Repeatability of associations between analytical methods of adaptability, stability, and productivity in soybean

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Abstract – The objective of this work was to evaluate the association between estimates of adaptability, stability, and productivity in soybean (*Glycine max*), and to estimate the repeatability coefficient of these associations between years. A total of 22 genotypes were evaluated in 27 environments in the 2012/2013 crop season and in 19 environments in 2013/2014. In the next crop seasons, 28 genotypes were evaluated in 26 environments, in 2014/2015, and in 25 environments in 2015/2016, totalizing 97 trials. Fourteen methods were evaluated; Spearman correlation coefficients were obtained for the parameters of stability, adaptability, and productivity; and the repeatability coefficients, as well as the minimum number of required environments for a coefficient of determination of 80 and 90%, were calculated. The minimum number of environments required to estimate the degree of association between the parameters was low (seven sites). The methods of Eberhart & Russell and GGE biplot are essential in the evaluation of productivity, adaptability, and stability in soybean because they are able to encompass these aspects using a minimum set of methods. The methods of Annicchiarico (AN), Silva & Barreto (SB), Cruz (CR), and Storck & Vencovsky (SV) can be used to generate complementary information, such as: stability for general, favorable, and unfavorable environments (AN); adaptability in favorable and unfavorable environments (SB, CR, and SV); and average productivity in all environments and in favorable or unfavorable environments (SV).

Index terms: *Glycine max*, cultivar recommendation, genotype x environment interaction.

Repetibilidade das associações entre métodos de análise de adaptabilidade, estabilidade e produtividade em soja

Resumo – O objetivo deste trabalho foi avaliar as associações entre estimativas de adaptabilidade, estabilidade e produtividade em soja (*Glycine max*), e estimar o coeficiente de repetibilidade dessas associações entre anos. Foram avaliados 22 genótipos em 27 ambientes, na safra 2012/2013, e em 19 ambientes na 2013/2014. Nas safras seguintes, foram avaliados 28 genótipos em 26 ambientes, em 2014/2015, e em 25 ambientes em 2015/2016, no total de 97 ensaios. Quatorze métodos foram avaliados; os coeficientes de correlação de Spearman foram obtidos para os parâmetros adaptabilidade, estabilidade e produtividade; e os coeficientes de repetibilidade, bem como o número mínimo de ambientes necessário para se obter um coeficiente de determinação de 80 e 90%, foram calculados. O número mínimo de ambientes necessários para estimar o grau de associação entre as estimativas dos parâmetros foi baixo (sete locais). Os métodos de Eberhart & Russell e GGE biplot são essenciais na avaliação da produtividade, da adaptabilidade e da estabilidade em soja, pois conseguem englobar estes aspectos com o uso de um conjunto mínimo de métodos. Já os métodos de Annicchiarico (AN), Silva & Barreto (SB), Cruz (CR) e Storck & Vencovsky (SV) podem ser utilizados para gerar informações complementares, tais como: verificação da estabilidade para ambientes em geral e para ambientes favoráveis e desfavoráveis (AN); adaptabilidade em ambientes favoráveis e desfavoráveis (SB, CR e SV); e produtividade média em todos os ambientes, e em ambientes favoráveis ou desfavoráveis (SV).

Termos para indexação: *Glycine max*, indicação de cultivares, interação genótipo x ambiente.

Introduction

Differences in soybean [*Glycine max* (L.) Merrill] genotype performance, when competition trials are conducted in different environments, are attributed to the genotype x environment interaction (GxE). The existence of GxE hinders the identification of superior genotypes, requiring adaptability and stability analyses to verify these variations and to allow greater security in the selection and recommendation of cultivars.

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The methodologies described by Yates & Cochran (1938) (traditional method, TR), Plaisted & Peterson (1959) (PP), Wricke (1965) (WR), and by Annicchiarico (1992) (AN) are commonly used to evaluate phenotypical stability of crops. These methodologies are based on the analysis of variance, in which the estimates are expressed as mean squares and variance components (Carvalho et al., 2016). Other methodologies use linear regression equations, where the dependent variable is expressed as a function of an environmental index that measures the quality of the evaluated environments. Among these, stand out those of Finlay & Wilkinson (1963) (FW), Eberhart & Russell (1966) (ER), and Tai (1971) (TA).

The methodologies based on linear bissegmented regression of Silva & Barreto (SB) (Barreto, 1985), Cruz et al. (1989) (CR), and Storck & Vencovsky (1994) (SV) contemplate an indexing variable that allows to evaluate the behavior of genotypes in unfavorable and favorable environments, with negative and positive values of the environmental index, respectively. Other methodologies, such as those of Huehn (1990) (HU) and Lin & Binns (1988) modified by Carneiro (1998) (LB), fall within the class of non-parametrical analyses.

There are also two methods that use multivariate analysis: additive main effects and multiplicative interaction (AMMI) and genotype plus genotype by environment interaction (GGE). The AMMI analysis combines the analysis of variance of the main additive effects of genotypes and environments with the principal component analysis of the multiplicative effect of GxE (Ndhlela et al., 2014). The GGE method combines genotype main effect (G) plus GxE in a biplot analysis, where the main effect of G is related to the average performance of the genotype, and GxE indicates stability in all evaluated environments (Yan et al., 2016).

The number of available environments, the required accuracy, and type of the information target are criteria that should be considered for choosing cultivar indication methods with greater safety. Comparisons between methodologies of adaptability and stability analysis have been performed for several crops, such as corn (Bujak et al., 2014), sugarcane (Paula et al., 2014), soybean (Freitas Monteiro et al., 2015), and wheat (Roostaei et al., 2014). However, comparisons between methodologies based on linear bissegmented regression and AMMI and GGE biplot are poorly understood and require further studies. In addition, the coefficient of repeatability of these associations in different years of evaluation is not known. The lack of information on this variable over a sequence of years may make it difficult to choose the best method and reduce the efficiency of plant breeding programs.

The objective of this work was to evaluate the association between estimates of adaptability, stability, and productivity in soybean, and to estimate the repeatability coefficient of these associations between years.

Materials and Methods

Grain yield data from 97 competition trials of soybean genotypes, in four crop seasons, were used. The trials were conducted in the M1 and M2 soybean macroregions in Brazil (Table 1). Twenty-two genotypes were evaluated in 27 environments, in the 2012/2013 crop season, and in 19 environments in 2013/2014. In the following biennium, 28 genotypes were evaluated in 26 and 25 environments, in the 2014/2015 and 2015/2016 crop seasons, respectively.

The experimental units were composed of four 5-m rows, spaced 0.50 m apart from each other. Grain yield was obtained from the two central lines of each plot (useful area of 5 m^2). A randomized complete block design, with three replicates, was used.

Seed density was 30 seeds m^{-2} and base fertilization was 350 kg ha^{-1} $N\text{-}P_2O_5\text{-}K_2O$ (02-20-20). Cultural practices were carried out according to the technical recommendations for this crop.

The joint analysis of variance and the F-test were performed in each set of trials (within the same year) in order to verify the existence of GxE and the percentage of genotypes that interact with the environment (Storck et al., 2016). The parameters of stability, adaptability, and productivity for the genotypes of each trial were calculated with different methods (Table 2). The methods based on the analysis of variance were those of: Yates & Cochran (1938), or traditional, estimated by the mean square of the environment within each genotype ($MS_{E/G}$), where the higher the $MS_{E/G}$, the lower the stability; Plaisted & Peterson (1959), in which the stability index (W) is the arithmetic mean of the variance components between GxE pairs involving a given genotype, and the larger the W, the lower the stability; Wricke (1965), where the stability parameter

(W) corresponds to the sum of squares of the GxE effect for each genotype, and the smaller the W, the greater the stability; and Annicchiarico (1992), in which the stability parameter (recommendation index, W) is measured by the superiority of the genotype in relation to the mean of each environment, for general (Wg), unfavorable (Wd), and favorable (Wf) environments, and the higher the W index, the greater the stability for the respective environment.

The methods based on linear regression were those of: Finlay & Wilkinson (1963), Eberhart & Russell (1966), and Tai (1971). In these methods, the higher the coefficient of the regression (b1), the greater the response to environmental variation and the greater the adaptability. Also, the stability parameters are estimated by the coefficient of determination (R^2) or by the variance of the lack of adjustment to the model (Vd). The greater the R^2 (or lower the Vd), the greater the stability of the genotype.

Table 1. Number of trials conducted per crop season (sowing from 2012 to 2015) in different Brazilian macroregions for soybean (*Glycine max*) cultivation.

Municipality, state(1)	Macroregion	2012/2013	2013/2014	2014/2015	2015/2016	Latitude (S)	Longitude (W)	Altitude (m)
Abelardo Luz, SC	1	1	1	2	1	26°33'	52°19'	760
Assis, SP	2	1	-	-	-	22°39'	50°24'	546
Brasilândia, MS	2	-	-	1	1	21°15'	52°02'	343
Campo Mourão, PR	2	1	-	-	-	24°02'	52°22'	630
Campos Novos, SC	1	1	-	1	1	27°24'	51°13'	946
Cândido Mota, SP	2	1	1	1	-	22°44'	50°23'	479
Canoinhas, SC	1	1	-	-	-	26°10'	50°23'	839
Cascavel, PR	2	1	1	1	1	24°57'	53°27'	781
Chapada, RS	1	1	1	1	1	28°03'	53°04'	436
Cruzália, SP	2	-	1	-	-	22°40'	50°47'	318
Dourados, MS	2	1	1	1	1	22°13'	54°48'	430
Erechim, RS	1	1	1	-	-	27°38'	52°16'	783
Guarapuava, PR	1	1	1	2	1	25°23'	51°27'	1,120
Itaberá, SP	1	-	-	1	-	23°51'	49°08'	651
Londrina, PR	2	1	1	1	1	23°18'	51°09'	610
Mamborê, PR	2	-	-	1	-	24°19'	52°31'	750
Maracajú, MS	2	1	1	-	1	21°36'	55°10'	384
Maringá, PR	2	1	-	-	-	23°25'	51°56'	515
Missal, PR	2	1	-	-	-	25°05'	54°14'	320
Não-Me-Toque, RS	1	-	-	-	1	28°27'	52°49'	514
Palma Sola, SC	1	1	1	1	-	26°20'	53°16'	870
Palmas, PR	1	1	-	-	-	26°29'	51°59'	1,115
Palotina, PR	2	1	-	1	1	24°17'	53°50'	335
Pantano Grande, RS	1	-	1	-	-	30°11'	52°22'	100
Perobal, PR	2	1	-	1	1	23°53'	53°24'	410
Ponta Porã, MS	2	1	-	1	1	22°32'	55°43'	755
Realeza, PR	1	2	2	2	3	25°46'	53°31'	520
Rio Brilhante, MS	2	-	-	1	1	21°48'	54°32'	312
Santa Cruz do Sul, RS	1	1	1	1	1	29°43'	52°25'	73
Santo Augusto, RS	1	1	1	-	1	27°51'	53°46'	528
São Francisco de Assis, RS	1	-	-	1	1	29°33'	55°07'	151
São Jorge do Ivaí, PR	2	-	-	1	1	23°25'	52°17'	600
São Miguel do Iguaçu, PR	2	-	-	1	1	25°20'	54°14'	312
Sidrolândia, MS	2	1	-	1	1	20°55'	54°57'	484
Terra Roxa, PR	2	-	1	-	-	24°09'	54°05'	417
Ubiratã, PR	2	-	1	1	1	24°32'	52°59'	508
Vacaria, RS	1	1	1	-	1	28°30'	50°56'	971
Verê, PR	1	1	-	-	-	25°52'	52°54'	485
No. of environments per year	-	27	19	26	25			

(1)Brazilian states: SC, Santa Catarina; SP, São Paulo; MS, Mato Grosso do Sul; PR, Paraná; and RS, Rio Grande do Sul.

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The methods based on bissegmented linear regression were those of: Silva & Barreto (1985), Cruz et al. (1989), and Storck & Vencovsky (1994). There are two regression coefficients as measures of adaptability in these methods: one for unfavorable environments (negative environmental index, b1) and one for favorable environments (positive environmental index, b12). The coefficient of determination is used as a measure of stability. In these methods, the use of the average yield of each genotype in general (mg), unfavorable (md), and favorable (mf) environments is recommended for the identification of genotypes adapted for the respective environments.

The methods of non-parametric statistics used in this study were those of: Huehn (1990), which estimates the stability measures S1, S2, and S3; and Lin & Binns (1988) modified by Carneiro (1998), which estimates the stability measures Pg, Pd, and Pf for general,

Table 2. Stability and adaptability methods evaluated, along with their measures and the abreviation of the statistics.

Method	Measure	Abreviation
Yates & Cochran (1938) (TR); traditional	Stability	TR
Plaisted & Peterson (1959) (PP); Anova	Stability	PPW
Wricke (1965) (WR); Anova	Stability	WRW
Annicchiarico (1992) (AN); Anova	Stability in general environments	ANWg
	Stability in unfavorable environments	ANWd
	Stability in favorable environments	ANWf
Eberhart & Russell (1966) (ER); regression	Adaptability	ERb
	Stability	ERd
	Stability	ERR^2
Finlay & Wilkinson (1963) (FW); regression	Adaptability	FWb
Tai (1971) (TA); regression	Adaptability	TAb
	Stability	TAλ
Silva & Barreto (1985) (SB); segmented regression	Stability in unfavorable environments	SBb1
	Adaptability in favorable environments	SBb12
	Stability	SBR^2
Cruz et al. (1989) (CR); segmented regression	Stability in unfavorable environments	CRb1
	Adaptability in favorable environments	CRb12
	Stability	CRR^2
Storck & Vencovsky (1994) (SV); segmented regression	Adaptability in unfavorable environments	SVb1
	Adaptability in favorable environments	SVb12
	Stability	SVR^2
	Average yield in all environments	SVmg
	Yield in unfavorable environments	SVmd
	Yield in favorable environments	SVmf
Huehn (1990) (HU); non-parametric	Stability	HUS1
	Stability	HUS2
	Stability	HUS3
Lin & Binns (1988) /Carneiro (1998) (LB); non-parametric	Stability in general enviroment	LBPg
	Stability in unfavorable environments	LBPd
	Stability in favorable environments	LBPf
AMMI (Zobel et al., 1988); multivariated	Stability	AMMI
GGE (Yan, 2001); multivariated	Yield	PC1
	Stability	PC2
	Mean and stability	Rank

unfavorable, and favorable environments, respectively. In the AMMI analysis, stability is measured by the magnitude of scores (absolute value) of the first major component of the GxE (IPCA1) (Zobel et al., 1988). In the method based on the GGE biplot (Yan, 2001), the measures of productive average (PC1), stability (PC2), and a parameter that analyzes mean and stability (Rank) jointly are used, ordering the genotypes in relation to an ideal, theoretical genotype, which would be the best for all evaluated environments.

In order to verify the degree of association between the estimates for the set of trials, in each season, Spearman's rank correlation coefficient (r_s) was used among the 595 pairs of estimates (combination of 35 estimates, two-by-two). Therefore, four matrices (four seasons) of size 35 were obtained. Afterwards, the average matrix was obtained by calculating the mean between the r_s of the four matrices. The repeatability coefficient was estimated as being Pearson's linear correlation coefficient, equivalent to the structural method between the pairs of Spearman's correlation matrices of each biennium.

When the correlation between two methods is high and positive, one method can replace the other; that is, they are concordant methods and both have the same indication of recommended genotypes. When the correlation is high and negative, there is disagreement of the classification ranks among the evaluated estimates. Finally when the correlation is null or low, the methods are independent. However, depending on the parameters under analysis, positive correlations represent disagreement between methods, and negative correlation represent concordance; thus, there is a necessity to interpret the usefulness of the values for each pair of the evaluated estimates.

The Genes software (Cruz, 2016), a personal software compiled in Turbo Pascal for the discontinuous bissegmented method (Storck & Vencovsky, 1994), the GGEbiplot software (Yan, 2001), and the Microsoft Excel software were used for the analyses.

Results and Discussion

The joint analysis of variance showed a significant GxE for grain yield, in each macroregion and in both of them together (set), for the four years of trials (Table 3). In all analyses, the variance between environments and the differences between genotypes were also significant. All genotypes significantly interacted ($p<0.05$) with the environment in three of the four crop seasons, and 96.4% in the remaining crop season, when the two macroregions were considered jointly (M1 + M2). Smaller percentages of genotypes interacting with the environment (CI) were found when the analysis was performed per macroregion. In six cases, CI was higher than 89% and, in two cases, CI was close to 68%.

The GxE reflects the differentiated behavior of the genotypes in different environments. Therefore, the indication of genotypes through adaptability and stability analyses is an adequate procedure, especially when this interaction occurs with the contribution of most of the genotypes under analysis. This GxE was also found in other trial sets (Cargnelutti Filho et al., 2007, 2009).

Estimates of Spearman's correlation coefficients with high magnitudes were found (Tables 4 and 5). Repeatability coefficients (r_o) ranged from 0.719 to 0.922 for the biennium involving the 2012/2013 and 2013/2014 harvests (Table 6). For the biennium 2014/2015 and 2015/2016, r_o varied from 0.570 to 0.924, considering estimates of stability, adaptability, and productivity in general (n = 35), and estimates of stability (n = 20) and of adaptability and productivity (n = 15) alone. The M2 macroregion presented the lowest values of r_o, in both biennia, indicating that the environmental variability in the evaluated sites was higher than in the M1 region. The lower values of r_o in the M2 macroregion make it necessary to have a greater number of sites to obtain a coefficient of determination equal to 80% (n_{80}) or 90% (n_{90}).

To obtain n_{90} in the macroregions separately, in the set of macroregions and for each set of estimates, seven evaluation sites were needed in each macroregion per year of evaluation. Considering the high repeatability of the associations between years, in the two biennia, the mean of the correlation coefficients of the four years was used for the interpretation of the associations between the estimates of the yield, adaptability, and stability parameters.

The first set of estimates of the stability parameters with positive associations (mean of the correlations, r_s = 0.65) is composed by the parameters ANWg, ANWd, and ANWf; by the determination coefficients of linear regression, ERR^2, and of segmented regressions, SBR^2, CRR^2, and SVR^2. This result reveals agreement between the estimates obtained with the different methods, indicating that both generate similar information. This set of parameters also showed a positive association (r_s = 0.60) with the grain yield averages in general (SVmg), favorable (SVmf), and unfavorable (SVmd) environments by the SV method. This behavior was expected because the parameters ANWg, ANWd, ANWf, ERR^2, SBR^2, CRR^2, and SVR^2 use the stability concept in the dynamic sense since they are related to the productivity of the genotypes, which makes the cultivars indicated by these methods also the most productive ones.

SVmg, SVmf, and SVmd also agreed regarding their respective estimates of stability by the LB method for general (LBPg; r_s = -0.97), favorable (LBPf; r_s = -0.84), and unfavorable (LBPd; r_s = -0.87) environments. Therefore, the genotypes with the lowest LBPg, LBPf, and LBPd scores, and with higher AN parameters by the linear regression coefficients of ER and of segmented regressions (SB, CR, and SV), are the most indicated for recommendation and also the most

Table 3. Mean squares (MS) and degrees of freedom (df) for the sources of variation in macroregions 1 (M1), 2 (M2), and M1+M2, in four crop seasons.

Sources of variation	M1+M2		M1		M2	
	df	MS	df	MS	df	MS
2012/2013 crop season						
Block/Environment (E)	54	1.22984	28	0.92429	26	1.5589
Genotype (G)	21	8.02173**	21	4.80944**	21	3.98293**
E	26	41.93507**	13	41.07799**	12	32.456**
G x E	546	0.75222**	273	0.68788**	252	0.82038**
Error	1134	0.13649	588	0.11166	546	0.16323
Percentage of genotypes, CI	-	100	-	100	-	95.5
Mean (t ha^{-1})	-	2.938	-	3.233	-	2.621
CV (%)	-	12.5	-	10.3	-	15.4
2013/2014 crop season						
Block/Environment (E)	38	0.25537	22	0.2131	16	0.31349
Genotype (G)	21	4.55157**	21	4.54692**	21	1.94244**
E	18	39.22741**	10	19.74469**	7	58.83982**
G x E	378	0.95228**	210	0.9805**	147	0.77117**
Error	798	0.1862	462	0.17618	336	0.19998
Interaction percentage,CI	-	100	-	95.5	-	68.2
Mean (t ha^{-1})	-	3.652	-	3.889	-	3.326
CV (%)	-	11.8	-	10.8	-	13.4
2014/2015 crop season						
Block/Environment (E)	54	2.95362	24	2.69657	30	3.15927
Genotype (G)	27	2.75466**	27	4.55764**	27	1.16401**
E	26	74.28663**	11	74.62032**	14	76.63547**
G x E	702	0.73287**	297	0.45212**	378	0.79388**
Error	1458	0.03764	648	0.03582	810	0.0391
Interaction percentage,CI	-	96.4	-	100	-	100
Mean (t ha^{-1})	-	4.424	-	4.569	-	4.309
CV (%)	-	4.4	-	4.1	-	4.6
2015/2016 crop season						
Block/Environment (E)	52	0.35202	26	0.34493	26	0.35911
Genotype (G)	27	4.18161**	27	2.49539**	27	3.16321**
E	25	34.8374**	12	51.23323**	12	10.98601**
G x E	675	0.61617**	324	0.60026**	324	0.56034**
Error	1404	0.17999	702	0.20317	702	0.1568
Interaction percentage,CI	-	100	-	67.9	-	89.3
Mean (t ha^{-1})	-	4.607	-	4.846	-	4.369
CV (%)	-	9.2	-	9.3	-	9.1

**Significant at 1% probability by the F-test. CI, percentage of genotypes that significantly interacted with the environment.

productive. This result is more evident when one looks at the high association (mean of correlations = -0.88) of the parameters LBPg, LBPd, and LBPf with the parameters ANWg, ANWd, and ANWf, and, in a smaller magnitude (-0.40), with ERR^2, SBR^2, CRR^2, and SVR^2. Similar results have been reported in other studies (Silva & Duarte, 2006; Cargnelutti Filho et al., 2009). Cargnelutti Filho et al. (2009) pointed out that the high agreement of the LB and AN parameters with the average of grain yield indicates a possible inefficiency of these methods, since the recommendation of genotypes based on these parameters and the average of productivity is similar and, in this case, the effects of the GxE would not be considered.

Estimates of the stability parameters of PPW, WRW, ERd, and the variance of lack of adjustment of ERd, TAλ, HUS1 and HUS2, AMMI, and PC2 were also positively associated, indicating a high concordance between these different methods of analysis. This group of parameters uses the concept of stability in the static sense, since they do not consider the average yield of the genotypes. Similar results have been reported in other studies. Tadege et al. (2014) obtained an association of 0.98 between the WR method and the ERd regression deviations. Mohammadi et al. (2010) found positive associations, and with high repeatability between years, for the WRW, AMMI, and ERd methods. Roostaei et al. (2014) observed an association of medium magnitude (0.56) between the concepts of stability for AMMI and GGE. Cargnelutti Filho et al. (2009), with competition trials of corn genotypes, verified total concordance (r_s = 1.00) among the estimates of the PPW and WRW stability parameters, a result also obtained in this study (r_s = 1.00). These authors also reported concordance of these parameters (PPW and WRW) with the estimates TAλ, ERR^2, SBR^2, CRR^2, HUS1, HUS2, and AMMI, which are results very close to those found here. Therefore, the most stable genotypes are those with the lowest PPW, WRW, TAλ, HUS1, HUS2, and AMMI scores, and the highest ERR^2, SBR^2, and CRR^2 scores, which explains the negative correlation coefficients for the parameters based on the regression analysis.

The rank estimate obtained with the GGE biplot method makes reference to the ideal genotype, that is, the genotype that presents high average yield combined with stability in performance. This rank estimate was related (mean of correlations = 0.87) to the estimates of: LBPg, LBPd, and LBPf; ANWg, ANWd, and ANWf (-083); PC1 (-0.99); and productivity in general (SVmg), unfavorable (SVmd), and favorable (SVmf) environments (-0.84). This concordance between the

Table 4. Spearman's correlation coefficient matrix (r_s)(1) among estimates of adaptability, stability, and yield, obtained with 14 methods (Part 1).

	PPW	WRW	ANWg	ANWd	ANWf	ERb	ERd	ERR^2	FWb	TAb	TAl	SBb1	SBb12	SBR^2	CRb1	CRb12	CRR^2	SVb1	SVb12	SVR^2
TR	0.47	0.47	-0.15	-0.29	0.14	0.85	0.48	0.02	0.85	0.85	0.48	0.35	0.53	0.05	0.76	0.50	0.05	0.36	0.50	0.03
PPW		1.00	-0.45	-0.45	-0.35	0.08	0.97	-0.79	0.08	0.08	0.95	-0.05	0.07	-0.76	0.04	0.08	-0.76	-0.12	0.08	-0.76
WRW			-0.45	-0.45	-0.35	0.08	0.97	-0.79	0.08	0.08	0.95	-0.05	0.07	-0.76	0.04	0.08	-0.76	-0.12	0.08	-0.76
ANWg				0.97	0.84	0.07	-0.43	0.44	0.07	0.07	-0.42	0.32	-0.11	0.41	0.18	-0.06	0.42	0.33	-0.06	0.42
ANWd					0.71	-0.08	-0.41	0.35	-0.08	-0.08	-0.41	0.22	-0.20	0.31	0.01	-0.10	0.33	0.24	-0.10	0.33
ANWf						0.36	-0.35	0.54	0.36	0.36	-0.36	0.45	0.09	0.52	0.48	-0.02	0.54	0.34	-0.02	0.53
ERb							0.08	0.44	1.00	1.00	0.08	0.47	0.55	0.46	0.90	0.50	0.46	0.48	0.50	0.44
ERd								-0.79	0.08	0.08	1.00	-0.05	0.07	-0.76	0.06	0.09	-0.76	-0.13	0.09	-0.75
ERR^2									0.44	0.44	-0.80	0.35	0.21	0.98	0.43	0.16	0.98	0.39	0.16	0.97
FWb										1.00	0.08	0.47	0.55	0.46	0.90	0.50	0.46	0.48	0.50	0.44
TAb											0.08	0.47	0.55	0.46	0.90	0.50	0.46	0.48	0.50	0.44
TAl												-0.05	0.06	-0.76	0.06	0.08	-0.76	-0.13	0.08	-0.75
SBb1													-0.37	0.34	0.68	-0.22	0.35	0.84	-0.22	0.35
SBb12														0.22	0.30	0.76	0.21	-0.23	0.76	0.19
SBR^2															0.45	0.17	0.97	0.39	0.17	0.98
CRb1																0.17	0.45	0.52	0.17	0.44
CRb12																	0.13	0.14	1.00	0.11
CRR^2																		0.37	0.13	0.98
SVb1																			0.14	0.35
SVb12																				0.11

(1)Average of four years. Description of experiment sites on Table 1 and of methods on Table 2; for absolute values of r_s>0.42 ($p<0.05$).

ranks and the other methods can be explained by the association of all parameters under analysis with the average grain yield, so that both have an association with each other.

The adaptability estimates based on the linear regression of ERb, FWb, and TAb showed a positive and exact association between each other ($r_s = 1.00$). Therefore, only one of these statistics should be used, in order to avoid redundant information. In addition, the parameter SVb12 also showed a positive and exact association with CRb12, indicating the redundancy between them. Cargnelutti Filho et al. (2009) found an exact correlation between ERb and TAb; however, the correlations between ERb and FWb, and between TAb and FWb were $r_s = 0.50$. The parameters ERb, FWb, and TAb were also positively associated (0.57) with the estimates of the first and second segment of the segmented regression methods: SBb1 and SBb12, CRb1 and CRb12, and SVb1 and SVb12.

The stability estimate of the traditional method (TR) was positively associated (0.85) to the adaptability estimates ERb and TAb. According to Cargnelutti Filho et al. (2009), genotypes with ERb and TAb values lower than 1 are more suitable for unfavorable environments. Thus, the most indicated cultivars (lower scores) by the TR method are also the most indicated (lower scores) for unfavorable environments, as also reported by those authors. This positive association (0.85) was also

Table 5. Spearman's correlation coefficient matrix (r_s)⁽¹⁾ among estimates of adaptability, stability, and yield parameters, obtained with 14 methods (Part 2).

	SVmg	SVmd	SVmf	HUS1	HUS2	HUS3	LBPg	LBPd	LBPf	AMMI	PC1	PC2	Rank
TR	0.02	-0.20	0.24	0.36	0.38	0.17	0.07	0.05	0.07	0.29	-0.08	0.23	0.10
PPW	-0.27	-0.29	-0.19	0.73	0.79	0.23	0.37	0.39	0.30	0.66	-0.30	0.60	0.37
WRW	-0.27	-0.29	-0.19	0.73	0.79	0.23	0.37	0.39	0.30	0.66	-0.30	0.60	0.37
ANWg	0.95	0.95	0.84	-0.25	-0.30	0.63	-0.98	-0.92	-0.90	-0.24	0.89	-0.23	-0.90
ANWd	0.89	0.96	0.72	-0.24	-0.29	0.61	-0.91	-0.87	-0.85	-0.21	0.84	-0.16	-0.85
ANWf	0.87	0.73	0.93	-0.15	-0.19	0.61	-0.87	-0.82	-0.82	-0.25	0.81	-0.26	-0.81
ERb	0.18	-0.06	0.40	0.06	0.05	0.10	-0.14	-0.19	-0.08	-0.01	0.10	-0.06	-0.11
ERd	-0.27	-0.27	-0.18	0.74	0.80	0.24	0.36	0.35	0.31	0.67	-0.31	0.63	0.37
ERR^2	0.37	0.25	0.41	-0.58	-0.63	-0.12	-0.43	-0.45	-0.37	-0.60	0.36	-0.57	-0.41
FWb	0.18	-0.06	0.40	0.06	0.05	0.10	-0.14	-0.19	-0.08	-0.01	0.10	-0.06	-0.11
TAb	0.18	-0.06	0.40	0.06	0.05	0.10	-0.14	-0.19	-0.08	-0.01	0.10	-0.06	-0.11
TAλ	-0.27	-0.26	-0.19	0.74	0.80	0.24	0.37	0.35	0.32	0.67	-0.32	0.63	0.38
SBb1	0.40	0.28	0.47	0.11	0.09	0.34	-0.38	-0.36	-0.34	-0.09	0.32	-0.08	-0.31
SBb12	-0.05	-0.21	0.11	-0.01	-0.03	-0.12	0.09	0.02	0.11	0.03	-0.10	-0.08	0.09
SBR^2	0.34	0.21	0.39	-0.58	-0.64	-0.14	-0.40	-0.42	-0.33	-0.61	0.33	-0.58	-0.39
CRb1	0.29	0.04	0.53	0.11	0.09	0.23	-0.25	-0.28	-0.20	-0.09	0.22	-0.11	-0.21
CRb12	-0.04	-0.10	-0.01	-0.03	-0.02	-0.10	0.08	0.05	0.10	0.08	-0.08	-0.03	0.06
CRR^2	0.35	0.22	0.41	-0.59	-0.65	-0.13	-0.41	-0.43	-0.35	-0.60	0.33	-0.56	-0.39
SVb1	0.37	0.29	0.35	-0.05	-0.04	0.24	-0.35	-0.35	-0.28	-0.13	0.32	-0.13	-0.34
SVb12	-0.04	-0.10	-0.01	-0.03	-0.02	-0.10	0.08	0.05	0.10	0.08	-0.08	-0.03	0.06
SVR^2	0.34	0.22	0.40	-0.61	-0.67	-0.14	-0.41	-0.43	-0.33	-0.62	0.34	-0.58	-0.40
SVmg		0.93	0.93	-0.09	-0.13	0.76	-0.97	-0.89	-0.93	-0.14	0.89	-0.15	-0.88
SVmd			0.76	-0.09	-0.13	0.73	-0.93	-0.87	-0.87	-0.10	0.86	-0.08	-0.85
SVmf				-0.03	-0.07	0.73	-0.88	-0.83	-0.84	-0.12	0.80	-0.14	-0.79
HUS1					0.98	0.45	0.19	0.19	0.12	0.54	-0.16	0.51	0.22
HUS2						0.42	0.23	0.24	0.16	0.58	-0.20	0.53	0.27
HUS3							-0.66	-0.61	-0.67	0.24	0.66	0.19	-0.61
LBPg								0.91	0.93	0.21	-0.91	0.22	0.91
LBPd									0.74	0.25	-0.81	0.27	0.82
LBPf										0.14	-0.88	0.12	0.87
AMMI											-0.21	0.82	0.29
PC1												-0.20	-0.99
PC2													0.27

⁽¹⁾Average of four years. Description of experiment sites on Table 1 and of methods on Table 2; for absolute values of $r_s>0.42$ ($p<0.05$).

found between TR and the FWb estimate, similarly to what was verified (0.89) by Silva & Duarte (2006).

The high repeatability between the estimates of the adaptability and stability parameters obtained in the present study allows the safe indication of adequate methods for the identification of the best soybean genotypes for the different evaluated environments. In general terms, a repeatability of the associations was found between methods of adaptability analysis and productive stability. Several of the assessed methods have similar behavior over the years, in the soybean M1 and M2 adaptive macroregions, which increases the reliability of the comparison between methods. In this sense, the ANWg, ANWd, ANWf, ERR^2, SBR^2, CRR^2, and SVR^2 parameters showed a high association with each other, indicating that it is possible to use only one of them to identify genotypes with dynamic stability. However, in the static sense, the choice should be made between one of the following parameters: PPW, WRW, ERd, TAλ, HUS1 and HUS2, AMMI, and PC2. As for adaptability, the choice should be between: ERb, FWb and TAb, SBb1 and SBb12, CRb1 and CRb12, and SVb1 and SVb12. As to the rank parameter, obtained with the GGE method, it refers to the ideal genotype (high production average and high stability) and is associated with LBPg, LBPd, LBPf, ANWg, ANWd, ANWf, SVmg, SVmd, and SVmf. This indicates that these methods measure simultaneously for yield and stability.

Table 6. Coefficient of repeatability (r_o) and minimum number of necessary environments, based on coefficients of determination equal to 80 (n_{80}) and 90% (n_{90}), per biennium and macroregion, on the association between 35 estimates of adaptability and stability parameters, and grain yield of soybean (*Glycine max*) genotypes.

Macro-region(1)	2012/2013 and 2013/2014			2014/2015 and 2015/2016		
	r_o	n_{80}	n_{90}	r_o	n_{80}	n_{90}
	Productivity, adaptability, and stability estimates (n=35)					
M1	0.896**	0.5	1.0	0.856**	0.7	1.5
M2	0.719**	1.6	3.5	0.570**	3.0	6.8
M1+M2	0.782**	1.1	2.5	0.790**	1.1	2.4
	Stability estimates (n=20)					
M1+M2	0.791**	1.1	2.4	0.924**	0.3	0.7
	Productivity and adaptability estimates (n=15)					
M1+M2	0.922**	0.3	0.8	0.786**	1.1	2.5

(1)Experiment site description in Table 1. **Significant at 1% probability by Student's t test

Considering the various parameters indicated for adaptability, stability, and productivity, there are methods that have parameters in more than one group, which could form a minimum set of methods to identify productive, adapted, and stable genotypes. In this sense, Eberhart & Russell and GGE biplot are considered two essential methods since they can encompass all aspects of interest of the breeder using a minimum number of methods. If more methods are to be used, those of Annicchiarico (1992), Silva & Barreto (1985), Cruz (1989), and Storck & Vencovsky (1994) should be indicated. These methods allow evaluating the stability of genotypes for: general, favorable, and unfavorable environments (AN); adaptability in favorable and unfavorable environments (SB, CR, and SV); and average productivity in all environments and in favorable and unfavorable environments (SV).

Finally, the results obtained in this work with soybean mostly corroborate those of Cargnelutti Filho et al. (2009) with corn, indicating that there are methods that stand out in the evaluation of the parameters of adaptability and stability for different crops. Moreover, the results of both studies were obtained from experiments conducted in a large number of sites and over several years. In the work of Cargnelutti Filho et al. (2009), 65 trials were conducted in three seasons. In the present study, data from 97 competition trials of cultivars conducted in four seasons were used. Thus, this work expands the knowledge of the behavior of the methods over the years, and makes it possible to indicate more clearly which methods are more efficient to identify highly productive, adapted, and stable genotypes.

Conclusions

1. Trial sets with seven environments in the soybean (*Glycine max*) adaptation macroregions 1 and 2, performed in one or two years, are sufficient to estimate the associations between parameters of adaptability, stability, and productivity.
2. The method of Eberhart & Russell and the GGE biplot are essential for the evaluation of productivity, adaptability, and stability in soybean because they are able to encompass these aspects using a minimum number of methods.
3. The methods of Annicchiarico (AN), Silva & Barreto (SB), Cruz (CR), and Storck & Vencovsky (SV) can be used to generate complementary information,

when evaluating genotype stability for general, favorable, and unfavorable environments (AN); adaptability in favorable and unfavorable environments (SB, CR, and SV); and average productivity in general, favorable, and unfavorable environments (SV).

4. The associations between the estimates of adaptability and stability parameters present high repeatability between years, conferring credibility to the estimates obtained.

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