Agronomic performance of modern soybean cultivars in multi-environment trials

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Abstract – The objective of this work was to evaluate the productive performance, and the adaptability and stability parameters of modern soybean (*Glycine max*) cultivars in multi-environment trials, as well as to identify the ideal genotypes for eight growing environments in Brazil. A randomized complete block experimental design was carried out, with three replicates, for the evaluation of 46 soybean cultivars in eight environments, in the microregions of adaptation 102, 201, and 202, in the 2014/2015 crop season. A complex genotype x environment interaction occurred, with changes in the ranking of genotypes among locations. The NA 5909 RG, M6410IPRO, NS 5959 IPRO, NS6823RR, M5917IPRO, NS 6767 RR, and 6563RSF IPRO cultivars showed the highest mean yields. The NA 5909 RG, NS6823RR, M6410IPRO, and NS 5959 IPRO cultivars showed high adaptability and stability and high grain yield, in the evaluated environments, and were ranked next to the ideal genotype for the analyzed environments. There are modern soybean cultivars, which are adapted, stable, and highly productive, for cultivation in the microregions 102, 201, and 202 for soybean crop adaptation in Brazil.

Index terms: *Glycine max*, adaptability and stability, genotype x environment interaction, GGE biplot, mixed models.

Desempenho agronômico de cultivares modernas de soja em ensaios multiambientes

Resumo – O objetivo deste trabalho foi avaliar o desempenho produtivo, a adaptabilidade e a estabilidade de cultivares modernas de soja (*Glycine max*), em ensaios multiambientes, assim como identificar os genótipos ideais para oito ambientes de cultivo no Brasil. Utilizou-se um delineamento experimental de blocos ao acaso, com três repetições, para a avaliação de 46 cultivares em oito ambientes, nas microrregiões de adaptação 102, 201 e 202, na safra 2014/2015. Ocorreu interação genótipo x ambiente complexa, com alterações do ranqueamento de cultivares entre os locais. As cultivares NA 5909 RG, M6410IPRO, NS 5959 IPRO, NS6823RR, M5917IPRO, NS 6767 RR e 6563RSF IPRO apresentaram as maiores médias produtivas. As cultivares NA 5909 RG, NS6823RR, M6410IPRO e NS 5959 IPRO apresentaram elevada adaptabilidade e estabilidade e alta produtividade de grãos, nos ambientes avaliados, e posicionaram-se próximo do que seria considerado ideal para os ambientes analisados. Há cultivares modernas de soja adaptadas, estáveis e com elevada produtividade, para o cultivo nas microrregiões 102, 201 e 202 de adaptação da cultura da soja no Brasil.

Termos para indexação: *Glycine max*, adaptabilidade e estabilidade, interação genótipo x ambiente, GGE biplot, modelos mistos.

Introduction

Soybean [*Glycine max* (L.) Merr.] is one of the most important crops for the Brazilian economy. Its domestic production reached 96.2 Tg in the 2014/2015 crop season, with a mean yield of approximately 3,000 kg ha^{-1} (Conab, 2016).

Genotype × environment interaction (GEI) is one of the main challenges of soybean breeding programs for both the phases of cultivar selection and recommendation (Branquinho et al., 2014). GEI consists in differentiated genotypic expressions, in different growing environments, and it is responsible for reducing the association between phenotype and genotype, reducing genetic progress in breeding programs (Lopes et al., 2012).

Data from multi-environment trials are necessary to assess the presence of GEI, for the evaluation of yield, and genotype adaptability and stability. Adaptability is the ability of the genotype to respond predictably to environmental stimuli, and stability indicates the predictability of performance in different environments. Several methods for adaptability and stability analyses have been described in the literature, which differ according to the statistics – as the analysis of variance, nonparametric regression, multivariate analysis, and the mixed-model analysis –, and according to the parameters used. Methods based on mixed models enable the analysis of genotypes, as that of the random effect analysis; and the multivariate analysis has innovative solutions for the visualization of results.

The mixed-model methods, such as the restricted maximum likelihood/best linear unbiased prediction (REML/BLUP), enable the estimation of variance components and the prediction of genetic values free of environmental effects (Peixouto et al., 2016). The following methods may be used: the harmonic mean of genotypic values (HMGV), in order to infer mean and stability; the relative performance of predicted genotypic values (RPGV), to analyze the genotypic adaptability and the mean yield; and the harmonic mean of the relative performance of predicted genotypic values (HMRPGV), to identify highly-productive, adapted, and stable genotypes (Gomez et al., 2014; Costa et al., 2015; Spinelli et al., 2015). As mixed models rank the effects of genotypes as random, these methods provide estimates of stability and genotypic adaptability (Resende, 2004).

The use of multivariate statistics, using tools as the GGE biplots, enables summarizing data from a large dataset into a few principal components (PC) (Yan, 2015). Biplots assessing the mean, phenotypic stability, and ideal genotype enable the graphical representation of each cultivar performance, facilitating the selection of superior genotypes (Qin et al., 2015).

The simultaneous use of mixed models based on REML/BLUP and multivariate methods enables the exploration of different adaptability and stability concepts, thereby complementing the collected data, thus increasing the efficacy of the selection of superior genotypes (Andrade et al., 2016).

This study differs from other published ones on the parameters of soybean adaptability, stability, and yield performance because it combines the methods of mixed-models and GGE biplots, in order to assess cultivars widely grown in the Brazilian macroregions of adaptation 1 and 2.

The objective of this work was to evaluate the yield performance, and the adaptability and stability parameters of modern soybean cultivars, as well as to identify the ideal genotypes for eight growing environments in Brazil, in multi-environment trials.

Materials and Methods

Forty-six modern soybean cultivars, widely grown in the Brazilian soybean macroregions of adaptation 1 and 2, which were provided for cultivation from 2007 to 2013, were evaluated (Table 1). These cultivars were classified according to their maturity groups (MG) into: early, 4.8 to 5.7; medium, 5.8 to 6.2; and late, 6.3 to 7.3.

The experiments were conducted in a randomized complete block design, with three replicates, in eight representative sites of the microregions of adaptation 102, 201, and 202, in the 2014/2015 crop season (Table 2). The sites were selected within microregion 201 and nearby regions with similar sowing season and climatic characteristics. This region has the highest soybean production in Southern Brazil. The experimental units consisted of four 5 m rows, spaced at 0.5 m between rows. The sowing density was 30 seed m^{-2}, and base fertilization was performed using 7, 70, and 70 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. Mechanical sowing and harvesting were carried out. The evaluated trait was grain yield (GY, kg ha^{-1}), in the two central rows of each plot (5 m^2 useful area), with grain moisture corrected to 13% (wet basis). Crop managements were conducted according to the technical recommendations for soybean cultivation (Oliveira & Rosa, 2014).

Initially, variance components were evaluated using the REML, and mean components were obtained using the BLUP, with the Selegen statistical package (Resende, 2002). The models 21 (for the analysis of genetic parameters for each site) and 54 (for the combined analysis of sites) were used.

The analysis of variance was also performed to verify the presence of genotype × environment

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Table 1. Description of 46 soybean cultivars, maturity group, cycle, year of release, technology and releaser.

Number	Cultivar	Maturity Group	Cycle	Year of release	Technology	Releaser
1	BMX Potência RR	6.7	Later	2007	RR	GDM Genética
2	DMario 58i	5.5	Early	2007	RR	GDM Genética
3	NK 7059 RR	6.2	Medium	2007	RR	Syngenta
4	A 6411RG	6.4	Later	2008	RR	Nidera
5	BMX Ativa RR	5.6	Early	2008	RR	GDM Genética
6	BMX Energia RR	5.3	Early	2008	RR	GDM Genética
7	NA 5909 RG	5.9	Medium	2008	RR	Nidera
8	NS 4823	4.8	Early	2008	RR	Nidera
9	BMX Turbo RR	5.8	Medium	2009	RR	GDM Genética
10	NS 5858	5.8	Medium	2010	RR	Nidera
11	NS 6262	6.2	Medium	2010	RR	Nidera
12	SYN1059 RR	5.9	Medium	2010	RR	Syngenta
13	NS 6767 RR	6.7	Later	2011	RR	Nidera
14	TMG 7262RR	6.2	Medium	2011	RR	TMG
15	NS 4901	4.9	Early	2012	RR	Nidera
16	NS 5258	5.2	Early	2012	RR	Nidera
17	NS 5290	5.2	Early	2012	RR	Nidera
18	NS 5401 RR	5.4	Early	2012	RR	Nidera
19	NS 6209	6.2	Medium	2012	RR	Nidera
20	NS6121RR	6.1	Medium	2013	RR	Nidera
21	NS6823RR	6.8	Later	2013	RR	Nidera
22	M6210IPRO	6.2	Medium	2011	IPRO	Monsoy
23	M6410IPRO	6.4	Later	2011	IPRO	Monsoy
24	5958RSF IPRO	5.8	Medium	2012	IPRO	GDM Genética
25	6458RSF IPRO	6	Medium	2012	IPRO	GDM Genética
26	6563RSF IPRO	6.3	Later	2012	IPRO	GDM Genética
27	AS 3570IPRO	5.7	Early	2012	IPRO	Monsoy
28	AS 3610IPRO	6.1	Medium	2012	IPRO	Monsoy
29	M5917IPRO	5.9	Medium	2012	IPRO	Monsoy
30	NS 5000 IPRO	5	Early	2012	IPRO	Nidera
31	NS 5106 IPRO	5.1	Early	2012	IPRO	Nidera
32	NS 5151 IPRO	5.1	Early	2012	IPRO	Nidera
33	NS 5445 IPRO	5.4	Early	2012	IPRO	Nidera
34	NS 5959 IPRO	5.9	Medium	2012	IPRO	Nidera
35	NS 6909 IPRO	6.9	Later	2012	IPRO	Nidera
36	NS 7000 IPRO	7	Later	2012	IPRO	Nidera
37	NS 7209 IPRO	7.2	Later	2012	IPRO	Nidera
38	NS 7237 IPRO	7.2	Later	2012	IPRO	Nidera
39	NS 7300 IPRO	7.3	Later	2012	IPRO	Nidera
40	NS 7338 IPRO	7.3	Later	2012	IPRO	Nidera
41	NS 5727 IPRO	5.7	Early	2013	IPRO	Nidera
42	NS 6006 IPRO	6	Medium	2013	IPRO	Nidera
43	NS6060IPRO	6	Medium	2013	IPRO	Nidera
44	NS6700IPRO	6.7	Later	2013	IPRO	Nidera
45	NS6906IPRO	6.9	Later	2013	IPRO	Nidera
46	TMG2158IPRO	5.8	Medium	2013	IPRO	TMG

interactions. Subsequently, a cluster analysis of means was performed using the Scott-Knott test, at 5% probability, and the Genes statistical software package (Cruz, 2013). Yield means of each genotype, at each site, and for the set of sites, were also indicated.

Data on genetic effects (g), predicted genotypic values (u+g), and the gain of each genotype with the removal of the environmental component were also determined in the analysis, using the model 54 of the Selegen software package (Resende, 2002).

The new genotype mean was obtained with this gain, and ranking was performed using this new value. Furthermore, the mean genotypic value (u+g+gem) was obtained in the various environments; this indicated the average interaction with all evaluated environments (Resende, 2002). Using this model, the following parameters could also be obtained: genotypic stability using HMGV; genotypic adaptability and yield performance, using RPGV multiplied by the overall mean (OM) of all sites (RPGV*OM); and the genotypic stability and adaptability, and crop yiel performance, using HMRPGV*OM.

Stability was also assessed using the GGEbiplot software (Yan, 2001), which analyzes the stability of genotypes associated with their mean yield. For this purpose, the following parameters were used: data transformation (Transform = 0, without transformation), data scale (Scaling = 0, without scale), data centering (Data centering = 2, genotype plus genotype by environment interaction (G+GEI), and singular-value partitioning (SVP = 1, focus on genotype). The concept of ideal genotype was also evaluated with the GGEbiplot software (Yan, 2001), using the same parameters as those for the mean and stability analyses.

Table 2. Identification of test locations in the states of Paraná (PR) and São Paulo (SP), Brazil, used to evaluate 46 soybean cultivars, in the 2014/2015 crop season[(1)].

Municipality, state[(1)]	Macro-region[(2)]	Micro-region[(2)]	Latitude	Longitude	Altitude (m)	Climate[(3)]
Cambé, PR	2	201	23°16'S	51°16'W	520	Cfa
CM, SP	2	201	22°44'S	50°23'W	440	Cwa
Corbélia, PR	2	201	24°47'S	53°18'W	650	Cfa
Mamborê, PR	2	201	24°19'S	52°31'W	715	Cfa
Palotina, PR	2	201	24°17'S	53°50'W	330	Cfa
Realeza, PR	1	102	25°46'S	53°31'W	520	Cfa
SJI, PR	2	202	23°25'S	52°17'W	560	Cfa
SMI, PR	2	201	25°20'S	54°14'W	290	Cfa

[(1)]CM, Cândido Mota municipality; SJI, São Jorge do Ivaí municipality; SMI, São Miguel do Iguaçu municipality. [(2)]Macroregion is determined by latitude (photoperiod/temperature) and rainfall; and microregions, within a same macroregion, differ by temperature (altitude) and soil type (Kaster & Farias, 2012). [(3)]The climate refers to Köppen climate classification.

Results and Discussion

In the combined analysis, the estimation of heritability in the broad sense (h^2_g) for grain yield (GY) was 0.37 (±0.05), which is lower than the estimate usually obtained for agronomic characters controlled by a few genes, but within the expected range for characters controlled by many genes of small effects, as GY (Table 3). Low values of h^2_g indicate the need for a breakdown in the GEI because they result from changes in the behavior of the genotypes in the studied sites (Rosado et al., 2012). Interaction analysis allows the maximization of selection gains, when testing homozygous clones or lines. Similar results were obtained by other authors (Pinheiro et al., 2013; Rocha et al., 2015; Andrade et al., 2016), who also found low-heritability estimates for soybean GY. The value of interaction variance ($V_{G\times A}$), when higher than the genotypic variance (V_G), also contributes to the low values of the h^2_g estimates. In the individual analysis of the sites, h^2_g was higher, ranging from 0.60 to 0.92, which indicates that a large part of the phenotypic variance (V_F) resulted from V_G. The value of standard deviation, at each site, was higher than that verified for the set of study environments, ranging from 0.19 to 0.23. However, these standard deviation values are within acceptable limits, which indicates that the predictions are reliable for use in breeding (Resende, 2004).

The genotypic coefficient of variation (CVgi%) was 11.73% in the combined analysis of sites, and ranged from 10.49%, in the municipality of Cambé, in Paraná state, to 23.41%, in the municipality of Cândido Mota, in São Paulo state. Sites with higher CVgi% values favor the discrimination of genotypes, that is, they promote a wider performance range, favoring selection. The residual coefficient of variation (CVe%) ranged from 4.95% in the municipality of Realeza, to 9.19% in the municipality of Palotina, both in the state of Paraná. These values are considered low and indicate good experimental

Tabela 3. Estimation of genetic parameters for each of the eight locations and of the set of locations for grain yield (GY) of 46 soybean cultivars.

Parameter	Location								Parameter	Mean of locations
	Cambé, PR	Corbélia, PR	Mamborê, PR	Palotina, PR	Realeza, PR	São Jorge do Ivaí, PR	São Miguel do Iguaçu, PR	Cândido Mota, SP	V_G	222102
V_G	198089	771929	903687	370107	327417	276953	683526	586966	V_{GxA}	292728
Ve	130764	105619	74431	69894	51372	117540	59123	87360	Ve	87014
V_F	328853	877548	978118	440001	378790	394494	742649	674326	V_F	601844
h^2_g	0.60(±0.19)	0.88(±0.22)	0.92(±0.23)	0.84(±0.22)	0.86(±0.22)	0.70(±0.20)	0.92(±0.23)	0.87(±0.22)	h^2_g	0.37 (±0.05)
h^2_{mg}	0.82	0.96	0.97	0.94	0.95	0.88	0.97	0.95	h^2_{mg}	0.85
Acgen	0.91	0.98	0.99	0.97	0.97	0.94	0.99	0.98	Acgen	0.92
CVgi%	10.49	18.42	22.85	21.15	12.49	12.69	20.23	23.41	c^2_{int}	0.49
CVe%	8.53	6.81	6.56	9.19	4.95	8.26	5.95	9.03	rgloc	0.43
PEV	35727	33671	24147	21918	16273	34324	19156	27744	CVgi%	11.73
SEP	189.01	183.50	155.39	148.05	127.57	185.27	138.40	166.56	CVe%	7.34
GY mean (kg ha^{-1})	4,242	4,770	4,160	2,876	4,582	4,148	4,087	3,273	General mean	4,017

V_G, genotypic variance; V_{GxA}, genotype x environment interaction variance; Ve, residual variance; V_F, individual phenotypic variance. h^2_g, heritability of individual plots of the total genotypic effects (in the broad sense); c^2_{int}, coefficient of determination of the G x E interaction effects; h^2_{mg}, heritability of the genotype mean; Acgen, accuracy of genotype selection; rgloc, genotypic correlation between perfomances in various environments; CVgi%, coefficient of genotypic variation; CVe%, coefficient of residual variation; PEV, variance of the prediction error of genotypic values; SEP, standard deviation of the predicted genotypic value.

precision. Genotypic selection accuracy (Acgen) for the set of sites was 0.92, and ranged from 0.91 in Cambé to 0.99 in Mamborê and in São Miguel do Iguaçu, all municipalities in the state of Paraná, indicating the high experimental precision obtained in all study environments. This parameter involves correlating the true genotypic value of the genetic treatment with the genotypic value estimated, or predicted, from experimental data. These values may be classified within the very high-accuracy class (Acgen > 0.90) (Resende & Duarte, 2007).

The genotypic correlation between performances in the various environments (rgloc) was 0.43. This value indicates the occurrence of a complex interaction between genotypes and test sites, which entails different genotypic responses at the different sites where they are evaluated, changing the ranking between sites (Costa et al., 2015). Furthermore, this also indicates that sites in the same soybean microregion of adaptation show considerable differences for cultivar performance. This is the case with microregion 201 (macroregion 2). The sites Realeza, in microregion 102 (macroregion 1), and São Jorge do Ivaí, in microregion 202 (macroregion 2), both in the state of Paraná, showed crop yield performance similar to that assessed in microregion 201. Besides, large variations of performance were observed even in study sites with latitude variation smaller than 3°. Therefore, breeders should conduct several comparative trials of cultivars within the same subregion, in order to identify the specificity of each site where they intend to plant their cultivars.

The mean GY of the trials was 4,017 kg ha^{-1} (Table 4), which is higher than the mean of the Midwestern-Southern region of Brazil (3,016 kg ha^{-1}), and higher than those of regions in Paraná (3,294 kg ha^{-1}) and São Paulo (2,970 kg ha^{-1}) states, according to Companhia Nacional de Abastecimento (Conab, 2016). The mean yields obtained in the trials for each site ranged from 2,876 kg ha^{-1}, in Palotina, to 4,770 kg ha^{-1} in Corbélia, both in the state of Paraná.

In the set of the evaluated environments, the highest yields were observed for NA 5909 RG, M6410IPRO, NS 5959 IPRO, NS6823RR, M5917IPRO, NS 6767 RR, and 6563RSF IPRO cultivars with 4,851, 4,705, 4,670, 4,644, 4,590, 4,589, and 4,578 kg ha^{-1} GY, respectively. The highest absolute production (6,265 kg ha^{-1}) was obtained

Table 4. Grain yield (kg ha-1) of soybean cultivars, grouping means by the Scott-Knott test, and mean of cultivars in eight sites GY ($\bar{X}$ G), mean of each location ($\bar{X}$ L), and mean of 46 soybean cultivars classified according to their cycle, in each site, in the 2014/2015 crop season.

Cultivar	Locations								
	Cambé, PR	Corbélia, PR	Mamborê, PR	Palotina, PR	Realeza, PR	São Jorge do Ivaí, PR	São Miguel do Iguaçu, PR	Cândido Mota, SP	$\bar{X}$ G
BMX Potência RR	4151cB	6186 aA	4453bB	3072cD	4348cB	4706bB	3656dC	3859bC	4304c
DMario 58i	4241cB	4373dB	4804bA	2325eC	4623bA	3982cB	4580bA	2602dC	3941d
NK 7059 RR	4020cC	5813bA	3957cC	3579bD	4461bC	3955cC	5277aB	3364cD	4303c
A 6411RG	3495dB	4105eA	1174eD	2307eC	3997cA	2840eC	2286fC	2601dC	2851h
BMX Ativa RR	2770eB	3030fA	972eD	1743eC	3308dA	2525eB	2269fB	1653fC	2284i
BMX Energia RR	3624dB	4445dA	4850bA	2817dC	4953bA	4088cB	3580dB	3857bB	4027d
NA 5909 RG	4614bB	5557bA	5373aA	3240cC	5343aA	4808bB	5283aA	4588aB	4851a
NS 4823	3816cB	3129fC	3771cB	2251eD	5086aA	3635dB	2836eC	2463dD	3373g
BMX Turbo RR	4495bB	5108cB	5577aA	2445eE	5000bB	3928cC	4824bB	3202cD	4322c
NS 5858	3947cB	3548fB	3897cB	2242eC	4619bA	4301cA	4278cA	3437cB	3784e
NS 6262	4156cB	3938eB	4664bA	2230eD	4980bA	4195cB	3963cB	2726dC	3856e
SYN1059 RR	5099aA	4810cA	4475bB	2586dD	4749bA	4320cB	4278cB	3605cC	4240c
NS 6767 RR	4999aB	5886bA	4686bB	3673bD	4104cD	4447cC	4909bB	4011aD	4589a
TMG 7262RR	4441bB	5123cA	4800bB	2158eC	5315aA	4634bB	4288cB	2502dC	4158c
NS 4901	3911cB	4182eB	3915cB	2255eD	5090aA	4067cB	3943cB	2832dC	3774e
NS 5258	4299bB	4052eB	4035cB	2175eC	4678bA	4670bA	4181cB	3677bB	3971d
NS 5290	4446bA	4228eA	4478bA	2424eB	4586bA	4441cA	4109cA	2317eB	3879e
NS 5401 RR	4093cA	3161fB	4008cA	2474dC	4083cA	4081cA	4033cA	2638dC	3571f
NS 6209	4199cB	5167cA	5253aA	3122cC	3984cB	3969cB	3607dB	3767bB	4134c
NS6121RR	3906cB	5345cA	3958cB	2886dC	4247cB	4189cB	3186eC	2976dC	3836e
NS6823RR	4586bB	6097aA	4277cC	3923bC	4699bB	4675bB	4458cB	4437aB	4644a
M6210IPRO	4328bC	5605bA	4257cC	3777bC	4117cC	4794bB	4705bB	3889bC	4434b
M6410IPRO	4613bB	5711bA	4184cC	2920dD	4815bB	5453aA	5296aA	4645aB	4705a
5958RSF IPRO	4686bB	5402cA	4657bB	3107cD	4188cC	3947cC	4951bB	3499cD	4305c
6458RSF IPRO	4056cC	4753dB	4668bB	3103cD	5130aA	4373cB	4158cC	3905bC	4268c
6563RSF IPRO	5342aA	5539bA	4970bB	3253cD	4763bB	4029cC	4373cC	4358aC	4578a
AS 3570IPRO	4200cA	3874eA	4063cA	2243eC	3834cA	4140cA	3084eB	3526cA	3621f
AS 3610IPRO	4329bB	5175cA	4625bA	3303cC	4776bA	4068cB	4870bA	4149aB	4412b
M5917IPRO	4215cC	5430cA	4793bB	3368cD	4797bB	4864bB	4870bB	4379aC	4590a
NS 5000 IPRO	4216cB	3360fC	3853cC	2785dD	4861bA	3762dC	3637dC	2217eE	3586f
NS 5106 IPRO	4131cC	4051eC	3961cC	2567dD	5416aA	4807bB	4370cC	2436dD	3967d
NS 5151 IPRO	4043cB	4238eB	3879cB	2656dD	5443aA	4093cB	3805cB	3259cC	3927d
NS 5445 IPRO	3328dC	4004eB	4355cB	2125eD	5056aA	3776dB	3172eC	2602dD	3552f
NS 5959 IPRO	4765bC	5120cB	5532aA	2725dE	5668aA	4490bC	5124aB	3936bD	4670a
NS 6909 IPRO	4579bA	4654dA	4600bA	2521dC	4665bA	4617bA	3796cB	2122eC	3944d
NS 7000 IPRO	4360bC	5730bA	3411dD	3866bD	4527bC	4923bB	4151cC	4152aC	4390b
NS 7209 IPRO	4178cB	6080aA	3026dD	4494aB	3489dC	4320cB	4613bB	3792bC	4249c
NS 7237 IPRO	4077cB	4895cA	3663cC	3437cC	3399dC	4326cB	2281fD	3019dC	3637f
NS 7300 IPRO	4114cC	6087aA	3975cC	3340cD	3091dD	3592dD	4852bB	3366cD	4052d
NS 7338 IPRO	4098cB	4628dA	3729cC	3647bC	3936cC	3629dC	4177cB	2712dD	3819e
NS 5727 IPRO	4722bA	3885eB	4274cB	2678dD	5182aA	3062eC	3178eC	2539dD	3690f
NS 6006 IPRO	4643bA	4420dB	5103aA	2754dC	4870bA	3961cB	4691bA	2505dC	4118c
NS6060IPRO	3224dB	3575fB	1343eD	1948eC	4898bA	2997eB	2150fC	2098eC	2779h
NS6700IPRO	4395bA	4691dA	4091cA	3369cB	4396cA	4376cA	4258cA	4251aA	4228c
NS6906IPRO	3940cC	6265aA	4474bB	3983bC	4279cC	3968cC	4945bB	3827bC	4460b
TMG2158PRO	5231aA	4975cA	4513bB	2388eD	4946bA	4005cC	4664bB	2275eD	4124c

with the NS6906IPRO, in Corbélia, PR, however, it did not differ significantly from the BMX Potência RR, NS6823RR, NS 7300 IPRO, and NS 7209 IPRO in the same environment; this behavior was not repeated in the other sites. BMX Ativa RR showed the worse average performance in the set of study sites, with 2,284 kg ha^{-1} GY.

The strongest, positive genetic effects were obtained for NA 5909 RG, M6410IPRO, NS 5959 IPRO, and NS6823RR, which had therefore the highest genetic values free of interaction (μ+g) (Table 5). The highest negative effects were obtained for the BMX Ativa RR, NS6060IPRO, and A 6411RG, with genetic values far below the average. The new estimated means suggest that the genotype ranking remained similar to that obtained by the comparison of the fixed-model means, and that changes occurred in genotypes with intermediate ranking. Similarly, the predicted genotypic (μ+g) values and the mean genotypic values (μ+g+gem) showed the same classification between genotypes; this indicates that the recommendation – besides being the same – can be made by both parameters; this also makes it possible to recommend the cultivars for untested sites in the experimental network using (μ+g) values, as the genotypic performance is free of interactions in this case. A similar result was also reported by Borges et al. (2012).

The NA 5909 RG, NS6823RR, M6410IPRO, and M5917IPRO were the most stable cultivars and had the highest mean yield based on the HMGV method. BMX Ativa RR, NS6060IPRO, and A 6411RG were the most unstable and least productive cultivars. The genotypic stability analysis using that method is related to the dynamic concept of stability, associated with GY (Resende, 2004); thus, the lower is the standard deviation of the genotypic performance between sites, the higher is the HMGV. Therefore, selection by HMGV simultaneously leads to selection for both yield and stability (Resende & Duarte, 2007).

NA 5909 RG, NS6823RR, M6410IPRO, NS 6767 RR, M5917IPRO, and NS 5959 IPRO cultivars had the highest RPGV*OM values. Selection using RPGV*OM enables the identification of the most adapted genotypes by increasing the ability of each genotype to respond favorably to an improvement in the production environment. Furthermore, this parameter is associated with the mean yield, which enables the identification of both well-adapted and productive genotypes. This method can be compared with the one reported by Annicchiarico (1992), since it uses relative performance. However, these two methods differ for their measurement of adaptability, which is genotypically performed by the RPGV*OM and, phenotypically performed in the method of Annicchiarico (1992) (Carbonell et al., 2007).

NA 5909 RG, M6410IPRO, NS6823RR, and NS 5959 IPRO cultivars had the highest values, based on the HMRPGV*OM method, which indicates that they are simultaneously the most productive, stable, and adapted to the study sites. BMX Ativa RR, NS6060IPRO, and A 6411RG cultivars had the worst yield performances, adaptability, and stability. That method has the advantage of assessing the relative performance of genotypes in the genotypic context, unlike other widely used methods, as the methods by Lin & Binns (1988) and Annichiarico (1992), which consider the values in the phenotypic context (Borges et al., 2010).

In the total set of cultivars, NA 5909 RG, NS 5959 IPRO, and M6410IPRO had the highest mean yields, based on the GGE biplot method (Figure 1). The classification is done in relation to the single-arrow line indicating that the farther to the right it is, the higher the genotype average will be. AS 3570IPRO, NS 6209, 6563RSF IPRO, and NA 5909 RG were the most stable cultivars because they showed a small projection in relation to the two-arrow line. However, these genotypes respond poorly to environmental changes. AS 3570IPRO cultivar failed to show both a high stability and mean yield, failing to meet the breeding objectives. However, NA 5909 RG cultivar had adequate values for both characteristics.

Among the early cultivars, BMX Energia RR and DMario 58i had the highest mean yields, and NS 4901 was the most stable cultivar. Among the medium-cycle cultivars, NA 5909 RG, NS 5959 IPRO, and M5917IPRO were the most productive genotypes, and 5958RSF IPRO the most stable ones. Among the late-cycle cultivars, M6410IPRO had the best yield performance associated with high stability. Similarly, the NS 6767 RR and NS6823RR cultivars were also productive and stable. The A 6411RG, NS 7237 IPRO, and NS 7338 IPRO showed high stability; however, they had the worst yield performances. Stability is measured biologically by the GGE biplot method, that is, the genotype has a consistent performance among all the environments, but fails to respond to environmental improvements (Jamshidmoghaddam & Pourdad, 2013).

Table 5. Genetic effects (g), predicted genotypic values (u+g), gain, new mean of the genotype, ranking of genotypes by the new mean (u+g+gem), mean genotypic value in the environments, and methods of adaptability and stability, using mixed models.

Cultivar	g	u+g	Gain	New mean	Rank	u+g+gem	HMGV	RPGV *OM	HMRPGV *OM
BMX Potência RR	242	4260	424	4441	14	4300	4155	4300	4254
DMario 58i	-64	3953	247	4265	29	3942	3702	3904	3852
NK 7059 RR	242	4259	412	4429	15	4299	4178	4317	4260
A 6411RG	-988	3029	57	4075	44	2867	2559	2866	2605
BMX Ativa RR	-1468	2550	0	4017	46	2308	2056	2291	2111
BMX Energia RR	8	4025	295	4313	25	4027	3913	4042	3998
NA 5909 RG	706	4723	706	4723	1	4839	4718	4855	4829
NS 4823	-545	3472	81	4099	43	3382	3195	3363	3293
BMX Turbo RR	258	4276	454	4472	12	4318	4059	4278	4219
NS 5858	-198	3819	181	4198	35	3787	3631	3785	3736
NS 6262	-136	3881	214	4231	32	3859	3630	3823	3773
SYN1059 RR	189	4206	376	4394	18	4237	4073	4223	4203
NS 6767 RR	484	4502	557	4574	6	4582	4497	4615	4572
TMG 7262RR	119	4136	354	4371	20	4156	3795	4081	3992
NS 4901	-206	3812	170	4187	36	3778	3582	3745	3716
NS 5258	-39	3978	282	4300	26	3972	3780	3960	3908
NS 5290	-118	3900	225	4243	31	3880	3634	3841	3782
NS 5401 RR	-378	3640	108	4126	41	3577	3445	3580	3533
NS 6209	98	4116	341	4359	21	4132	4028	4155	4104
NS6121RR	-153	3864	203	4220	33	3839	3701	3830	3800
NS6823RR	531	4548	593	4610	4	4635	4572	4683	4634
M6210IPRO	353	4370	505	4522	9	4428	4366	4473	4427
M6410IPRO	582	4599	644	4661	2	4695	4529	4704	4646
5958RSF IPRO	243	4261	438	4455	13	4301	4179	4306	4279
6458RSF IPRO	212	4230	399	4417	15	4265	4178	4283	4266
6563RSF IPRO	475	4492	545	4562	7	4570	4460	4590	4555
AS 3570IPRO-(M 3570 IPRO)	-336	3681	133	4150	39	3626	3493	3632	3586
AS 3610IPRO	334	4352	488	4505	10	4407	4332	4436	4412
M5917IPRO	484	4502	571	4588	5	4582	4501	4612	4585
NS 5000 IPRO	-365	3652	121	4138	40	3592	3422	3585	3520
NS 5106 IPRO	-42	3975	270	4288	27	3968	3721	3932	3862
NS 5151 IPRO	-76	3941	237	4254	30	3928	3789	3918	3896
NS 5445 IPRO	-394	3624	96	4114	42	3559	3337	3522	3466
NS 5959 IPRO	552	4570	613	4631	3	4661	4451	4639	4601
NS 6909 IPRO	-62	3955	259	4276	28	3945	3648	3895	3809
NS 7000 IPRO	315	4333	472	4489	11	4385	4301	4436	4353
NS 7209 IPRO	196	4213	387	4405	17	4246	4113	4328	4130
NS 7237 IPRO	-322	3695	145	4163	38	3642	3495	3681	3540
NS 7300 IPRO	30	4047	307	4325	24	4052	3895	4074	3956
NS 7338 IPRO	-168	3850	192	4209	34	3822	3744	3858	3807
NS 5727 IPRO	-277	3740	158	4175	37	3694	3492	3676	3597
NS 6006 IPRO	85	4103	319	4337	23	4117	3883	4087	4024
NS6060IPRO	-1048	2969	33	4050	45	2796	2473	2764	2546
NS6700IPRO	179	4196	366	4383	19	4225	4187	4276	4243
NS6906IPRO	375	4392	524	4541	8	4454	4356	4496	4416
TMG2158IPRO	91	4108	330	4347	22	4123	3778	4059	3960

HMGV, harmonic mean of the genotypic values; RPGV*OM, relative performance of the predicted genotypic values multiplied by the overall mean of all environments; HMRPGV*OM, harmonic mean of the relative performance of the genotypic values multiplied by the overall mean of all environments.

The ideal cultivar – the one closest to the center of the concentric circles – is based on high yield and stability criteria (Yan, 2015). Therefore, in the combined analysis, NA 5909 RG and M6410IPRO may be considered ideal cultivars (Figure 2). BMX Energia RR and DMario 58i stood out among all the early cultivars, and NA 5909 RG, which proved ideal, stood out among the medium-cycle cultivars. Among the late cultivars, M6410IPRO was the closest to the ideal cultivar. Identifying adapted and stable genotypes for a wide region enables breeders to use this source of germplasm towards developing

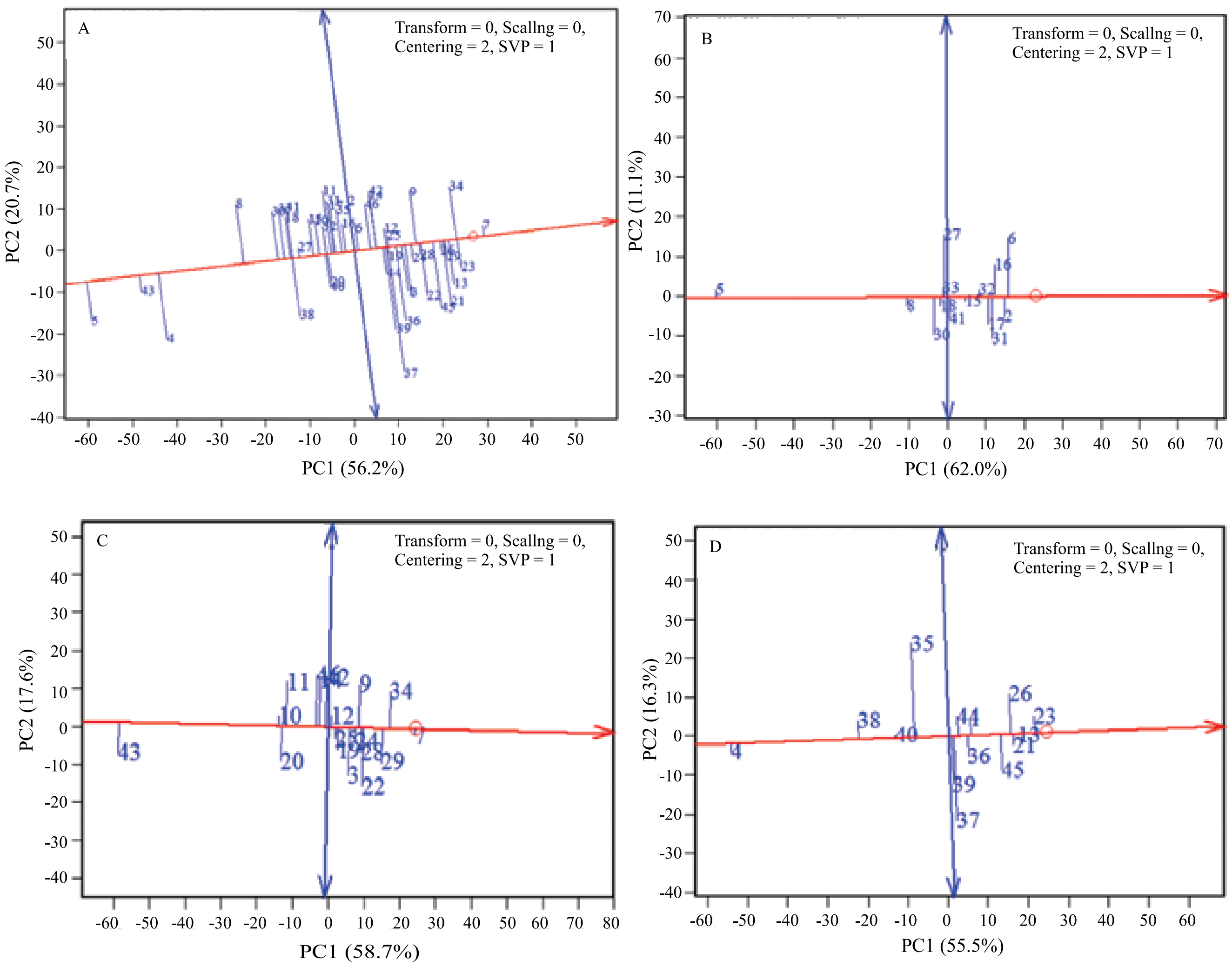

Figure 1. Mean and stability for the set of 46 soybean cultivars (A), and for the cultivar division in early (B), medium (C) and late cycles (D), evaluated in eight locations – seven of which in the state of Paraná (Cambé, Corbélia, Mamborê, Palotina, Realeza, São Jorge do Ivaí, and São Miguel do Iguaçu), and one in the state of São Paulo (Cândido Mota) –, in the 2014/2015 crop season. Cultivars: BMX Potência RR (1), DMario 58i (2), NK 7059 RR (3), A 6411RG (4), BMX Ativa RR (5), BMX Energia RR (6), NA 5909 RG (7), NS 4823 (8), BMX Turbo RR (9), NS 5858 (10), NS 6262 (11), SYN1059 RR (12), NS 6767 RR (13), TMG 7262RR (14), NS 4901 (15), NS 5258 (16), NS 5290 (17), NS 5401 RR (18), NS 6209 (19), NS6121RR (20), NS6823RR (21), M6210IPRO (22), M6410IPRO (23), 5958RSF IPRO (24), 6458RSF IPRO (25), 6563RSF IPRO (26), AS 3570IPRO (27), AS 3610IPRO (28), M5917IPRO (29), NS 5000 IPRO (30), NS 5106 IPRO (31), NS 5151 IPRO (32), NS 5445 IPRO (33), NS 5959 IPRO (34), NS 6909 IPRO (35), NS 7000 IPRO (36), NS 7209 IPRO (37), NS 7237 IPRO (38), NS 7300 IPRO (39), NS 7338 IPRO (40), NS 5727 IPRO (41), NS 6006 IPRO (42), NS6060IPRO (43), NS6700IPRO (44), NS6906IPRO (45), and TMG2158IPRO (46). PC, principal component.

new cultivars for adaptation to a wide range of environments.

The methods to identify ideal genotypes via GGE, and stability via HMGV, coincided to show NA 5909 RG and M6410IPRO as superior cultivars. However, these two methods are not always coincident in the identification of adapted and stable genotypes. Yang et al. (2009) suggest that their simultaneous use is advantageous because these parameters consider the phenotype, when using GGE, and the genotype, when using mixed models. These methods also showed agreement regarding the cultivars with the worst performances, in which BMX Ativa RR, NS6060IPRO, and A 6411RG were the least stable and productive ones.

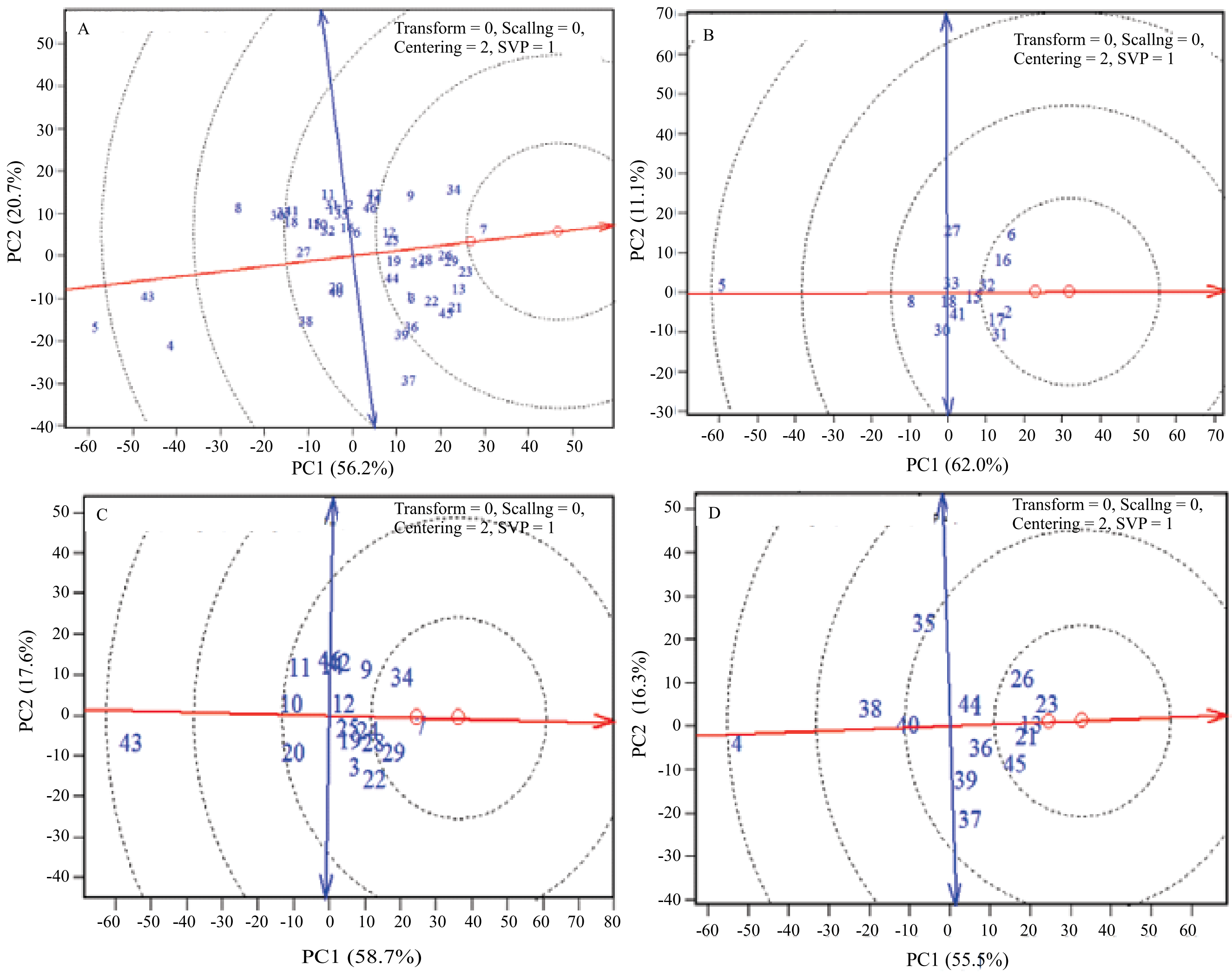

Figure 2. Ideal genotype of the set of 46 soybean cultivars (A), and for the cultivar divisions in early (B), medium (C) and late cycles (D), evaluated in eight locations – seven of which in the state of Paraná (Cambé, Corbélia, Mamborê, Palotina, Realeza, São Jorge do Ivaí, and São Miguel do Iguaçu), and one in the state of São Paulo (Cândido Mota) –, in the 2014/2015 crop season. Cultivars: BMX Potência RR (1), DMario 58i (2), NK 7059 RR (3), A 6411RG (4), BMX Ativa RR (5), BMX Energia RR (6), NA 5909 RG (7), NS 4823 (8), BMX Turbo RR (9), NS 5858 (10), NS 6262 (11), SYN1059 RR (12), NS 6767 RR (13), TMG 7262RR (14), NS 4901 (15), NS 5258 (16), NS 5290 (17), NS 5401 RR (18), NS 6209 (19), NS6121RR (20), NS6823RR (21), M6210IPRO (22), M6410IPRO (23), 5958RSF IPRO (24), 6458RSF IPRO (25), 6563RSF IPRO (26), AS 3570IPRO (27), AS 3610IPRO (28), M5917IPRO (29), NS 5000 IPRO (30), NS 5106 IPRO (31), NS 5151 IPRO (32), NS 5445 IPRO (33), NS 5959 IPRO (34), NS 6909 IPRO (35), NS 7000 IPRO (36), NS 7209 IPRO (37), NS 7237 IPRO (38), NS 7300 IPRO (39), NS 7338 IPRO (40), NS 5727 IPRO (41), NS 6006 IPRO (42), NS6060IPRO (43), NS6700IPRO (44), NS6906IPRO (45), and TMG2158IPRO (46). PC, principal component.

Conclusions

1. NA 5909 RG, M6410IPRO, NS 5959 IPRO, NS6823RR, M5917IPRO, NS 6767 RR, and 6563RSF IPRO are the most productive cultivars in the study environments, and BMX Ativa RR shows the worst yield performance.
2. NA 5909 RG, NS6823RR, M6410IPRO, and NS 5959 IPRO show high yield, adaptability, and stability, and may be considered ideal cultivars for cultivation in the study sites.
3. There are modern soybean cultivars which are ideal for cultivation in the Brazilian soybean microregions of adaptation 102, 201, and 202.

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