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ADAPTABILITY AND STABILITY OF SOYBEAN GENOTYPES RECOMMENDED FOR ALTO PARANAÍBA IN MINAS GERAIS

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ABSTRACT - The cultivation of soybean (*Glycine max* (L.) Merr.) stands out in the national and world scenario. Brazil, from different points of view, has a high productive capacity of this oilseed, which resulted in the classification of the country as the world's largest producer. The state of Minas Gerais is one of Brazil's agricultural granaries, and in soybean culture it is the sixth largest producing state. Thus, the objective was to evaluate the interaction genotypes x environments in soybean genotypes grown in Alto Paranaíba, Minas Gerais, and to identify genotypes with general response, those recommended for favorable or unfavorable environments through the different methodologies of adaptability and stability. Five experiments were conducted in the experimental block design, with four repetitions, in the 2020/2021 agricultural season, in which 14 soybean genotypes were analyzed by productivity, in kg ha^{-1}. An individual analysis of variance was performed (for each environment) along with joint analysis of the experiments, average grouping test (for each environment), decomposition of the interaction between genotypes and pairs of environments and the adaptability and stability analyses were performed. It was concluded that the interaction genotypes x environments was significant and between pairs of environments it was predominantly complex, the genotypes M5917IPRO, TMG7063IPRO and BMXFocoIPRO are recommended for general environment, the genotypes TMG2374IPRO and TMG7363RR are recommended for favorable environments, and the genotypes BS2606IPRO, TEC7849IPRO and BRS5980IPRO are recommended for unfavorable environments.
Keywords: *Glycine max* (L.) Merr., artificial neural networks, genetic improvement.

ADAPTABILIDADE E ESTABILIDADE DE GENÓTIPOS DE SOJA RECOMENDADOS PARA O ALTO PARANAÍBA EM MINAS GERAIS

RESUMO - A cultura da soja (*Glycine max* (L.) Merr.) destaca-se no cenário nacional e mundial. O Brasil, sob diferentes óticas, possui elevada capacidade produtiva desta oleaginosa o que resultou na classificação do país em maior produtor mundial. O estado de Minas Gerais é um dos celeiros agrícolas do Brasil, sendo que na cultura da soja é o sexto maior estado produtor. Assim, objetivou-se avaliar a interação genótipos x ambientes em genótipos de soja cultivados no Alto Paranaíba, Minas Gerais e identificar genótipos com reposta geral, os recomendados para ambientes favoráveis ou desfavoráveis, por meio das diferentes metodologias de adaptabilidade e estabilidade. Foram conduzidos cinco experimentos no delineamento experimental em blocos, com quatro repetições, na safra-agrícola 2020/2021, nos quais foram analisados 14 genótipos de soja por meio da produtividade, em kg ha^{-1}. Procedeu-se a análise de variância individual (para cada ambiente), análise conjunta dos experimentos, teste de agrupamento de média (para cada ambiente), decomposição da interação entre genótipos e pares de ambiente. A interação genótipos x ambientes foi significativa e entre os pares de ambientes ela foi predominantemente complexa; os genótipos M5917IPRO, TMG7063IPRO e BMXFocoIPRO são recomendados para ambiente geral; os genótipos TMG2374IPRO e TMG7363RR são recomendados para ambientes favoráveis; e os genótipos BS2606IPRO, TEC7849IPRO e BRS5980IPRO são recomendados para ambientes desfavoráveis.
Palavras-chave: *Glycine max* (L.) Merr., redes neurais artificiais, melhoramento genético.

INTRODUCTION

Soybean production in the 2021/2022 harvest is expected to increase by 2.5 % over the previous harvest, reaching 140.75 million tons, maintaining Brazil as the world's largest producer of the oilseed (CONAB, 2021). Minas Gerais was the first state to introduce and improve cultivars for adaptation to the Cerrado region, besides developing technologies for planting, harvesting, seed quality, weed management, soil fertility, and pest and disease reduction (SEDIYAMA et al., 2021). In the estimate for the 2021/2022 harvest, the state of Minas Gerais stands out as the third state with the highest average productivity, with an estimated productivity of 3,709 kg ha^{-1}, exceeding the Brazilian average by 5.2 %, and as the sixth state in total production, with an estimated production of 7.04 million tons (CONAB, 2021).

Triângulo Mineiro/Alto Paranaíba is in the edaphoclimatic region 303, REC 303, within macro-region 3, MRS 3, (EMBRAPA, 2018). The Agricultural Climate Risk Zoning for soybean culture in the state of Minas Gerais, crop year 2021/2022 was approved by the Bureau of Agricultural Policies of the Ministry of Agriculture, Livestock and Supply, on May 11, 2021, according to the Ordinance n. 121. This decree indicates, by soybean crop

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macro-region, the soybean cultivars for the state of Minas Gerais (BRASIL, 2021). A large number of new soybean cultivars are launched on the market to meet the growing demand resulting from agricultural expansion, besides offering cultivars that have high productivity performance and that add other essential agronomic characteristics required by the consumer and producer market (RODRIGUES et al., 2020).

The large number of cultivars with potential use for the same growing region makes it difficult to identify the one that will perform best in a given location within the REC 303, because grain yield evaluation in soybean breeding improvement is one of the most costly and time-consuming phases, and the new strain must be compared with at least two standard cultivars of the growing region (within a given maturity group) (SEDIYAMA et al., 2015).

When a series of environments is considered, it is possible to detect, in addition to the genetic and environmental effects, an additional effect provided by their interaction (CRUZ et al., 2004). The evaluation of the interaction genotypes x environments becomes of great importance in breeding, because if it exists, there is the possibility that the best genotype in one environment is not in another, and this fact, according to the authors, hinders the recommendation of cultivars with wide adaptability (CRUZ et al., 2017). The identification of cultivars with predictable behavior and that are responsive to environmental variations, under specific or broad conditions, can be performed through the analysis of adaptability and stability (CRUZ et al., 2004).

Several methods have been proposed for the evaluation of phenotypic adaptability and stability, where the difference between them is based on the proper biometric concepts and procedures to quantify the interaction genotypes x environments (RODRIGUES et al., 2020). The method of Eberhart and Russell (1966) has been the most used for adaptability and stability studies in soybean and corn crops in the last 50 years (REZENDE et al., 2021). Nascimento et al. (2013) proposed a methodology for phenotypic adaptability and stability based on training an artificial neural network (ANN) considering the methodology of Eberhart and Russell (1966). Several studies have reported the efficiency of this ANN compared to the Eberhart and Russell technique (ALVES et al., 2019; ODA et al., 2022).

The interaction genotypes x environments can also be studied focused on adaptability and stability through methodologies based on principal component analysis, such as the centroid method. The use of an alternative method for studying the genotype x environment interaction in plant species, based on multivariate analysis methodology using principal components, which is characterized by associating the advantages of this methodology to studies of the genotype x environment interaction, namely the centroid method, consists of comparing the individual response of cultivars with the response of four ideal cultivars, of maximum or minimum response in relation to the set of data that was evaluated (ROCHA et al., 2005).

The methodology of Lin and Binns (1988) is very promising to be used by breeders to recommend cultivars (CARNEIRO, 1998). This author suggested, in this methodology, the decomposition of the Pi estimator in the parts due to favorable and unfavorable environments that reflect, in a certain way, environments where there is employment of high and low technology, respectively.

In this context, the information obtained in the adaptability and stability methodologies should be a complement to the information obtained in the field, helping the improver in the recommendation of their cultivars (RODRIGUES et al., 2020). Thus, the objective was to evaluate the interaction genotypes x environments in soybean genotypes grown in Alto Paranaíba, Minas Gerais and to identify genotypes with general response and those recommended for favorable and unfavorable environments, through the different methodologies of adaptability and stability.

MATERIAL AND METHODS

In the 2020/2021 crop year at Rio Paranaíba, Minas Gerais, were conducted soybean experiments in five environment (environment 1: 19°16’21,7” S, 46°06’1,4” W and 1,169 m of altitude; environment 2: 19°15’59.9” S, 46°14’42.3” W and 1,138 m of altitude, environment 3: 19°15’29.4” S, 46°14’21.4” W and 1,147 m of altitude, environment 4: 19°15’37.8” S, 46°14’47.5” W and 1,144 m of altitude and environment 5: 19°20’39.6” S, 46°12’40.0” W and 1,153 m of altitude). The sowing date was 05th, 17th, 18th, 19th and 22nd November, 2020 and the harvest date was 22nd, 24th, 25th, 25th and 11th March, 2021, respectivety to environment 1, 2, 3, 4, and 5. In these, it was analyzed the productivity (kg ha^{-1}) of fourteen genotypes (96Y90, 95R95IPRO, M5917IPRO, M6972IPRO, TMG7368IPRO, TMG2374IPRO, TMG7063IPRO, TMG7363RR, TEC7849IPRO, DS6217IPRO, BS2606IPRO, BMXFocoIPRO, BRS5980IPRO and CZ26B77IPRO).

The experiments were conducted using a randomized block design with four repetitions. The plots were formed by four 5.0 m long rows of plants, spaced 0.50 m apart. The useful area of the plot was 4.0 m^2, with the two central rows being harvested, disregarding 0.50 m of border at the extremities, threshed and measured the mass per plot. Later, the productivity was adjusted to 13% humidity.

The results were submitted to the individual analysis of variances of each environment (considering previous tests to evaluate the normality of errors and homogeneity of variances), followed by the joint analysis of variance. To evaluate the homogeneity of the residual variances of the experiments it was used the ratio between the largest and smallest residual average square of the individual trials and considered homogeneous variances if this ratio is less than 7.0, as recommended by Pimentel-Gomes (2009). The analysis of variance was performed using the randomized block model, consisting of fixed effects for genotypes and random effects for environments and interaction of genotypes x environments. The model for this analysis is given by Equation 1:

$Y_{ijk} = m + G_i + B/A_{jk} + A_k + GA_{ik} + E_{ijk}$ (Equation 1)

Where:

Y_{ijk} = productivity in genotype i in block j and within environment k,

m = overall mean,

G_i = effect of genotype i,

B/A_{jk} = random effect of block j within environment k,

A_k = random effect of environment k,

GA_{ik} = random effect of the interaction of genotype i with environment k and

E_{ijk} = experimental error.

The averages of the genotypes in each environment were grouped using the Scott-Knott test at 5% probability, and then for pairs of environments, the percentage of the complex part resulting from the decomposition of the interaction between genotypes and pairs of environments was obtained, according to the methodology of Cruz and Castoldi (1991). The adaptability and stability analyses were performed by the methods of Artificial Neural Networks (NASCIMENTO et al., 2013), Lin and Binns (1988) modified by Carneiro (1998) and Centroid method (ROCHA et al., 2005).

Regarding the artificial neural network (ANN), the data set used for training purposes was established by simulation from the parameters of the model of Eberhart and Russell (1966), and the criteria for the classification of genotypes as to adaptability and stability by the ANN were established as described by Nascimento et al. (2013). In the present work, the neural network of the perceptron type, with back-propagation single hidden layer training algorithm was used. Specifically, the ANN has 1 input layer, 1 intermediate layer, and 1 output layer. The first layer has 5 inputs, which refer to the average yield values evaluated in 5 environments. In the intermediate layer the number of neurons varied from 1 to 10 neurons.

The output layer was composed of 6 neurons, whose output was given by the classification of the genotype in one of six classes (class 1: general adaptability and low predictability; class 2: specific adaptability to favorable environments and low predictability; class 3: specific adaptability to unfavorable environments and low predictability; class 4: general adaptability and high predictability; class 5: specific adaptability to favorable environments and high predictability; class 6: specific adaptability to unfavorable environments and high predictability), defined by Eberhart and Russell (1966).

The necessary arguments for the network function, such as number of neurons in the hidden layer, initial values for the weights, decay rate and maximum iterations were chosen considering the network that provided an error value of at most 2% for the test set, as performed by Nascimento et al. (2013) and Barroso et al. (2013). The best network architecture was established considering a classification error of less than 2%. For ANN analysis, of the 14 soybean genotypes under study, the *nnet* function of the *nnet* package (VENABLES; RIPLEY, 2002) implemented in R (R Development Core Team, 2021) was used for adaptability evaluation by means of the artificial neural network.

The Centroid method is based on the comparison of cartesian distance values between the genotypes and four ideal references (ideotypes), created based on experimental data to represent the genotypes of maximum general adaptability, maximum specific adaptability to favorable or unfavorable environments and the genotypes of minimum adaptability (ROCHA et al., 2005). The genotypes can be classified in one of the ideotypes: ideotype I: presents maximum general adaptability, having maximum values observed in all environments; ideotype II: has maximum specific adaptability to favorable environment, presenting maximum response in favorable environment and minimum in unfavorable environment; ideotype III: has maximum specific adaptability to unfavorable environment, presenting maximum response in unfavorable environment and minimum in favorable environment or ideotype IV: has minimum adaptability, presenting minimum values observed in all environments (ROCHA et al., 2005). To use this method, the environments are classified into favorable and unfavorable, using the environmental index proposed by Finlay and Wilkinson (1963). Consequently, the genotypes were classified in one of the classes: class I: general adaptability; class II: specific adaptability to favorable environments; class III: specific adaptability to unfavorable environments; class IV: poorly adapted (ROCHA et al., 2005).

In the methodology proposed by Lin and Binns (1988), the mean square of the distance between the mean of the genotype and the maximum mean response obtained in the environment is defined as a measure to estimate the stability and adaptability of genotypes, given by Equation 2:

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

Where:

P_i = estimate of stability and adaptability of genotype I,

X_{ij} = yield of the i-th genotype at the j-th location (environment),

M_j = maximum observed response among all genotypes at location (environment) j and

n = number of locations (environments).

In the methodology proposed by Carneiro (1998), modifications were made to the method proposed by Lin and Binns (1988) so that the recommendation would meet the groups of favorable and unfavorable environments. For this, the parameter P_i was named MAEC (Measure of Adaptability and Stability of Behavior) referring to the performance and behavior of environmental variations. The classification of these environments was made based on the environmental indices, defined as the difference between the average of the genotypes evaluated in each location and the general average.

The MAEC parameters, for favorable and unfavorable environments according to Carneiro (1998) are defined below. For favorable environments, with positive rates including the value zero, the MAEC parameter (P_{if}) is given by Equation 3:

$$P_{if} = \frac{\sum_{j=1}^{f}(X_{ij}-M_j)^2}{2f} \quad \text{(Equation 3)}$$

Where:

P_{if} = estimate of stability and adaptability of genotype *i* in favorable environments,

X_{ij} = productivity of the i-th genotype in the j-th location (environment),

M_j = maximum observed response among all genotypes in location (environment) *j* and

f = number of favorable locations (environments).

For unfavorable environments, with positive indices including the value zero, the MAEC parameter (P_{if}), is given by Equation 4:

$$P_{id} = \frac{\sum_{j=1}^{d}(X_{ij}-M_j)^2}{2d} \quad \text{(Equation 4)}$$

Where:

P_{id} = estimate of stability and adaptability of the genotype *i* in unfavorable environments

X_{ij} = productivity of the i-th genotype in the j-th location (environment),

M_j = maximum response observed among all genotypes in location (environment) *j* and

d = number of unfavorable locations (environments).

Statistical analyses, except for ANN-specific ones, were performed in the Genes Program (CRUZ, 2013).

RESULTS AND DISCUSSION

In each environment, the treatment effect was significant at less than 5% significance level (Table 1), indicating the possibility of selecting superior genotypes within each of the experiments. The mean yield values obtained in all experiments were higher than those reported by Conab (2021), whose national average yield for the 2020/2021 crop was 3527.80 kg ha^{-1} and for the state of Minas Gerais, the average yield was 3845.80 kg ha^{-1}.

TABLE 1 - Estimates of mean square of blocks, genotypes and residual, p-valor, average (kg ha^{-1}) and coefficient of variation of five environment, agricultural year 2020/2021.

Environments	Mean squares			p-value	Averages	CV(%)
	Blocks	Genotypes	Residue	for genotypes	(kg ha^{-1})	
1	276701.695	456348.732	99487.124	0.001	4519.72	6.98
2	80311.269	173410.635	58895.549	0.005	4761.17	5.10
3	50613.549	56936.715	28206.976	0.046	4595.88	3.65
4	34610.955	921897.020	95175.584	0.001	4994.63	6.18
5	309578.332	392939.360	177564.862	0.028	4347.45	9.69

The values of coefficient of variation, obtained in the five environments, are lower than those found in the literature (BICALHO et al., 2019; ODA et al., 2022) and similar to that found by Finoto et al. (2021), whose objectives of the mentioned works were similar to the present manuscript. The estimate of the ratio of the highest QMR by the lowest QMR of the individual analysis of variance was 6.3. This indicates that it is possible to analyze the data through the joint analysis, from a mean residual, since the ratio between the largest and smallest residual mean square of the individual trials was less than 7 which can be considered as homogeneous variances (PIMENTEL-GOMES, 2009).

The variances associated with the random effects of the interaction between genotypes and environments, of environments and the effect of genotype, in the joint analysis of variance, were significant ($p < 0.01$) (Table 2).

TABLE 2 - Summary of the joint variance analysis for grain yield of 14 soybean genotypes at five environment, agricultural year 2020/2021.

Sources of variation	Degrees of freedom	Mean Square
Blocks/Environments	15	150363.1600
Genotypes	13	342370.0423**
Environments	4	3393211.6911**
Genotypes x Environments	52	414790.6047**
Residue	195	91866.0190
General average (kg ha^{-1})		4643.80
Coefficient of variation (%)		6.53

**Significant at 1% probability by the F test.

The significance of the interaction genotype and environment demonstrates that there is a variation in the response of genotypes in different environments, indicating the existence of genotypes adapted to particular environments and/or with wider adaptation. With this, it becomes necessary to study in detail the response of genotypes to environmental variations, for example, through the analysis of adaptability and stability (CRUZ et al., 2004; ODA et al., 2022).

The average grain yield ranged from 3909.8 kg ha^{-1} (environment 5) to 5581.1 kg ha^{-1} (environment 4), that is, a range of 1671.3 kg ha^{-1} (27.9 bags of 60 kg), and with an overall average of 4643.8 kg ha^{-1} (Table 3). In environment 1, the highest yields were obtained with the genotypes: 95R95IPRO, M5917IPRO, TMG7368IPRO, TMG2374IPRO, TMG7063IPRO, TEC7849IPRO, DS6217IPRO and BRS5980IPRO. In environment 2, the highest yields were obtained with the genotypes: 96Y90, 95R95IPRO, M5917IPRO, DS6217IPRO, BMX Focus and CZ26B77IPRO. In environment 4, the highest were: 96Y90, TMG7368IPRO, TMG2374IPRO, TMG7063IPRO, TMG7363RR, DS6217IPRO and BMXFocoIPRO. In environment 5: 96Y90, 95R95IPRO, M6972IPRO, BS2606IPRO, BMXFocoIPRO and BRS5980IPRO.

TABLE 3 - Average grain yield, in kg ha^{-1}, of 14 soybean genotypes, evaluated in five environments (ENV) in the state of Minas Gerais, agricultural year 2020/2021.

Genotypes	ENV 1	ENV 2	ENV 3	ENV 4	ENV 5
96Y90	4157.4b[1]	4901.4a	4614.3a	5120.3a	4545.7a
95R95IPRO	4632.5a	4825.2a	4514.6a	4792.9b	4679.0a
M5917IPRO	4677.6a	4945.6a	4574.2a	4954.1b	4344.7b
M6972IPRO	4197.7b	4740.2b	4410.3a	4110.9c	4762.3a
TMG7368IPRO	4763.9a	4685.8b	4640.2a	5399.2a	4063.7b
TMG2374IPRO	4922.2a	4731.5b	4542.2a	5413.1a	3975.6b
TMG7063IPRO	4943.6a	4654.5b	4722.3a	5431.8a	4117.5b
TMG7363RR	4002.9b	4659.6b	4383.2a	5581.1a	4057.8b
TEC7849IPRO	4770.6a	4339.7b	4681.7a	4574.2b	4304.7b
DS6217IPRO	4936.1a	4842.3a	4665.3a	5444.4a	4096.8b
BS2606IPRO	4444.9b	4754.2b	4838.8a	4683.2b	4672.3a
BMXFocoIPRO	4130.7b	5167.4a	4526.0a	5469.1a	4797.6a
BRS5980IPRO	4560.0a	4458.1b	4600.9a	4621.2b	4536.8a
CZ26B77IPRO	4136.0b	4950.9a	4628.4a	4329.3c	3909.8b
Average (kg ha^{-1})	4519.7	4761.2	4595.9	4994.6	4347.5
General Average (kg ha^{-1})			4643.80		
CV(%)			6.53		

[1]Averages followed by the same letter in each column constitute a homogeneous group by the Scott-Knott test at 5% probability

Average grain yield, in kg ha^{-1}, regarding adaptability and phenotypic stability of 14 soybean genotypes, evaluated in five environments in the state of Minas Gerais, by the ANN method (NASCIMENTO et al., 2013), in the 2020/2021 agricultural crop. Most pairs of environments had complex type interaction (Table 4). These indicates that there is inconsistency in the superiority of the genotype with the environmental variation, which makes it difficult to indicate the genotypes (CRUZ; CASTOLDI, 1991; VENCOVSKY; BARRIGA, 1992). The single recommendation for all locations, when the interaction is of the complex type, it cannot be performed, since there is the possibility of loss in production (PELUZIO et al., 2008; BARROS et al., 2010). Thus, the interaction of complex nature reveals the need to use elaborate strategies in breeding programs in terms of specific genotype recommendations for each region (POSSOBOM et al., 2020).

TABLE 4 - Environment pairs and percentage of the complex part resulting from the decomposition of the interaction between genotypes and pairs of environments, according to the methodology of Cruz and Castoldi (1991), agricultural season 2020/2021.

Pairs of environments	Complex part of the interaction	Pairs of environments	Complex part of the interaction
I x II	108.0	II x IV	61.1
I x III	35.1	II x V	81.3
I x IV	80.1	III x IV	48.6
I x V	115.7	III x V	71.8
II x III	94.8	IV x V	109.4

According to Cruz et al. (2004), values above 100% occur in cases where the correlation of the means of the genotypes in two environments is negative.

By the ANN method (NASCIMENTO et al., 2013) it was possible to establish the neural network with 5 neurons in the input layer, 9 neurons in the hidden layer, and 6 neurons in the output layer. When analyzing the averages of the genotypes, based on all experiments, it was identified that 96Y90 (4667.8 kg ha^{-1}), 95R95IPRO (4688.8 kg ha^{-1}), M5917IPRO (4699.3 kg ha^{-1}), TMG7368IPRO (4710.6 kg ha^{-1}), TMG2374IPRO (4716. 9 kg ha^{-1}), TMG7063IPRO (4773.9 kg ha^{-1}), DS6217IPRO (4797.0 kg ha^{-1}), BS2606IPRO (4678.7 kg ha^{-1}) and BMXFocoIPRO (4818.2 kg ha^{-1}) had higher average yields than the general average, which was 4643.8 kg ha^{-1}.

The classification of the genotype by means of ANN (NASCIMENTO et al. 2013) considers one of the six adapted classes of Eberhart and Russell (1966). The interpretation of the results of the adaptability analysis, fundamental for the recommendation of genotypes according to Eberhart and Russell (1966), is done in the same way as described for the methodology of Finlay and Wilkinson (1963) (CRUZ et al., 2004).

Considering the genotypes with the highest averages compared to the general average of the experiments, it was identified that 96Y90, 95R95IPRO, M5917IPRO, TMG7368IPRO, TMG7063IPRO, DS6217IPRO and BMXFocoIPRO present general adaptability. When adding the criterion of high stability, 96Y90, M5917IPRO, TMG7063IPRO and BMXFocoIPRO were retained. For adaptability to favorable environments and high stability, TMG2374IPRO was identified. And, for adaptability to unfavorable environments and high stability, BS2606IPRO is indicated (Table 5).

TABLE 5 - Average grain yield, in kg ha^{-1}, regarding adaptability and phenotypic stability of 14 soybean genotypes, evaluated in five environments in the state of Minas Gerais, by the ANN method (NASCIMENTO et al., 2013), agricultural season 2020/2021.

Genotypes	Average (kg ha^{-1})	Adaptability	Stability
96Y90	4667.8 $^{+}$	General	High
95R95IPRO	4688.8 $^{+}$	General	Low
M5917IPROIPRO	4699.3 $^{+}$	General	High
M6972IPRO	4444.3	Unfavorable	High
TMG7368IPRO	4710.6 $^{+}$	General	Low
TMG2374IPRO	4716.9 $^{+}$	Favorable	High
TMG7063IPRO	4773.9 $^{+}$	General	High
TMG7363RR	4536.9	Favorable	High
TEC7849IPRO	4534.2	Unfavorable	High
DS6217IPRO	4797.0 $^{+}$	General	Low
BS2606IPRO	4678.7 $^{+}$	Unfavorable	High
BMXFocoIPRO	4818.2 $^{+}$	General	High
BRS5980IPRO	4555.4	Unfavorable	High
CZ26B77IPRO	4390.9	General	High
General Average (kg ha^{-1})	4643.8		

$^{+}$Average of the genotype higher than the general average of the experiments.

Using the environmental index proposed by Finlay and Wilkinson (1963) and used in Carneiro (1998) and the Centroid Method (ROCHA et al., 2005), environments 1, 3 and 5 were classified as unfavorable, with environmental indices, respectively, equal to -124.052, -47.888 and -296.319 and environments 2 and 4 as favorable with environmental indices, respectively, equal to 117.399 and 350.860.

The concept of adaptability and stability used in the Centroid method considers that the genotype of maximum specific adaptation is not the one that presents good performance in the groups of favorable or unfavorable environments, but the genotype that presents maximum values for a certain group of environments (favorable and unfavorable) and minimum for the other set (ROCHA et al., 2005). Thus, by this method and considering the genotypes with higher averages, compared to the general average of the experiments, it was identified that M5917IPRO, TMG7368IPRO, TMG2374IPRO, TMG7063IPRO, DS6217IPROand BMXFocoIPRO are recommended as high general adaptability, 96Y90 is recommended as specific adaptability to favorable environments and 95R95IPRO and BS2606IPRO are recommended as the specific adaptability to unfavorable environments (Table 6).

The genotypes DS6217IPRO, TMG7063IPRO, BMXFocoIPRO, M5917IPRO and TMG7368IPRO showed higher averages than the general average of the experiments and lower Pi values by the methodology of Lin and Binns (1988) modified by Carneiro (1998) indicating response to general environment (Table 7). When considering favorable and unfavorable environments separately, it was observed that for favorable environments, the genotypes BMXFocoIPRO, DS6217IPRO, TMG2374IPRO, TMG7363RR and TMG7368IPRO had higher means than the general average of favorable environments and the lowest Pi values for response in favorable environments; and the genotypes 95R95IPRO, BS2606IPRO, BRS5980IPRO , TEC7849IPRO and M5917IPRO had higher means than the general average of unfavorable environments and the lowest P_i values for response in unfavorable environments.

By the ANN methodology (NASCIMENTO et al., 2003), the concept of adaptability is similar to that of Eberhart and Russell (1966) in which it is adopted that adaptability refers to the ability of genotypes to advantageously take advantage of the stimulus of the environment and can be classified into genotypes with general (or broad) adaptability, with specific adaptability to favorable environments, or with specific adaptability to unfavorable environments. Regarding stability, Nascimento et al. (2013) reported that the concept in the proposed neural network is based on the work of Finlay and Wilkinson (1963) which differs from Eberhart and Russell (1966) by considering stability as invariance rather than predictability.

TABLE 6 - Average grain yield, in kg ha^{-1}, and the classification of 14 soybean genotypes in one of the groups characterized by the centroid method and their respective probabilities (Prob) associated with their classification, evaluated in five environments in the state of Minas Gerais, agricultural season 2020/2021.

Genotypes	Average[1]	Classification[2]	Prob(I)	Prob(II)	Prob(III)	Prob(IV)
96Y90	4667.8	II	0.278	0.320	0.195	0.208
95R95IPRO	4688.8	III	0.285	0.211	0.291	0.213
M5917IPRO	4699.3	I	0.308	0.258	0.229	0.206
M6972IPROIPRO	4444.3	III	0.176	0.176	0.326	0.322
TMG7368IPRO	4710.6	I	0.315	0.305	0.191	0.189
TMG2374IPRO	4716.9	I	0.316	0.300	0.194	0.190
TMG7063IPRO	4773.9	I	0.352	0.266	0.202	0.181
TMG7363RR	4536.9	II	0.192	0.500	0.134	0.175
TEC7849IPRO	4534.2	III	0.191	0.169	0.377	0.263
DS6217IPRO	4797.0	I	0.367	0.280	0.184	0.170
BS2606IPRO	4678.7	III	0.251	0.200	0.320	0.230
BMXFocoIPRO	4818.2	I	0.342	0.328	0.166	0.164
BRS5980IPRO	4555.4	III	0.203	0.179	0.357	0.261
CZ26B77IPRO	4390.9	IV	0.163	0.221	0.208	0.407
General Average (kg ha^{-1})	4643.8					

[1]Average considering all environments, [2]Classification: class I: high general adaptability, class II: specific adaptability to favorable environments, class III: specific adaptability to unfavorable environments and class IV: poorly adapted.

TABLE 7 - Average grain yield, in kg ha^{-1} and the estimates P_i for general, favorable and unfavorable environments of 14 soybean genotypes, evaluated in five environments in the state of Minas Gerais, by the method of Lin and Binns (1988) modified by Carneiro (1998), agricultural season 2020/2021.

General Response			Favorable Environments			Unfavorable Environments		
Gen[1].	Average	P_i	Gen.	Average	$P_{i(f)}$	Gen.	Average	$P_{i(d)}$
10	4797.0	64558.8	12	5318.2	3138.3	2	4608.7	35988.0
7	4773.9	76138.4	10	5143.4	31093.0	11	4652.0	44063.6
12	4818.2	77104.3	6	5072.3	54547.0	13	4565.9	45286.2
3	4699.3	78809.1	8	5120.4	64462.3	9	4585.6	49585.4
5	4710.6	87524.1	5	5042.5	66255.1	3	4532.2	57627.5
2	4688.8	95435.0	1	5010.9	70772.4	7	4594.4	79337.8
6	4716.9	98219.1	7	5043.1	71339.4	10	4566.1	86869.4
1	4667.8	101497.0	3	4949.8	110582.0	5	4489.3	101703.0
11	4678.7	124136.0	2	4809.0	184606.0	1	4439.1	121980.0
13	4555.4	169610.0	11	4718.7	244246.0	4	4456.8	123525.0
8	4536.9	189737.0	13	4539.7	356094.0	12	4484.8	126415.0
9	4534.2	199644.0	14	4640.1	403496.0	6	4480.0	127334.0
4	4444.3	308508.0	9	4457.0	424732.0	14	4224.7	247446.0
14	4390.9	309866.0	4	4425.5	585983.0	8	4148.0	273253.0
M_G[2]	4643.8		M_F[3]	4877.9		M_D[4]	4487.7	

[1]Gen = genotypes (1: 96Y90, 2: 95R95IPRO, 3: M5917IPRO, 4: M6972IPRO, 5: TMG7368IPRO, 6: TMG2374IPRO, 7: MG7063, 8: TMG7363RR, 9: TEC7849IPRO, 10: DS6217IPRO, 11: BS2606IPRO, 12: BMXFocoIPRO, 13: BRS5980IPRO, 14: CZ26B77IPRO), [2]M_G = averages of all environments, [3]M_F = averages of the favorable environments and [4]M_D = averages of the unfavorable environments.

The P_i of Lin and Binns (1988) measures the deviation of the productivity of a genotype in relation to the maximum in each environment. For the recommendation to attend to the groups of favorable and unfavorable environments, which reflect, in a way, environments where high and low technology is employed, respectively, Carneiro (1998) suggested the decomposition of the P_i estimator of the method proposed by Lin and Binns (1988), in the parts due to favorable and unfavorable environments (CRUZ; CARNEIRO, 2006).

The concept of adaptability and stability used in the Centroid method differs from the others, since the genotype of maximum specific adaptation is not the one that presents good performance in the groups of favorable or unfavorable environments, but the genotype that presents maximum values for a certain group of environments (favorable and unfavorable) and minimum for the other set (ROCHA et al., 2005).

Considering the results together, it was verified that the genotypes M5917IPRO, TMG7063IPRO and BMXFocoIPRO are recommended for general environment and present individual average above the general average of the experiments. The parameter estimated by the method of Lin and Binns (1988) is, according to Cruz and Carneiro (2006), a measure relative to a hypothetical genotype of general adaptability, whose regression coefficient is equal or close to unity, that is, this parameter quantifies the adaptability as defined by Finlay and Wilkinson (1963). The genotype of general adaptability, proposed by Finlay and Wilkinson (1963), responds satisfactorily to improvements in the environment, and is also capable of maintaining its yield when environmental conditions are adverse (CRUZ et al., 2004).

When considering favorable environments, the recommendation of the genotype TMG2374IPRO by the ANN methodology (NASCIMENTO et al., 2013) and Lin and Binns (1988) modified by Carneiro (1998) was observed. For the genotype TMG7363RR, the three methodologies indicate the recommendation for favorable environments, but due to the average of this genotype below the general average, the ANN and Centroid methods do not consider it as a potential genotype for favorable environments. It is noteworthy that when considering the average of the genotype only in favorable environments, TMG7363RR showed productivity 5.0% higher than the average of the favorable environments, that is, 242.5 kg ha^{-1} more.

For unfavorable environments, the BS2606IPRO genotype was recommended by all three methodologies used in this work. According to Cruz et al. (2004), using the Finlay and Wilkinson (1963) methodology, genotypes adapted to unfavorable environments are considered hardy because they maintain their yields under adverse conditions. However, they are not attractive for high technology areas, because they do not respond satisfactorily to investments aimed at improving the environment and maximizing yields (CRUZ et al., 2004).

In a detailed analysis of the genotypes recommended for unfavorable environments, it was observed that the genotypes TEC7849IPRO and BRS5980IPRO were recommended for unfavorable environments but presented individual average below the general average of the experiments by the ANN (NASCIMENTO et al., 2013) and Centroid (ROCHA et al., 2005) methods. However, when analyzing the averages of each genotype compared to the general average considering only the unfavorable environments, it was identified that these genotypes are potential to be recommended for these environments. The genotypes TEC7849IPRO and BRS5980IPRO presented, respectively, 2.2 % and 1.7 % more than the average productivity of unfavorable environments.

CONCLUSIONS

The interaction genotypes x environments was significant and between pairs of environments it was predominantly complex, the genotypes M5917IPRO, TMG7063IPRO and BMXFocoIPRO are recommended for general environment, the genotypes TMG2374IPRO and TMG7363RR are recommended for favorable environments, and the genotypes BS2606IPRO, TEC7849IPRO and BRS5980IPRO are recommended for unfavorable environments.

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