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Environmental variables in the G x E interaction in soybean in the semiarid[1]

Variáveis ambientais na interação G x A em soja no semiárido

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ABSTRACT - The objective of the present work was to evaluate the influence of environmental variables on the interaction between genotypes and environments and to identify adapted and stable genotypes for grain seed yield. Twenty-one cultivars were evaluated in randomized blocks with four replications in the years 2016, 2017, and 2018 in the northeastern semi-arid region of Brazil, for seed yield and oil content. Factor regression methodologies and principal component analysis were used with predictions of the sum of the genotypic effects and the interaction to quantify the role of five environmental covariates in the genotype x environment interaction; the Harmonic Mean Method of Relative Performance of Genotypic Values was used for identifying adapted and stable genotypes. The covariance biplot model is useful for relating important environmental factors and indicating their relative effect on seed yield and oil content. Rainfall, relative humidity and maximum temperature contribute positively to increasing oil content while minimum temperature and solar radiation reduce it. Within the limits of the work, the maximum temperature positively influences grain production while the minimum reduces it. The most stable genotypes and those adapted for grain seed yield and oil content are BMX OPUS IPRO, P 98Y70 RR, BRS 333 RR, BRS 9280 RR, M 8644 IPRO, M 8372 IPRO, and ST 920 RR.

Key words: *Glycine max* L. Mixed models. Multivariate analysis. Oilseed. REML/BLUP.

RESUMO - O objetivo do presente trabalho foi avaliar a influência de variáveis ambientais na interação entre genótipos e ambientes e identificar genótipos adaptados e estáveis para a produção de sementes. Vinte e uma cultivares foram avaliadas em blocos ao acaso com quatro repetições nos anos de 2016, 2017 e 2018 no semiárido nordestino do Brasil, para rendimento de sementes e teor de óleo. Metodologias de regressão fatorial e análise de componentes principais foram utilizadas com previsões da soma dos efeitos genotípicos e a interação para quantificar o papel de cinco covariáveis ambientais na interação genótipo x ambiente; o Método da Média Harmônica de Desempenho Relativo de Valores Genotípicos foi usado para identificar genótipos adaptados e estáveis. O modelo biplot de covariância é útil para relacionar fatores ambientais importantes e indicar seu efeito relativo no rendimento de sementes e no teor de óleo. A precipitação, a umidade relativa e a temperatura máxima contribuem positivamente para aumentar o teor de óleo, enquanto a temperatura mínima e a radiação solar o reduzem. Dentro dos limites do trabalho, a temperatura máxima influencia positivamente a produção de grãos enquanto a mínima a reduz. Os genótipos mais estáveis e adaptados para rendimento de sementes de grãos e teor de óleo são BMX OPUS IPRO, P 98Y70 RR, BRS 333 RR, BRS 9280 RR, M 8644 IPRO, M 8372 IPRO e ST 920 RR.

Palavras-chave: *Glycine max* L. Modelos mistos. Análise multivariada. Oleaginosa. REML / BLUP.

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INTRODUCTION

The soybean [*Glycine max* (L.) Merrill] production chain is driven by the expansion of agricultural frontiers, mainly due to the launch of cultivars adapted to the most diverse climatic conditions in the country, showing the high potential of Brazilian agriculture for the aforementioned oilseed. In the semiarid region, soy is not yet sown, although some cultivars are rustic and can be adapted in this region.

When genotypes are evaluated under different environmental conditions, their relative performance can be altered, leading to the phenomenon called genotype x environment interaction. This phenomenon has great relevance for breeders since it has an effect on phenotypic manifestation in characters of economic interest, especially seed yield. The presence of the interaction reduces genotypic correlation throughout the environments and therefore makes it difficult to recommend cultivars for a given region (MONTVERDE *et al*., 2019).

The term environment refers to all variations of non-genetic origin (MACKAY, 2010). The environ-mental factors that contribute to the interaction between genotypes and environments are classified as predictable or unpredictable. The first includes variations in the environment that occur from place to place, within the area of crop distribution, such as soil type and agronomic techniques. The second is related to variations such as the frequency and distribution of rain, air and soil temperature, and occurrence of frosts, among others (ALLARD; BRADSHAW, 1964). Therefore, the interaction between genotypes and environments can occur between different locations (spatial) or over the years of evaluation (temporal) (MALOSETTI *et al*., 2016). In addition, the environment can be a combination of year and location (BERNARDO, 2010).

One of the great challenges of research is understanding the interaction between genotypes and environments. For this, information about the environmental factors that determine the different behavior of genotypes is essential. The possibility of exploring the genotype × environment interaction depends on understanding the characteristics related to expression of the interaction, the genotypes and the environmental variables. When genotypic and/or environmental information is available, it is possible to assess its effects on the interaction (GAUCH, 2006). Environmental variables have been used to explain the genotype x environment interaction in various crops, such as sorghum (SAEED; FRANCIS, 1984) millet (RAMASAMY, 1996) wheat (BRANCOURT-HULMEL; LECOMTE, 2003; VOLTAS; LÓPES-CÓRCOLES; BORRÁS, 2005), soybean (OLIVEIRA *et al*., 2006) and melon (NUNES *et al*., 2011).

In these studies, environmental variables are considered to be covariates. Factor regression by ordinary least squares is applied and the contribution of each characteristic to the interaction is estimated (VAN EEUWIJK; DENIS; KANG, 1996). Another way to study the contribution of environmental variables is to consider the effect of random genotypes and to use multivariate techniques as the main components or factor analyses. One of the pioneering works with this approach was successfully carried out on cowpea beans (*Vigna unguiculata* L. Walp) from covariable seasonal and geographical environments (CARVALHO, 2015).

In soybean culture, there have been many investigations of the interaction between genotypes and environments, but there are few studies involving environmental covariates. (OLIVEIRA *et al*., 2006) reported that altitude, maximum temperature, soil fertility and rainfall are the environmental covariables that most explain the interaction between genotypes and environments in Goiás, Brazil. In the case of the Northeast region, with a predominance of high temperatures and rainfall concentrated in a few months of the year, there is little in-formation on the interaction between genotypes and environments associated with environmental variables. In addition, little is known about the stability and adaptability of genotypes in terms of seed yield and oil content; therefore, research is needed to generate information to help consolidate culture in the Brazilian semiarid region.

The added value of soybean is due to the fact that it is one of the largest and best sources of vegetable protein and oil consumed worldwide, adequately meeting food needs, both human and animal, within a range of oilseeds grown in the country. Soy is one the most important crop worldwide (RODRIGUES; ABREU; OLIVEIRA, 2017).

In view of these considerations, the objective of the present work was to evaluate the influence of environmental variables on the interaction between genotypes and environments and to identify adapted and stable genotypes for grain seed yield and oil content.

MATERIAL AND METHODS

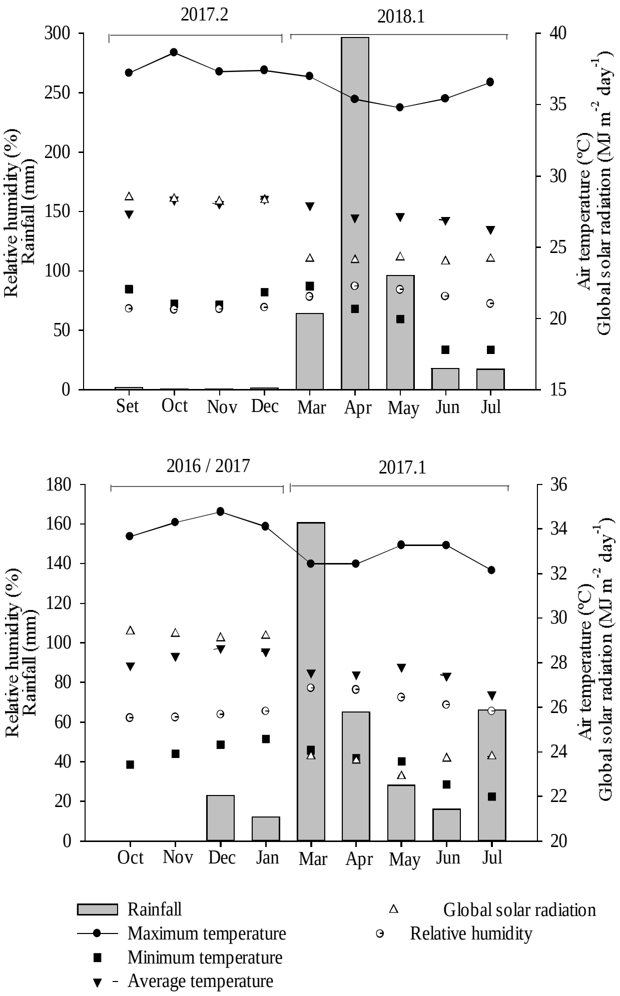
Environment

The study was carried out during the dry seasons of 2016 and 2017 and rainy seasons of 2017 and 2018 in the municipality Mossoró, Rio Grande do Norte, Brazil (5°03’37”S, 37°23’50”W, 72 m altitude). According to the Köppen classification (KÖPPEN, 1936), it is BShw – dry and very hot.

The average meteorological data for the period of the experiments are presented in Figure 1. The trials were conducted on the following planting dates:

September 25, 2016, March 29, 2017, September 30, 2017 and March 16, 2018. The meteorological data were obtained at the experimental meteorological station, installed at a distance of 2 km from the experiment on the premises of the UFERSA experimental farm.

Figure 1 - Mean values of maximum, minimum and average air temperature (ºC), relative humidity (%), solar radiation (MJ m^{-2} day^{-1}) and rainfall (mm) for four soybean crops in the years 2016/2017, 2017.1, 2017.2 and 2018.1



The soil of the experimental field was classified as Typical Red Dystrophic Argisol (ALVARES *et al*., 2013), whose chemical analysis, at a depth of 0.20 m, before installing each experiment, is shown in Table 1.

Genotypes and experimental design

Twenty-one soybean genotypes (Table 2) were evaluated in randomized blocks with four replications. The plots were formed by four rows of plants 5 m long, with spacing of 0.50 m between rows and 0.07 m between plants. The useful area of the plot was 4 m^2, beans being harvested from the two central rows, with a 0.5 m edge cut at the ends. The genotypes studied are from Empresa Brasileira de Pesquisa Agropecuária – Embrapa Meio-Norte.

Experimental details

The seeds were inoculated before sowing with peat inoculant (TotalNitro Ultra®) applied at a dose of 4 g of inoculant per kg of seeds and liquid (TotalNitro Full®) applied in the planting furrow, on the seeds, at a dose of 500 ml ha^{-1}, ensuring that the seeds were completely covered by the inoculant. The inoculants were obtained from Total Biotecnologia®, Curitiba, Paraná, Brazil. Sowing was performed manually, with the aid of previously drilled wooden rulers, according to the desired spacing.

Weed control was performed manually with hoes. Due to the rainfall inconsistency in the period during which the experiments were conducted, there was water complementation additional irrigation was supplied. Thus, the supplementary irrigation was made on the basis of Eto, in the absence of rains during the vegetative and reproductive stages, through sprinkling.

Fertilization was carried out as recommended for the crop based on soil analysis, with 60 kg ha^{-1} of P_2O_5 being applied during planting and 60 kg ha^{-1} of K_2O in coverage (GOMES; COUTINHO, 2008). The sources of phosphorus and potassium were simple superphosphate and potassium chloride, respectively.

Traits evaluated

Table 1 - Chemical analysis of the soil, in the experimental areas, from 0 to 0.2 m, containing the four soybean crops

Crops	N (g kg^{-1})	OM** (g kg^{-1})	K	P	Na	Ca	Mg	pH	EC** ds m^{-1}
			------------- mg dm^{-3} --------------			-------- $cmol_c$ dm^{-3} -------			
2016/17	0.15	8.03	54.03	4.23	8.30	2.30	1.20	6.64	0.56
2017.1	0.42	12.95	41.71	2.17	8.61	1.05	0.93	6.32	0.67
2017.2	0.35	11.78	53.73	3.50	4.20	1.00	1.12	5.87	0.73
2018.1	0.41	10.53	27.12	2.34	8.54	1.56	1.24	6.20	0.47

* EC = electrical conductivity; ** OM = organic matter

Table 2 - Category, identification, name, maturation group and cycle of 21 soybean genotypes evaluated in four crops semiarid conditions

Category*	Identification	Name	Maturation group	Cycle (days)
	G02	'BRS Carnaúba'	9.6	101
	G03	'BRS Pérola'	8.8	103
1	G04	'BRS Tracajá'	9.2	101
	G05	'BRS Sambaíba'	9.3	100
	G07	'BRS 8590'	8.5	104
	G01	'BMX OPUS IPRO'	8.6	101
	G08	'BRS 9383 IPRO'	9.3	103
2	G09	'BRS 9180 IPRO'	9.1	111
	G12	'M 8644 IPRO'	8.6	102
	G13	'M 8372 IPRO'	8.3	106
	G06	'BRS Sambaíba RR'	9.3	107
	G10	'BRS 333 RR'	9.4	102
	G11	'BRS 9280 RR'	9.2	105
	G14	'P 98Y70 RR'	8.7	102
	G15	'ST 920 RR'	9.2	106
3	G16	'Pampeana 10 RR'	9.8	111
	G17	'Pampeana 20 RR'	10.0	118
	G18	'Pampeana 40 RR'	9.5	111
	G19	'Pampeana 50 RR'	9.6	111
	G20	'PAS 13565-74 RR'	9.5	117
	G21	'Pampeana 007 RR'	9.7	111

* Category 1: conventional soybean genotypes. * Category 2: high-yield soybean genotypes, resistant to glyphosate and which have protection and suppression against some soy pests. * Category 3: glyphosate resistant soybean genotypes

Two traits were evaluated: a) oil content: determined from the selection of 30 g (ground) of seeds from each plot. The oil content in the samples was determined in whole soybeans by the Near Infrared Reflection (NIR) technique and expressed as a percentage (%), according to (HEIL, 2010); and b) yield: at physiological maturity (95% mature pods), soybean plants were harvested in the two central rows of each plot, 4 m^2, with a 0.5 m edge border. Upon reaching 13 - 15% moisture, the harvest was carried out. After harvesting, the plants were benefited and the seeds then weighed, after drying (12% humidity) and cleaning, to determine the grain yield (R CORE TEAM, 2020).

Statistical analysis

To assess the specific effects of environmental covariates on the interaction between genotypes and environments, successive multiple linear regression analyses were performed with stepwise selection as detailed by (NUNES *et al*., 2011). Multivariate analysis to study the effect of environmental covariates on the genotype–environment interaction was performed as described by (CARVALHO, 2015). All analyses were performed using R® software (R CORE TEAM, 2020).

For the REML/BLUP analysis, the following mixed model was used: $y = Xb + Zg + Wc + e$, where y, b, g, c and e correspond, respectively, to data vectors, fixed effects (block averages across environments), genotype effects (random), genotype × environment interaction effects (random) and random errors; X, Z and W are the incidence matrices for b, e and c, respectively. With the effects obtained via joint deviance analysis, the predicted genotypic values were obtained by $\mu + gi$, where μ is the average of all sites and gi is the genotype-free effect of the genotype x environment interaction. The criterion for the joint selection of genotypes considering both stability and adaptability was given by the Harmonic Average Statistics of Relative Performance of Genotypic Values (RESENDE, 2007). To perform these analyses, the program SELEGEN was used (RESENDE, 2007).

RESULTS AND DISCUSSION

A significant effect was observed for genotype and for the interaction between genotype and environment (G x E) ($p < 0.05$) in the two traits evaluated (Table 3).

Table 3 - Deviance analysis, estimates of variance components and genetic and phenotypic parameters for the characters of oil content and seed yield in soybean genotypes evaluated in four crops semi-arid conditions

Effect	LRT (Likelihood Ratio Test) – (χ^2)	
	Oil content (%)	Seed yield (kg ha^{-1})
G	4.82**	3.99*
GE	373.71**	237.89**
REML	Estimates (Components of variance and genetic parameters)	
$_{G}V$	0.811 (20.53%)	147737.985 (17.23)
V_{GE}	2.764 (69.96%)	551814.410 (64.36)
$_{E}V$	0.376 (9.2%)	157793.675 (18.40)
$_{PHE}V$	3.951	857346.070
h^2_{gm}	0.53	0.50
as	0.73	0.71
Gc	0.23	0.21
$V_{GE}/_{G}V$	0.70	3.74
$C_{G}V$	4.28	16.47
$_{E}VC$	3.22	17.03
$C_{G}V/ _{E}VC$	1.33	0.97
Mean	19.05	2333.06

**, * Significant by the Chi-square test a ($p < 0.01$) and ($p < 0.05$) by the Chi-square test, respectively; $_{G}V$: genotypic variance; V_{GE}: variance of genotype interaction by environments (GE); $_{E}V$: residual variance; $_{PHE}V$: phenotypic variance; h^2_{gm}: heritability of the genotype mean, $_{S}A$: selective accuracy; R^2_{GE}: coefficient of determination of genotype interaction by environments; Gc: genetic correlation between all environments; $C_{G}V$: coefficient of genotypic variation; $_{E}VC$: residual coefficient of variation. Values in parentheses are the percentage of observed phenotypic variation ($_{PHE}V$)

The selective accuracy of selection that measures the correlation between predicted and observed genotypic values ranged from 0.71 (seed yield) to 0.73 (oil content).

The ratio between the coefficients of genotypic and residual variation was lower than the unit for all characters.

Phenotypic variance (PHEV) was mainly explained by the G x E interaction for both variables (Table 3). The ratio between the variance components VGE and GV was always higher than the unit. Estimates ranged from 0.70 (oil content) to 3.74 (seed yield). A low genotypic correlation was observed when considering all environments with values below 0.21.

Multi-environment tests are performed in order to recommend the most promising cultivars for a given growing region. Generally, these types of assays involve genotypes with high production performance carefully selected by the researchers. As a result, it is expected that small differences will be detected. Therefore, the challenge is to conduct the tests with high experimental precision. Experimental precision is traditionally measured by the residual variation coefficient (EVC). In the present study, the estimates obtained are within the range observed previously in tests for seed yield (BULEGON *et al*., 2016; LEMOS *et al*., 2011; PEREIRA *et al*., 2018) and oil content (CARNEIRO *et al*., 2019; SILVA *et al*., 2016).

In addition, selective accuracy (sA) has been used to assess the quality of genotype evaluation experiments. Accuracy measures the correlation between predicted and observed genotypic values (RESENDE, 2007). The accuracy of this study is within the range (0.70 to 0.89) and can be considered high (RESENDE; DUARTE, 2007). Indeed, considering the two measures, EVC and sA, they can be considered of high precision, without prejudice to the inferences.

Genotypic variability was found for both traits and reflects the different genetic backgrounds of the materials evaluated. In most multi-ambient assays, reports showing differences between genotypes for both seed yield and oil content are common (CAMARA; MORAES; SIMON, 2018; CARNEIRO *et al*., 2019; MARCHIORI *et al*., 2015; PEREIRA *et al*., 2018; SILVA *et al*., 2016). Genotypic variance explained only 20.53% of the genetic variance for oil content, indicating that genotypic heterogeneity, although present, was not accentuated. Two other results that reinforce this fact are the median heritability estimates and a weak relationship between the coefficients of genotypic (CGV) and residual (EVC) variation (Table 3). Heritability in the broad sense quantifies the fraction of PHEV due to genetic effects. Estimates close to the unit indicate less environmental effect on the character (BASTIAANSE *et al*., 2019).

Regarding the ratio CGV/EVC, the ideal condition is that this value is as high as possible, as it indicates a greater effect of genetic variability (VENCOVSKY; BARRIGA, 1992). However, in this study, the ratio was very low, showing reduced genotypic variability and the great influence of the environment on seed yield.

The presence of G x E interaction indicates the differential response of the genotypes in the different environmental conditions. This fact is common in genotype evaluations in various soybean environments for seed yield (CARNEIRO *et al*., 2019; MATEI *et al*., 2017; MILIOLI *et al*., 2018; TOLORUNSE *et al*., 2018). It has also been observed for oil content (27, 28). The variance due to the G x E interaction explained more than 60% of the PHEV and exceeded the genetic variance in both traits by more than three times (Table 3). This result is not common in multi-environment assays, in which the phenotypic expression is usually explained mainly by residual and genotypic variances a (BORNHOFEN *et al*., 2017; CARNEIRO *et al*., 2019; MATEI *et al*., 2017; PEREIRA *et al*., 2018; TOLORUNSE *et al*., 2018).

The G x E interaction present in this study is mainly due to the complex or crossed part. The predominance of cross-interaction occurs due to the reduced genotypic correlation (Gc) between all the assessment environments, as noted (Table 3). The consequence is alternation of the order of the genotypes in the four trials, making the process of recommending cultivars difficult (CRUZ; CASTOLDI, 1991; OLIVOTO *et al*., 2019). Many authors evaluating soybean genotypes for grain production and oil content have also noted the preeminence of the qualitative or crossover part of the G x E interaction over the simple part (CAMARA; MORAES; SIMON, 2018; CARNEIRO *et al*., 2019; ODA *et al*., 2019; PEREIRA *et al*., 2018; SILVA *et al*., 2016; SILVEIRA *et al*., 2018).

As the experiments were carried out in the same place, the variation occurred especially due to the climate. This indicates the importance of experimenting over a number of years. Often, the most productive genotype from the last harvest may not be the best in the following ones, even considering that the planting will be in the same place. Therefore, indication of the best cultivars should take into account other agricultural years, whenever possible.

Study of covariates and ecovalences

The a.17b environment was the one that most contributed to the G x E interaction for the two traits studied, since it has the greatest ecovalences. This year also had the highest average for the two traits (grain seed yield and oil content), thus being a favorable environment for assessment even with the highest maximum temperature (MAXT) and the second lowest rainfall (RF) (Table 4).

Grouping of environments

It was found that the environments were grouped into two groups according to analysis of the main components (Figure 2). The group composed of environments a.16, a.17a and a.18 (Figure 2) was mainly related to the minimum temperature (MINT) and RF, while the second group was composed only of the year a.17b, negatively associated with MINT and positively related to MAXT and ecovalences of oil content and seed yield. The environments with the greatest range of MAXT and MINT were the most productive. In general, MAXT and, to a lesser extent, relative humidity

Table 4 - Means of five environmental covariates and ecovalence of four soybean genotype evaluation environments under semiarid conditions

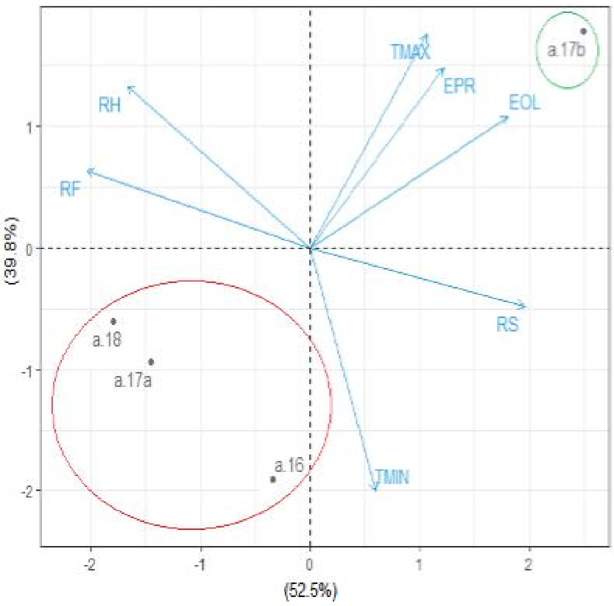
	Environment (Mean)			
	a.16	a.17 a	a.17 b	a.18
Covariable				
Maximum temperature (ºC)	34.10	32.80	37.63	35.80
Minimum temperature (ºC)	24.00	23.00	21.02	19.70
Rainfall (mm)	70.00	183.00	85.00	210.00
Relative humidity (%)	63.40	70.90	68.19	80.05
Solar radiation (MJ m^{-2} dia^{-1})	29.40	23.80	28.50	24.20
Traits				
Oil content (%)	17.14 d	18.74 c	20.60 a	19.74 b
Seed yield (kg ha^{-1})	1418.317 d	2320.856 c	2963.709 a	2629.34 b
Ecovalence				
Oil content (%)	17.05	10.76	64.34	7.85
Seed yield (kg ha^{-1})	13.46	23.13	44.42	19.00

Means followed by the same lowercase letter in the column do not differ from each other by the Tukey test ($p < 0.05$)

(RH) contributed to increase grain and oil seed yield while MINT reduced both characters evaluated. The data denote the productive potential of the crop under irrigated conditions, showing the production of soybean seed as a watershed in the semiarid region.

By definition, the environment includes all variables of non-genetic origin (SAEED; FRANCIS, 1984). In this sense, the environment can be represented by important covariables such as temperature, RF and others. In this work, five climatic covariates were measured in the four assessment environments. In the cluster analysis, it was found that environment a.17b differed from the others (Figure 2). This environment had the highest MAXT (37.63 °C) and the lowest MINT (21.02 °C). In addition, in this environment, higher average grain yield and oil content were observed. This was the environment that most contributed to the interaction between genotype and environment. Despite environments a.16, a.17a and a.18 being in the same group, they also differ especially in terms of RF and RH (Table 4), showing environmental variation. The magnitude of differences between environments influences the effect of genotype x environment interaction. The greater the range of edaphoclimatic conditions or even the management of culture, the more complex the genotypic response.

Figure 2 - Distribution of assessment years and environmental variable according to the first two main components



Contribution of environmental covariates to G x E interaction

The covariables MINT and RH for oil content and MAXT for seed yield were those that most contributed to the G x E interaction according to the factor regression analysis (Table 5).

Knowledge of the causes and nature of the G x E interaction has been a concern for researchers. Van Eeuwijk, Denis and Kang (1996) suggested the use of environmental covariables in factorial regression to explain the interaction between genotypes and environments. It was observed that the covariables minimum temperature and relative humidity for oil content and maximum temperature for seed yield were the covariables that most contributed to the interaction were G x E interaction according to the factor regression analysis (Table 5). In soy, Oliveira *et al*. (2006) found that altitude (57.21%), MAXT (36.25%), soil fertility (29.85%) and RF (28.20%) were the environmental covariables that most explained the interaction G x E in soybean genotypes evaluated in the State of Goiás.

Nunes *et al*. (2011), evaluating melon hybrids in semiarid conditions in Rio Grande do Sul, found that the minimum, average and maximum temperatures explained 39%, 35% and 33% of the G x E interaction. In work carried out with corn Liu *et al*. (2013), the effect of temperature, RF and solar radiation was observed. In sugar cane, it was found that the seasonal covariates temperature and water stress were the most important for stem yield (RAMBURAN; ZHOU; LABUSCHAGNE, 2011). Each species has a specific response to the environment in which it is inserted. In

Table 5 - Contribution of covariates to the interaction between genotypes by environment in oil content and seed yield evaluated in soybean genotypes in four harvests under semiarid conditions

Covariable	Contribution (%)	
	Oil content (%)	Seed yield (kg ha^{-1})
Maximum temperature (°C)	13.21	50.10
Minimum temperature (°C)	50.44	25.57
Rainfall (mm)	39.90	20.94
Relative humidity (%)	48.29	23.11
Solar radiation (MJ m^{-2} dia^{-1})	42.25	21.45

addition, even within a species, there is a distinction between cultivars that respond differently to stimuli caused by different environmental covariables. As a result, and due to the environmental variation, itself, different results are expected among manuscripts published in the literature.

In this work, all the studied variables contributed with different intensity to the G x E interaction. Regarding oil content, RF and RH contributed positively to increase the interaction. MAXT (32.80 to 37.63 °C) also contributed positively to the interaction, although to a lesser degree. The opposite behavior was observed for MINT (19.70 to 24.00 °C) and, partially, for solar radiation (Figure 3). These results agree with the correlation estimates (not shown) between the covariates and the general average for oil content, positive for the first three covariates mentioned and negative for the last two. MAXT were high, but soybeans can withstand this climate, as long as they have other factors to compensate. However, the minimums were also higher than in the Cerrado region, where temperatures can reach 10 to 15 °C. Furthermore, the effect of the semi-arid environment is potential, since soybeans can be grown all year round under irrigated conditions and using cultivars adapted to each season of the year.

Decomposition by singular values (DSV)

After DSV of the matrix of correlations between the BLUPS of the interactions and the values of the covariates in each of the environments, it was verified for oil content that the first two main components practically explained the whole variation (99.36%), so a two-dimensional graph is needed to explain the G x E interaction. The first main component can be explained as a contrast between the positive effects of RF and RH and the negative effects of the covariates MINT and solar radiation (SR). The second main component can be understood as a contrast between the positive effects of MAXT and SR and the negative effects of MINT (Figure 6).

For grain seed yield, the first two main components explained 99.31% of all G x E interaction. In the first main component, it was found that SR and, to a lesser extent, MAXT had a positive effect on the G x E interaction while RF and RH had a negative effect. In the second main component, MAXT and RH contributed positively to the G x E interaction while MINT contribution was negative (Table 6).

Concerning seed yield, the effect of covariates varied widely in the first two main components. Considering the two main components, MAXT was the only covariate that had a positive influence on the G x E interaction. The other covariates alternated between a positive/negative influence and a small effect. When considering the correlation of covariates and the general average for grain yield, it was found to be positive for MAXT and negative for MINT. The partially coherent results in this case may be due to other environmental covariables that interfere with the character average such as soil type and management, among others.

Using the same methodology, Carvalho (2015) concluded that the seasonal variables average temperature, RH, total sunshine, number of precipitation days and total precipitation were those that most influenced the performance and seed yield of cowpea genotypes. According to the same author, the difference in behavior of the genotypes can be attributed to geographical factors such as latitude and longitude. It is noteworthy that in that study, more environments with greater edaphoclimatic variation and geographical location were contemplated.

Covariance biplots generated by analysis of main components

In Figure 3, the cosine of the angle between the vectors of any two environmental covariables measures the association between them as a function of their effect on the G x E interaction. Therefore, for

Table 6 - Contribution of five environmental covariables in the first two main components for G x E interaction in oil content and grain seed yield in soybean genotypes evaluated under semiarid conditions

	Oil Content (%)		Yield (Kg ha^{-1})	
	PC 1	PC 2	PC 1	PC 2
MAXT	0.001	0.307	0.699	0.692
MINT	-0.401	0.143	-0.518	-0.639
RF	0.538	-0.576	-0.209	0.028
RH	0.539	-0.419	0.198	0.330
SR	-0.513	0.615	0.401	0.055

both characters, MAXT with obtuse angles (> 90°) with MAXT and RF, has a negative correlation in relation to these covariables, but a positive correlation with SR and RH (< 90°). MINT correlated negatively with all environmental variables with the exception of SR. SR was negatively correlated with RF and RH which, in turn, had a positive association with each other. Covariables with negative correlation have opposite effects on the G x E interaction while a positive correlation indicates a similar effect of the variables.

It is also possible to visualize a pattern of clusters of genotypes in relation to the distribution and influence of environmental covariates (Figure 3). Regarding oil content, the formation of four groups was observed. The first group refers to G02, G10, G08 and G21, positively related to RF and RH, but negatively to MINT, SR and MAXT (Figure 3). In the second group, genotypes G07, G15, G14, G04 and G17 are positively associated with RH and MAXT, but negatively with MINT and SR. Genotypes G06 and G11 have a positive association with SR, but a negative one with RF and RH. The last group has a positive effect of MINT and SR and a negative effect of RF, RH and MAXT.

Regarding grain seed yield, the first group was composed of genotypes G07, G16 and G14 that are positively affected by MINT and SR and negative by RF and RH and negatively by MINT and SR (Figure 3). The genotypes G09, G10, G20 and G12 are positively associated with RF, but negatively with MAXT, SR and RH. The genotypes of the fourth group (G15, G11, G08 and G21) are associated with the positive effect of MINT and the negative effects of other characteristics. The genotypes G06, G13 and G17 are associated with SR, but suffer negative effects from RF and RH, mainly. The largest group consists of genotypes (G01, G02, G03, G04, G05, G18 and G19) with less effect of environmental covariates on the G x E interaction.

Regarding the responses of the genotypes to each of the environmental covariates, variability was observed for groups of genotypes with different sensitivities (Figure 3 and 4). By varying the responses of the cultivars in relation to the five covariables studied, it is clear that the causes of the G x E interaction must be attributed to physiological and biochemical factors specific to each genotype evaluated. Considering that genotypes develop in dynamic systems, in which constant changes occur from sowing to harvest, they generally exhibit different behavior in terms of responses to environmental variations. This was verified by the different sensitivities of the genotypes in relation to the environmental covariates when using the two methodologies (Figure 3 and 4).

Figure 3 - GGE biplot representing the "Which-Won-Where", where the soybean genotypes at the vertices of the polygon represent the genotypes indicated for the respective mega-environments formed (dotted red lines), according to the first two axes generated by principal component analysis between five environmental variables and the effects of the GGE

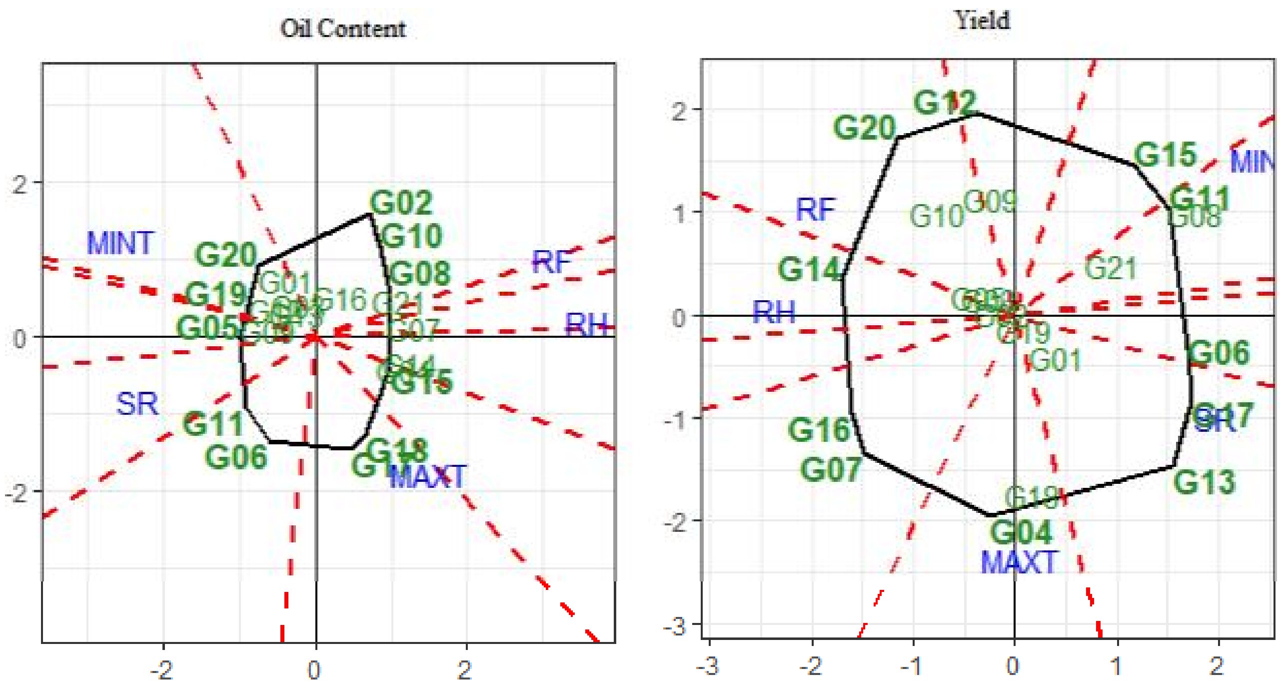
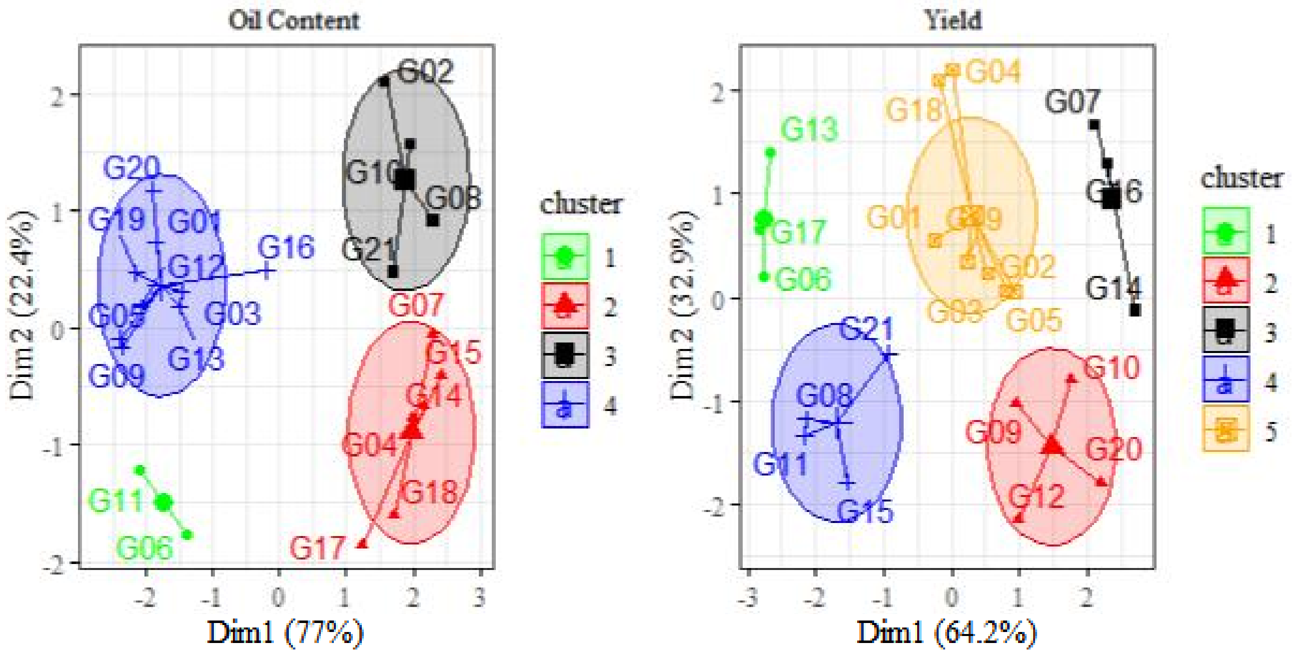


Figure 4 - Distribution K-means of soybean genotypes according to the first two axes generated by principal component analysis between five environmental variables and the effects of the GGE



It is noteworthy that the response of each genotype associated with the effect of the G x E interaction, when associated with the effects of environmental covariables, allowed genotypic discrimination and a partial understanding of the causes for the differential behavior of the soybean genotypes evaluated in the four environments. This is the first time that such a study has been carried out on soybeans under conditions in the Brazilian semiarid region. Further studies are needed that include more evaluation sites to study the effect of spatial variables on the G x E interaction.

CONCLUSION

The covariance biplot model is useful for relating important environmental factors and indicating their effect on relative seed yield and oil content. Precipitation, relative humidity and temperature contribute positively to increase oil content while minimum temperature and solar radiation contribute to reduce it. Maximum temperature positively influences grain production while minimum temperature reduces it. The most stable genotypes and those adapted for grain seed yield and oil content are BMX OPUS IPRO, P 98Y70 RR, BRS 333 RR, BRS 9280 RR, M 8644 IPRO, M 8372 IPRO and ST 920 RR.

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