responses when sown in the county of Guarapuava.

The use of an AMMI biplot 2 (IPCA 1 *vs.* IPCA 2) (Figure 1) permits correction for possible distortions in the analysis or interpretation produced using a single dimension (Yokomizo et al. 2013). In general, the genotypic behavior presented confirmed the previous analysis and indicated that the genotypes of lines UEL 110, UEL 153, UEL 115 and UEL 121 are stable. The cultivar BMX Potência RR and the lines UEL 112 and UEL 113 were classified as being of low stability and specifically adapted to the counties of Londrina and Ponta Grossa in the first sowing season and to the county of Ponta Grossa in the second season.

By analyzing the environments, the counties of Ponta Grossa and Londrina were found to be the main contributors to the GE interaction in both sowing seasons, with higher environmental scores in the interaction axis when the →

Table 3. Analysis of variance for grain yield of 12 genotypes of soybean food type, including the participation of the interaction genotype *vs.* environment (GE) according to the main additive effect and multiplicative interaction (AMMI) in eight environments in the Paraná State.

Source of variation	Degrees of freedom	Mean Square	Principal components (IPCA)	
			% explained	% accumulated
Block/Environment	24	0.1807		
Environment (E)	7	13.4199**		
Genotypes (G)	11	2.0203**		
G x E	77	0.3452**		
IPCA1	17	0.4977**	31.80	31.80
IPCA2	15	0.5117**	28.90	60.70
IPCA3	13	0.3272**	16.00	76.70
IPCA4	11	0.3313**	13.70	90.40
IPCA5	9	0.1496	5.10	95.50
Error	264	0.0839		
Variation coefficient (%)		12.17		
Means (t·ha^{-1})		2.38		

**Significant at 1% probability, by F.-test

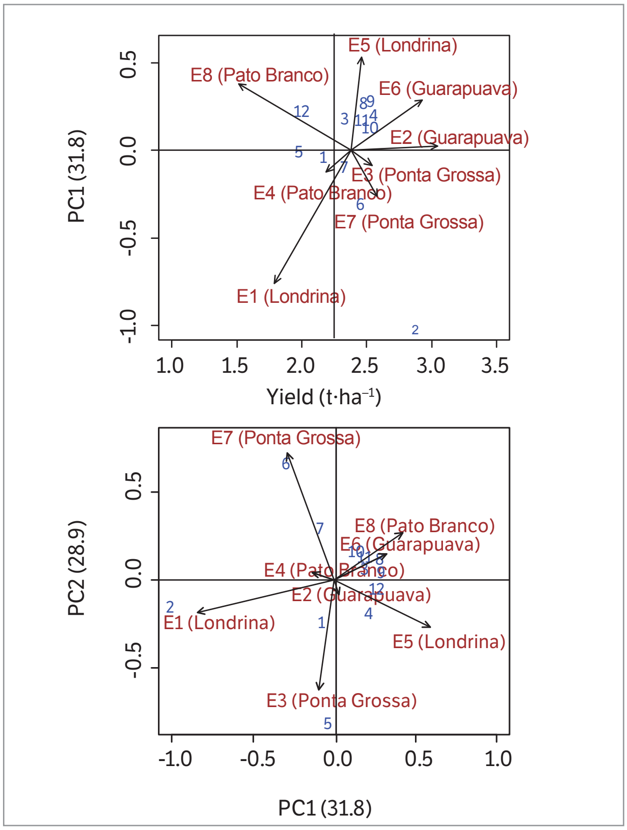


Figure 1. Biplot AMMI to yield of grain data of food type soybeans, with 12 soybean genotypes (1: BRS 257; 2: Potência; 3: UEL 101; 4: UEL 110; 5: UEL 112; 6: UEL 113; 7: UEL 114; 8: UEL 115; 9: UEL 121; 10: UEL: 122; 11: UEL 123; 12: UEL 153) and eight environments in the Paraná State, 2014/2015.

AMMI 2 was considered. According to Oliveira et al. (2003), environmental stability contributes to the reliability of genotype ordering in test environments in relation to the classification for the average of the tested environments. Our results did not correspond to those obtained using the environmental indices proposed by Cruz et al. (1989) and Lin and Binns (1988). In those indices, the counties considered unfavorable were Pato Branco (both sowing seasons) and Londrina (first sowing season).

The environmental index is a measure of environmental quality that allows classification of favorable or unfavorable environments. However, in the case of grain yield, the strongest criticism to the use of this criterion relates to the association of the environmental index (independent variable in the regression) with the dependent variable (Maia et al. 2006).

It was verified by the Wricke methodology (Table 4) that the UEL 153, UEL 114, UEL 101, UEL 121 and UEL 110 lines, which are considered the most stable lines, displayed the lowest ecovalence (ϖi) values. However, the genotypes BMX Potência RR, UEL 112 and UEL 113 were the most unstable in the face of environmental changes, and these results were concordant with the results of the AMMI analysis.

In the methodology proposed by Eberhart and Russell (1966), it was observed that the UEL 101 line and the BRS

Table 4. Estimates of the parameters of adaptability and phenotypic stability, obtained by methods of Wricke (1965) (Ecovalence-ϖ_i), Lin and Binns (1988), Eberhart and Russell (1966) and Cruz et al. (1989), for the character of grain yield in 12 soybean genotypes in eight environments in the State of Paraná, 2014/2015.

Genotypes	Grain Yield (t·ha^{-1})	Ecovalence (ϖ_i)	Lin & Binns (1988)			Eberhart and Russel			Cruz, Torres and Vencovsky			
			P_i	P_{if}	P_{id}	β_{1i}	δ^2_{di}	R^2 (%)	β_{1i}	$\beta_{1i} + \beta_{2i}$	δ^2_{di}	R^2 (%)
UEL 101	2.324	1.00	0.35	0.28	0.51	0.7529*	0.0008^{NS}	89.46	0.7230*	0.9416^{NS}	0.0958^{NS}	90.35
UEL 110	2.539	1.31	0.21	0.08	0.35	1.0236^{NS}	0.0338*	86.19	1.0922^{NS}	0.5903^{NS}	0.2163*	88.63
UEL 112	1.970	4.65	0.70	0.62	1.00	1.1506^{NS}	0.1654**	69.85	1.1688^{NS}	1.0358^{NS}	0.8914**	69.96
UEL 113	2.441	3.25	0.27	0.22	0.46	0.9684^{NS}	0.1142**	69.35	0.9326^{NS}	1.1947^{NS}	0.6362**	69.96
UEL 114	2.321	0.98	0.33	0.25	0.51	1.0042^{NS}	0.0200^{NS}	88.91	1.0159^{NS}	0.9302^{NS}	0.1956*	88.99
UEL 115	2.469	1.96	0.29	0.23	0.47	0.8165^{NS}	0.0496**	75.50	0.8381^{NS}	0.68022^{NS}	0.3340**	75.84
UEL 121	2.497	1.20	0.24	0.13	0.40	1.1355^{NS}	0.023^{NS}	90.54	1.1511^{NS}	1.0371^{NS}	0.2085*	90.65
UEL 122	2.517	2.49	0.27	0.17	0.43	1.3591**	0.0406**	90.73	1.2268*	2.1949**	0.1224^{NS}	96.16
UEL 123	2.458	1.32	0.24	0.08	0.36	0.9871^{NS}	0.0339*	85.26	0.9924^{NS}	0.9537^{NS}	0.2634*	85.28
UEL 153	1.991	0.69	0.65	0.44	0.84	1.1974^{NS}	-0.0048^{NS}	96.65	1.1805^{NS}	1.3048^{NS}	0.0750^{NS}	96.77
BRS 257	2.159	1.33	0.45	0.39	0.56	0.7947*	0.0207^{NS}	83.18	0.9154^{NS}	0.0323**	0.0558^{NS}	95.30
Potência	2.874	6.38	0.03	0.04	0.01	0.8099^{NS}	0.2333**	45.70	0.7633*	1.1045^{NS}	1.1989**	46.65

^{NS}, * and **: no significant, significant at the level of 5 and 1%, respectively, by the test t (H_0: $\beta_{1i} = 1.0$; and $\beta_{1i} + \beta_{2i} = 0$) and the F-test ($H_0$: $\delta^2_{di} = 0$).

257 cultivar presented values of $\beta_{1i} < 1$; these varieties are therefore considered adapted to unfavorable environments, whereas the UEL 122 line, with $\beta_{1i} > 1$, was considered to be adapted only to favorable environments. The other genotypes were considered to be of wide adaptability. The genotypes considered stable ($\delta^2_{di} = 0$) were UEL 101, UEL 114, UEL 121, UEL 153 and BRS 257 (Table 4).

The parameters of adaptability and stability of Eberhart and Russell (1966) are similar to those used by Cruz et al. (1989). However, the method of Cruz et al. (1989), which considers two regression lines (one for unfavorable environments and other for favorable environments), permitted better conclusions about the behavior of genotypes with respect to front environmental variations. This method considers the ideal genotype one that is less responsive to unfavorable environments ($\beta_1 < 1.0$), responsive to favorable environments ($\beta_1 + \beta_2 > 1.0$), has high stability ($\delta_{ij} = 0$) and has good grain yield. In the studied materials, such a genotype was not identified (Table 4).

The cultivar BMX Potência RR and the line UEL 101 were less responsive in unfavorable environments ($\beta 1i < 1.0$); the remaining genotypes, with the exception of UEL 122, showed average responsiveness in unfavorable environments ($\beta 1i = 1.0$). The UEL 122 line was highly responsive in favorable environments ($\beta 1i + \beta 2i > 1.0$); the remaining genotypes, with the exception of the cultivar BRS 257, displayed wide adaptability to favorable environments ($\beta 1i + \beta 2i = 1.0$). In relation to the stability parameter (δ^2 di), the genotypes that showed regression deviations close to zero and were therefore considered stable were the lines UEL 101, UEL 122 and UEL 153 and the cultivar BRS 257 (Table 4).

Low values of the coefficient of determination (R^2) indicate high dispersion of the data and therefore low reliability in the type of environmental response determined by the regression analysis. However, the relevance of the stability parameter can be minimized under conditions in which the value of R^2 is greater than 80% (Cruz and Carneiro 2003). These conditions were found in the genotypes that presented stability by the methods of Eberhart and Russell (1966) and Cruz et al. (1989).

Unlike the results obtained using the methodologies of Wricke (1965), Eberhart and Russell (1966) and Cruz et al. (1989), the cultivar BMX Potência RR was the genotype with the greatest adaptability and stability when the P_i values obtained by the methodology of Lin and Binns (1988) were considered. This result can be explained by the way in which the P_i statistics are estimated. The method results in cultivars whose grain yields in each environment are close to the maximum, being considered as having greater adaptability and stability (Cruz and Carneiro 2003). In cases involving favorable (P_{if}) and unfavorable (P_{id}) environments, the lowest values were attributed to the genotypes BMX Potência RR, UEL 110, UEL 121 and UEL 123. This indicates that these genotypes show responsiveness to improvement in the environmental conditions and low yield losses in unfavorable environments (Table 4).

In the methodology proposed by Eskridge (1990), the genotypes with higher stability for grain yield were the cultivar BMX Potência RR and the lines UEL 110, UEL 115, UEL 121, UEL 122 and UEL 123, also with the highest values for the parameters EV, FW, SH and ER. Higher estimative from the FW and SH parameters represent a close genotype response to the average of the genotypic group response and higher values of ER indicated high predictability of the genotypes (Table 5).

The REML/BLUP model (Resende 2007) obtained results similar to those founded by the of Lin and Binns (1988) and Eskridge (1990) methods. In this analysis, the cultivar BMX

Table 5. Estimates of the stability parameters obtained by method of Eskridge (1990) for grain yield in 12 soybean genotypes in eight environments in the State of Paraná, 2014/2015.

Genotypes	EV[1]	FW[2]	SH[2]	ER[2]
UEL 153	1.6499	1.9832	0.8372	1.9698
BRS 257	1.9851	2.1512	1.0059	2.1170
Potência	2.5439	2.8667	1.7202	2.6576
UEL 101	2.1791	2.3125	1.1710	2.2946
UEL 110	2.2602	2.5396	1.3859	2.4945
UEL 112	1.5343	1.9656	0.8163	1.8123
UEL 113	2.1308	2.4415	1.2879	2.3304
UEL 114	2.0604	2.3212	1.1674	2.2875
UEL 115	2.2662	2.4625	1.3154	2.4045
UEL 121	2.1695	2.4933	1.3432	2.4572
UEL 122	2.0494	2.4916	1.3638	2.4410
UEL 123	2.1960	2.4588	1.3050	2.4136

[1]EV: Safety-first index with variance across environments as stability parameter; [2]FW: Safety-first index with Finlay and Wilkinson regression coefficient as stability parameter; [3]SH: Safety-first index with Shukla variance as stability parameter; [4]ER: Safety-first index with Finlay and Wilkinson regression coefficient and Eberhart and Russel deviation of linear regression mean square as stability parameters.

Potência RR presented the highest values for MHVG, PRVG and MHPRVG (Table 6). According to Borges et al. (2010), the MHVG values represent the actual amount of grain yield penalized by the instability, which facilitates the selection of the most productive and more stable lines. The MHPRVG values allow simultaneous selection for grain yield, stability and adaptability. In this case, the highest values were observed for the genotypes BMX Potência RR, UEL 110, UEL 121, UEL 122 and UEL 115 (Table 6).

Table 6. Stability of genotypic values (MHVG), adaptability of genotypic values (PRVG), stability and adaptability of genotypic values (MHPRVG) and for grain yield in 12 soybean genotypes in eight environments in the State of Paraná, 2014/2015.

Genotypes	MHVG	PRVG	MHPRVG
UEL 153	1.8167	0.8282	0.8200
BRS 257	2.0594	0.9126	0.9097
Potência	2.7186	1.2144	1.1901
UEL 101	2.2486	0.9873	0.9824
UEL 110	2.4135	1.0671	1.0624
UEL 112	1.7278	0.8187	0.7886
UEL 113	2.314	1.0272	1.0188
UEL 114	2.1901	0.974	0.9710
UEL 115	2.3692	1.0445	1.0373
UEL 121	2.3557	1.0456	1.0412
UEL 122	2.3336	1.0461	1.0398
UEL 123	2.3404	1.0343	1.0302

The possibility of using one or more parameters of stability obtained by different methods for the response prediction of a particular genotype to environmental changes requires the establishment of the level of association between these estimates (Franceschi et al. 2010). Depending on the degree of association, this can be an auxiliary measure in the choice of the stability parameter that results in the best adjustment and provides more essential information to base the concept of stability (Duarte and Zimmermann 1995).

In this work, high positive correlations were found between the ecovalence parameter of Wricke (1965) and the regression deviation of the models of Eberhart and Russell (1966) and Cruz et al. (1989). This result corroborates the results obtained by Cargnelutti Filho et al. (2007) and Paula et al. (2014). According to Pereira et al. (2009), high correlation indicates redundancy in the information provided. Therefore, the regression models recommended by Eberhart and Russell (1966) and/or Cruz et al. (1989) are able to measure the adaptability and stability information provided by the Wricke model with reasonable accuracy and can replace it, as indicated by Silva and Duarte (2006).

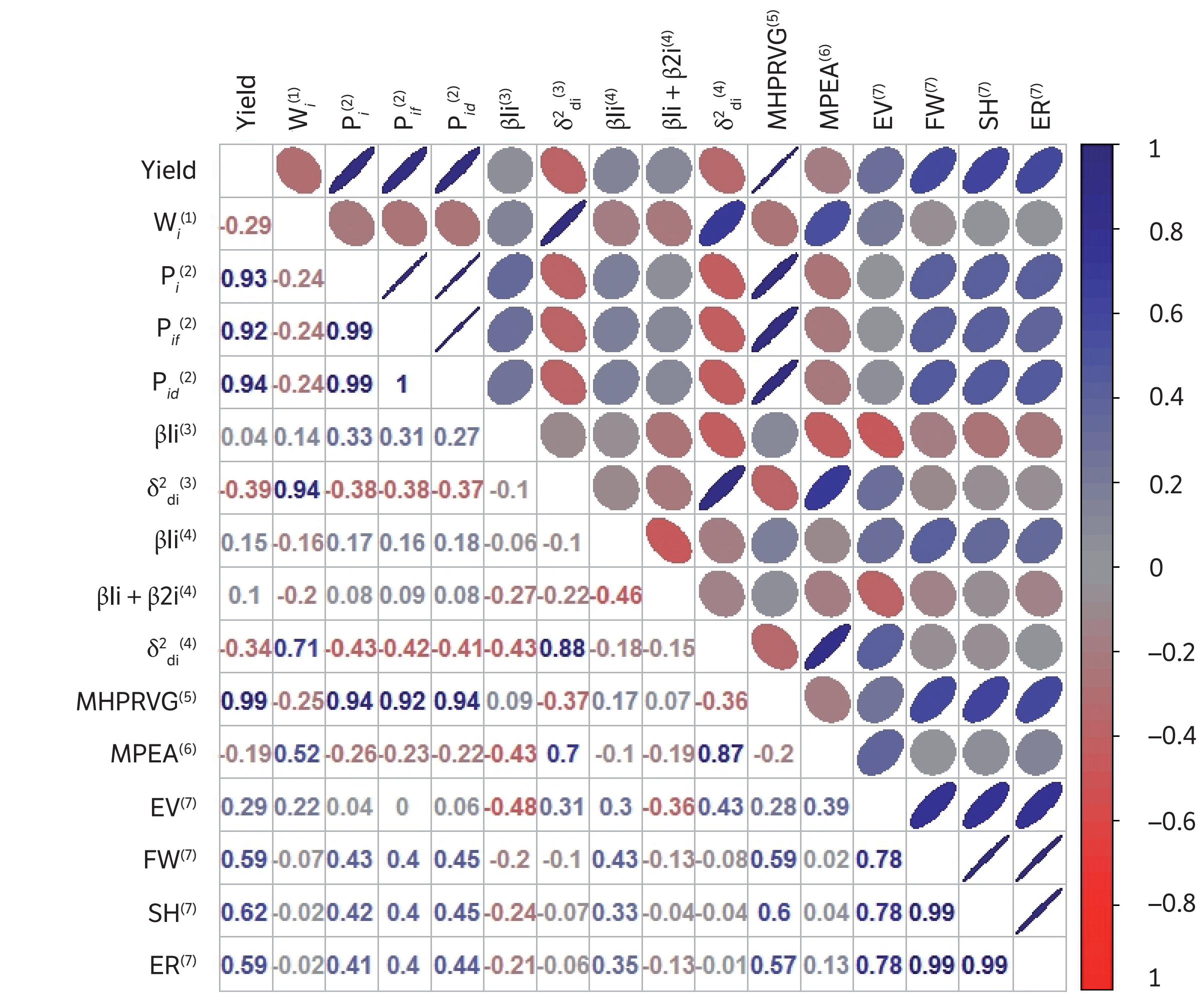
The adaptability parameters of the Eberhart and Russell (1966) and Cruz et al. (1989) methods yielded non-significant correlations and can thus be viewed as complementary, emphasizing the importance of the fractionation of regression in favorable and unfavorable environments. For the stability parameter, a positive correlation of 0.88 between the two models was found, since for both the stability is measured by the regression deviations.

High positive correlations were found among the parameters provided by the Lin and Binns method (1988) and MHPRVG of the REML/BLUP (Resende 2007), a fact that seems to be associated with high participation of grain yield in the substantiation of both models (Figure 2). The methods based on analysis of variance (Wricke 1965), linear regression (Eberhart and Russell 1966) and AMMI (Zobel et al. 1988) presented no correlation with grain yield. Therefore, according to Cruz and Carneiro (2003), in these models special attention should be given to grain yield in addition to adaptability and stability.

The decomposition of the values of P_i in favorable environments (P_{if}) and unfavorable environments (P_{id}) is adopted in several works (Barros et al. 2008). However, there was a high correlation with P_i, demonstrating redundancy of the information transmitted.

The parameters EV, FW, SH and ER by the methodology of Eskridge (1990) showed significant correlations between each other ($p \leq 0.01$), as well as the results observed by Kvitschal et al. (2009). According to Vidigal Filho et al. (2007), the ER parameter appears as the most robust indication for the genotype with higher stability and, therefore, the obtained results could be applied in an isolated form. The parameters FW, SH and ER showed moderated correlations with the grain yield and the methodologies of Lin and Binns (1988) and the MHPRVG parameter of the REML/BLUP model (Resende 2007). Was observed a lower correlation of the parameters FW, SH and ER with the remaining parameters, being promissory the reconciled use of these methodologies.

The weighted mean of the absolute scores obtained by AMMI analysis showed low correlation with other parameters, with the exception of the parameters linked to stability of Eberhart and Russell (1966) and Cruz et al. (1989) (these correlations were 0.7 and 0.87, respectively), similar to Paula et al. (2014).



Parameters obtained by method of [1] Wricke (1965), [2] Lin and Binns (1988) with decomposition in favorable and unfavorable environments, [3] Eberhart and Russell (1966), [4] Cruz et al. (1989), [5] REML/BLUP (Resende 2007), [6] weighted mean of the absolute scores from PC1 and PC2 of AMMI (Zobel et al. 1988), and [7] Eskridge (1990). Only correlations above 0.55 and 0.75 were significant at t student test, at 5% and 1% of significance, respectively.

Figure 2. Spearman correlation for the adaptability and stability parameters of each pair of methods and grain yield ($t.ha^{-1}$).

Based on the methods of Wricke (1965), Eberhart and Russell (1966) and Cruz et al. (1989), the genotypes UEL 114, UEL 121 and UEL 153 were indicated as being of wide adaptability and stable. On the other hand, in the analysis of Lin and Binns (1988), Eskridge (1990) and REML/BLUP (Resende 2007), the genotypes classified as stable and adaptable were the cultivar BMX Potência RR and the lines UEL 110, UEL 121, UEL 122 and UEL 123. In the AMMI analysis, most of the genotypes, with the exception of UEL 113, UEL 112 and BMX Potência RR, possessed wide stability. Considering grain yield together with adaptability and stability, the genotypes UEL 110, UEL 122, UEL 121 and UEL 123 appear to offer potential for the development of new cultivars of food-type soybean varieties in which lipoxygenases are absent.

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