

## Multi-environmental evaluation of sorghum hybrids during off-season in Brazil

**Abstract** – The objective of this work was to simultaneously select pre-commercial grain sorghum hybrids with high adaptability and yield stability, through mixed modeling, in 20 environments, during six years. The evaluated plant material consisted of 57 commercial grain sorghum hybrids. In all experiments, hybrids were arranged in a triple lattice design; some experiments used a 6x6 lattice, and others, a 5x5 lattice. Adaptability and stability parameters were obtained based on the prediction by harmonic mean of the relative performance of genotypic values (HMRPGV). The mixed models proved to be adequate to analyze the genotype x environment (GxE) interaction and the genotypic adaptability and stability studies on grain sorghum. The hybrids that stand out, considering all environments are 1G282, A9904, 50A50, A9902, and XB6022. The A9904 hybrid stands out in favorable environments, with a grain yield above average. Only 1G282 is among the five best hybrids for each group of environments, and it is the best grain sorghum hybrid for yield performance, adaptability, and stability. The predicted genotypic values based on genotypic means can be used in the environments with the same GxE interaction pattern because they are free of the GxE interaction.

**Index terms:** *Sorghum bicolor*, adaptability, genotypic means, mixed models, REML/BLUP, stability.

### Avaliação multiambiental de híbridos de sorgo durante a entressafra no Brasil

**Resumo** – O objetivo deste trabalho foi selecionar, simultaneamente, híbridos pré-comerciais de sorgo granífero com alta adaptabilidade e estabilidade da produção de grãos, por meio de modelagem mista, em 20 ambientes, por seis anos. O material vegetal avaliado consistia de 57 híbridos comerciais de sorgo granífero. Em todos os experimentos, os híbridos foram arrançados em delineamento fatorial triplo; alguns experimentos utilizaram um fatorial 6x6, e outros, um fatorial 5x5. Os parâmetros de adaptabilidade e estabilidade foram obtidos com base na predição por média harmônica da performance relativa dos valores genéticos (MHPRVG). Os modelos mistos mostraram-se adequados para analisar a interação genótipo x ambiente (GxE) e os estudos de adaptabilidade e estabilidade genotípica do sorgo granífero. Os híbridos que se destacam, considerando-se todos os ambientes, são 1G282, A9904, 50A50, A9902 e XB6022. O híbrido A9904 destaca-se em ambientes favoráveis, com rendimento de grãos acima da média. Apenas 1G282 está entre os cinco melhores híbridos para cada grupo de ambientes e é o melhor híbrido de sorgo granífero quanto ao rendimento, à adaptabilidade e à estabilidade. Os valores genotípicos preditos com base em médias genotípicas podem ser usados em relação aos ambientes com o mesmo padrão de interação GxE por estarem livres da interação GxE.

**Termos para Indexação:** *Sorghum bicolor*, adaptabilidade, médias genotípicas, modelos mistos, REML/BLUP, estabilidade.

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## Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is the fifth most important cereal crop globally, following wheat, maize, rice, and barley. It has much more adaptive characteristics for growing in marginal areas than these other cereals (Menezes et al., 2015). Sorghum production for the crop season 2019/2020 was 57.96 million tons. The estimated sorghum production for 2020/2021 is 61.62 million tons, which could represent an increase of 3.66 million tons, or 6.31% of sorghum production around the globe (USDA, 2020).

Brazil reached a crop production of about 2.6 million tons in an area of approximately 849,000 ha in 2020 (Acompanhamento..., 2021). The main producing states are Goiás, Minas Gerais, Bahia and Mato Grosso, a region where the Brazilian Cerrado predominates (Acompanhamento..., 2020). Sorghum is a major crop in the semiarid regions of the tropics and subtropics, and it is commonly grown in stressful environments with reduced inputs (Monk et al., 2014). Despite those limitations, sorghum has shown production gains over time due to enhanced farming practices and improved genetics and plant breeding (Pfeiffer et al., 2019).

Brazil has diverse climatic conditions, thus, the performance of sorghum hybrids is not equivalent in all regions. In the central region, sowing is done in succession to summer crops like soybean. In Midwest and Southern Brazil, sorghum is sown in the spring and harvested in the autumn. Meanwhile, in the Northeast, sorghum is planted in the rainy season (March-April) (Menezes et al., 2015). Therefore, the major challenge in the recommendation of cultivars is the different behavior of genotypes across locations due to the genotype x environment (G x E) interaction, especially for quantitative traits, such as grain yield. Several studies have addressed the importance of GxE interaction in sorghum for Brazilian regions (Almeida Filho et al., 2014; Menezes et al., 2015; Farias et al., 2016; Rono et al., 2016; Alvels et al., 2021).

In this sense, statistical methods have been proposed over the last few decades to deal with GxE interaction (Van Eeuwijk et al., 2016). In plant breeding, the GxE interaction refers to the differential performance of genotypes across environments. Thus, the selection methods that encompass stability and adaptability in a single statistics are more advantageous than selection using yield as single selection criterion (Resende, 2016).

Accordingly, genetic evaluation based on the mixed model restricted maximum likelihood/best linear unbiased prediction (REML/BLUP) are the standard procedures employed for genetic evaluation of GxE interaction in plant breeding, and it has proven to be a potential tool to obtain estimates of genetic progress (Smith et al., 2005; Resende, 2016).

To overcome the GxE interaction, the method of harmonic mean of the relative performance of genetic values (HMRPGV) has been proposed in the context of linear mixed models. The HMRPGV has been used in studies on stability and adaptability in sorghum (Menezes et al., 2015; Alvels et al., 2021). By this method, the genetic gain is simultaneously computed based on yield, stability, and adaptability.

The main advantages of this methodology are the provision of the adaptability and genotypic stability estimates, at the scale of the evaluated trait, and the use of unbalanced data with losses in replicates and/or treatments in different environments. The method also deals with the heterogeneity of variances, elimination of GxE interaction variation, consideration of the heritability of these effects, and correlated errors within locations. It generates genetic values discounted (penalized) from instability and generates results at the same magnitude or scale as the evaluated resources (Resende, 2016). These highlights of HMRPGV make it more recommended over other methods that consider the effect of genotypes as fixed, such as GGE (genotype main effects plus genotype-environment interaction) biplot and AMMI (additive main effects and multiplicative interaction).

The objective of this work was to select pre-commercial grain sorghum hybrids with higher adaptability and yield stability simultaneously, via mixed modeling, in twenty environments, in six years.

## Materials and methods

Evaluation data from the grain sorghum hybrids were tested in 2014, 2015, 2017, 2018, 2019, and 2020, in trials coordinated by Embrapa Milho e Sorgo, covering 20 experiments of the main Brazilian regions [testing locations (environments) and years (Table 1)]. The evaluated plant material consisted of 57 commercial grain sorghum hybrids supplied by several companies (Table 3). The hybrids derived from the series of VCU (value for cultivation and use) trials

that extended over several years and many locations, in standard experimental conditions.

In all experiments, hybrids were arranged in a triple lattice design; some experiments utilized a 6x6 lattice, and others, a 5x5 lattice. Most soils in these Brazilian regions are Latossolos (Table 1), i.e., Oxisols, according to the Brazilian system of soil (Santos et al., 2018). The experimental plots were formed by four 5 m rows, spaced at 0.50 m, with a population of 180,000 plants per hectare. In each plot, the grain yield ( $\text{Mg ha}^{-1}$ ) was evaluated in two central rows, corrected to 13% humidity.

Statistical analyses were performed considering stability and adaptability based on MHPRVG, using the model 52 of Selegen-REML/BLUP according to Resende (2007). The variance components were estimated by REML (Patterson & Thompson, 1971),

and genotypic values were predicted by BLUP (Henderson, 1975).

Thus, a joint analysis of variance of the trials was performed according to the statistical model described in Equation 1 below:

$$Y_{ijk} = \mu + G_i + b_{k/j} + E_j + G \times E_{ij} + \varepsilon_{ijk} \quad (1)$$

where:  $Y_{ijk}$  is the observation of the  $k^{\text{th}}$  block evaluated in the  $i^{\text{th}}$  genotype and  $j^{\text{th}}$  environment;  $\mu$  is the overall mean of the experiments;  $G_i$  is the effect of the  $i^{\text{th}}$  genotype considered as random;  $b_{k/j}$  is the effect of  $k^{\text{th}}$  block within  $j^{\text{th}}$  environment, considered as fixed;  $E_j$  is the effect of the  $j^{\text{th}}$  year, considered as fixed;  $G \times E_{ij}$  is the random effect of the interaction between the  $i$  genotype and the  $j$  environment; and  $\varepsilon_{ijk}$  is the random error associated with the  $Y_{ijk}$  observation, assumed to be independent  $\varepsilon \sim N(0, \sigma^2)$ .

This statistical model can be represented in matrix notation, according to Equation 2, as follows:

**Table 1.** Characterization of 57 commercial grain sorghum (*Sorghum bicolor*) hybrids, tested in 2014, 2015, 2017, 2018, 2019, and 2020, in trials coordinated by Embrapa Milho e Sorgo covering 20 experiments of the main Brazilian regions.

Year	Location (municipality, state)	Altitude (m)	Latitude	Longitude	AT (°C)	AR (mm)	Soil type
2014	Sete Lagoas, MG	773	19°28'S	44°14'W	20.8	608.6	Latossolo Vermelho
	Pelotas, RS	12	31°46'S	52°34'W	19.1	1,624.2	-
2015	Sete Lagoas <sup>(1)</sup> , MG	773	19°28'S	44°14'W	21.8	926.5	Latossolo Vermelho
	Sete Lagoas <sup>(2)</sup> , MG	773	19°28'S	44°14'W	21.8	926.5	Latossolo Vermelho
	Sete Lagoas <sup>(3)</sup> , MG	773	19°28'S	44°14'W	21.8	926.5	Latossolo Vermelho
2017	Nova Porteirinha <sup>(1)</sup> , MG	516	15°48'S	42°47'W	24.6	518.5	Latossolo Vermelho-Amarelo
	Nova Porteirinha <sup>(2)</sup> , MG	516	15°48'S	42°47'W	24.6	518.5	Latossolo Vermelho-Amarelo
	Nova Porteirinha <sup>(3)</sup> , MG	516	15°48'S	42°47'W	24.6	518.5	Latossolo Vermelho-Amarelo
2018	Nova Porteirinha <sup>(1)</sup> , MG	516	15°48'S	42°47'W	25.2	675.8	Latossolo Vermelho-Amarelo
	Nova Porteirinha <sup>(2)</sup> , MG	516	15°48'S	42°47'W	25.2	675.8	Latossolo Vermelho-Amarelo
	Nova Porteirinha <sup>(3)</sup> , MG	516	15°48'S	42°47'W	25.2	675.8	Latossolo Vermelho-Amarelo
2019	Sete Lagoas, MG	773	19°28'S	44°14'W	22.4	945.9	Latossolo Vermelho distrófico
	Santo Antônio de Goiás, GO	766	16°49'S	43°31'W	24.3	1,180.4	-
	Jardinópolis, SP	590	21°02'S	47°77'W	22.9	1,148.2	-
	Rio Verde, GO	780	17°79'S	50°92'W	23.6	841.4	Latossolo Vermelho-Amarelo distrófico
	Jatai, GO	754	17°47'S	50°55'W	22.7	1,013.4	Latossolo Vermelho distrófico
	Acreúna, GO	731	17°23'S	50°22'W	25.2	1,206.4	-
2020	Sete Lagoas, MG	773	19°28'S	44°14'W	22.5	1,461.4	Latossolo Vermelho distrófico
	Vilhena, RO	577	12°44'S	60°7'W	25.1	1,398.8	Latossolo Vermelho Escuro?
	Barreiras, BA	474	12°14'S	44°99'W	25.2	1,397.75	-

Sete Lagoas<sup>(1)</sup>: (control). Sete Lagoas<sup>(2)</sup> and Sete Lagoas<sup>(3)</sup>: cultivation in areas with aluminum saturation of 20% and 40%, respectively. Nova Porteirinha<sup>(1)</sup>: irrigated (control). Nova Porteirinha<sup>(2)</sup>: water stress induced at 45 days after seeding. Nova Porteirinha<sup>(3)</sup>: water stress induced in the post-flowering stage. AT: average temperature. AR: accumulated rainfall. Soil type according to the Brazilian system of soil classification (Santos et al., 2018). States: MG, Minas Gerais; RS, Rio Grande do Sul; GO, Goiás; SP, São Paulo; and BA, Bahia.

$$y = Xf + Zg + Wb + Ti + e \quad (2)$$

where:  $y$  represents the observations of the evaluated characteristic vector;  $f$  is the replicate effect vector (assumed as fixed) added to the general mean;  $g$  is the genotypic effect vector (assumed as random);  $b$  is the block effect vector (assumed as random);  $i$  represents the interaction effects of genotype  $\times$  environment vector (considered random);  $e$  is the error vector also considered as random.  $X$ ,  $Z$ ,  $W$  and  $T$  represent the matrices of incidence for the effects of  $f$ ,  $g$ ,  $b$  and  $i$ , respectively.

The likelihood ratio test (LRT) was used to verify the significance of the  $e$  model effects (Rao et al., 1973) at 1% probability.

The genotypic correlation between locations ( $r_{gxe}$ ) was obtained by Equation 3, as follows:

$$r_{gxe} = \frac{\sigma_g^2}{\sigma_g^2 + \sigma_{gxe}^2} \quad (3)$$

where:  $\sigma_g^2$  is the genotypic variance; and  $\sigma_{gxe}^2$  is the variance of the G $\times$ E interaction.

The harmonic means of the relative performance of genotypic values (HMRPGV) was used for simultaneous selection considering stability and genotypic adaptability, according to the Equation 4, as follows:

$$HMRPGV_i = \frac{\overline{GV}_{.j}}{\sum_j^n \frac{1}{GV_{ij}}} \quad (4)$$

where:  $n_i$  is the number of environments where the  $i$  genotype was evaluated;  $GV_{ij}$  is the genotypic value of the  $i$  genotype at a specific  $j$  environment, in which  $ij$  represents the average of the  $j$  environment;  $\overline{GV}_{.j}$  is the  $GV_{ij}$  average in the  $j$  environment (Resende, 2007). Thus, the genotypes with the highest HMRPGV are those that simultaneously gather the highest mean for grain yield, adaptability, and genotypic stability in the evaluated environments. Subsequently, separate analyses were performed for the favorable and unfavorable macroenvironments, resulting in the establishment of HMRPGV values for each case. The classification was according to Eberhart & Russell (1966), based on the environmental index, with favorable environments (positive environmental index, including zero value) and unfavorable environments (negative environmental index). All analyses were performed using the Selegen software (Resende, 2016).

## Results and Discussion

The variance components and genetic parameters were estimated for grain yield (Table 2). The variance of hybrids effect ( $\sigma_g^2$ ) was highly significant ( $p < 0.01$ ) by the  $\chi$ -square test for the likelihood ratio (LTR), indicating a significant variability among hybrids. Similarly, as for the effect of the genotypes, the variance of the G  $\times$  E ( $\sigma_e^2$ ) interaction was also highly significant, showing a different behavior of hybrids in the tested environments. Thus, there were changes in the ranking of hybrids, or changes in the magnitude of differences between them at the studied environments (Table 2). Similar results were recently observed by other authors in Brazil (Almeida Filho et al., 2014; Coan et al., 2018). G $\times$ E interaction is very important for plant breeding programs (Mortazavian et al., 2014; Sayar & Han, 2015). The assessment of genotypes in many locations and years could increase the reliability of plant breeding programs (Kendal & Sayar, 2016; Sayar & Han, 2016).

The residual variance estimate ( $\sigma_e^2$ ) can be considered high, as it was higher than the estimates of  $\sigma_g^2$  and  $\sigma_c^2$  for all situations (all environments, favorable and unfavorable environments), which characterizes it as the main component of the phenotypic variance ( $\sigma_r^2$ ). According to the classification proposed by Resende (2007), the estimates of  $\widehat{h}_g^2$  can be considered low for all groups of environments. These results were expected, as grain yield is a complex trait governed by several genes with little effect on the phenotype and considerably influenced by the environment.

The low magnitudes of  $\widehat{r}_{gloc}$  obtained for all environments and unfavorable environments (0.21 and 0.13, respectively), in addition to the moderate magnitude for favorable environments (0.34), indicate that the interaction between genotypes and environments is complex. However, the estimate of  $\widehat{r}_{gloc}$  can be considered moderate for favorable environments. The low correlations can occur when a performance of hybrids in a particular environment cannot be seen in other conditions, preventing a reliable recommendation (Mortazavian et al., 2014; Coan et al., 2018). The low value found in the present study for correlation was considered complex and indicated some changes in the rank order of hybrids. The CV $e$  estimate was considerably higher than the CV $g$  for grain yield in all situations (all environments, favorable and unfavorable environments) (Table 2).

Furthermore, these estimates indicate that the separation of all environments into favorable and unfavorable did not reduce the complex-type interaction. These results were similar to those of a study evaluating the adaptability and stability of wheat genotypes simultaneously in unbalanced multi-environment trials in four different regions of Brazil, using the HMRPGV, in which values of genotype-environment correlation ( $\widehat{r}_{\text{gloc}} = 0.25$ ) indicate the predominance of a complex correlation and that genotypic performance of genotypes was not exactly the same over the environments (Coan et al., 2018). In a study on grain yield of corn, Mendes et al. (2012) found a correlation of 0.45, which was reported as a result of a complex interaction, confirming the different genotypic behavior over the environments.

These sorghum genotypes were ranked based on HMRPGV of grain yield for all environments, favorable and unfavorable environments (Table 3). The

genotypes 1G282, A9904, 50A50, A9902, and XB6022 were the five hybrids with the highest predicted genotypic values free from any interaction with environments, and mean genotypic values in different environments, when considering all environments. The predicted genotypic value for the best hybrid (1G282) was 4.23 Mg ha<sup>-1</sup>. The worst hybrid was 'Bravo', whose predicted genotypic value was only 2.97 Mg ha<sup>-1</sup>.

In favorable environments, the five hybrids with the highest HMRPVG values were A9904, AG1090, 1G282, XB6022, and MSK330; while in unfavorable environments the hybrids 50A50, 50A40, 1G282, AG1090, and 1105661 were those with the highest mean for grain yield, adaptability, and genotypic stability simultaneously. It is important to highlight that only 1G282 was among the five best hybrids for each group of environments. Although there is a change in the ranking of hybrids, when comparing each group of environments, this change is more

**Table 2.** Deviance analysis and estimates of the variance components for grain yield of 57 hybrids of grain sorghum (*Sorghum bicolor*) tested in 2014, 2015, 2017, 2018, 2019, and 2020, in trials coordinated by Embrapa Milho e Sorgo, covering 20 experiments of the main Brazilian regions.

Parameter	All environments		Favorable		Unfavorable	
	Deviance	LRT+	Deviance	LRT+	Deviance	LRT+
Hybrids	1,459.03	27.14**	1,003.39**	16.15	426.17 <sup>ns</sup>	1.81
GxE	1,688.68	256.79**	1,088.04**	100.8	570.62**	146.26
Complete model	1,431.89		987.24		507.02	
$\widehat{\sigma}_g^2$	0.08		0.15		0.03	
$\widehat{\sigma}_c^2$	0.29		0.27		0.23	
$\widehat{\sigma}_e^2$	0.56		0.82		0.45	
$\widehat{\sigma}_f^2$	0.92		1.23		0.71	
$\widehat{h}_g^2$	0.08		0.12		0.05	
$c^2$	0.31		0.22		0.32	
$\widehat{r}_{\text{gloc}}$	0.21		0.34		0.13	
CVg (%)	7.50		9.21		7.61	
CVe (%)	20.11		21.81		27.40	
Mean	3.72		4.14		2.45	

\*\*Significant at 1% probability for the likelihood ratio test (LRT). +  $\chi^2$  tab (1 df): 6.63 at 1% probability;  $\widehat{\sigma}_g^2$ , genotypic variance;  $\widehat{\sigma}_c^2$ , genotype x environment (GxE) interaction variance;  $\widehat{\sigma}_e^2$ , residual variance between plots;  $\widehat{\sigma}_f^2$ , phenotypic variance;  $\widehat{h}_g^2$ , heritability in the broad sense;  $c^2$ , coefficient of determination of the GxE effects;  $\widehat{r}_{\text{gloc}}$ , genotypic correlation through environments. CV: coefficient of variation.

**Table 3.** Means of harmonic mean of the relative performance of genetic values (HMRPGV) for the 57 hybrids of grain sorghum (*Sorghum bicolor*) for the grain yield in all environments, favorable environments, and unfavorable environments.

Hybrid	All environments	Hybrid	Favorable environment	Hybrid	Unfavorable environment
1G282	4.23	A9904	5.76	50A50	2.93
A9904	4.21	1G282	4.83	50A40	2.91
50A50	4.15	AG1090	4.81	1G282	2.74
A9902	4.13	XB6022	4.73	AG1090	2.74
XB6022	4.07	A9902	4.69	1105661	2.73
AG1090	4.06	50A10	4.65	AS4615	2.66
AS4639	4.04	MSK330	4.63	A9721R	2.65
MSK330	4.04	AS4639	4.62	AS4625	2.64
50A60	4.03	50A60	4.59	AS4639	2.63
1G100	4.02	XGN90G10	4.57	DKB540	2.63
MSK326	3.97	1G100	4.44	1G233	2.62
DKB540	3.95	PtaNegra	4.40	1G245	2.61
1G244	3.95	MSK326	4.39	50A60	2.60
XGN90G10	3.93	Jade	4.39	Enforcer	2.60
AS4625	3.91	1G244	4.38	1G100	2.59
50A40	3.91	AS4625	4.35	MSK326	2.57
PtaNegra	3.91	MSK120	4.31	XB6022	2.55
DKB590	3.87	50A50	4.30	Bravo	2.55
MSK120	3.86	DKB590	4.28	1167048	2.55
50A10	3.84	AG1085	4.26	XGN90G10	2.53
AGN70635	3.82	Enforcer	4.26	AG1085	2.53
1G233	3.82	DKB540	4.23	AG1080	2.50
AG1085	3.81	1G233	4.22	DKB590	2.49
1G245	3.81	BRS380	4.19	MSK330	2.47
A9721R	3.80	BRS310	4.16	MSK120	2.46
Enforcer	3.77	Buster	4.11	BRS3318	2.45
AG1080	3.74	50A70	4.06	AGN70635	2.44
BRS310	3.73	AG1060	4.06	DKB550	2.41
AS4615	3.72	1167048	4.06	BRS373	2.40
1105661	3.71	1G245	4.06	A9904	2.38
1167048	3.70	A9735R	4.03	1G244	2.38
AG1060	3.69	A9721R	4.00	FOX	2.38
BRS380	3.65	BM737	3.98	BRS310	2.38
A9735R	3.61	AS4615	3.97	50A10	2.37
BRS3318	3.59	1G220	3.96	AG1040	2.35
BRS373	3.56	90G45	3.96	ADV123	2.33
DKB550	3.54	AG1080	3.90	AG1060	2.32
FOX	3.54	Nugrain4	3.88	BRS380	2.29
Jade	3.53	50A40	3.87	50A70	2.26
1G220	3.48	A6304	3.87	A6304	2.25
IPA2592	3.45	BRS3318	3.82	BRS330	2.25
A6304	3.44	DKB550	3.79	AGN8040	2.20
50A70	3.42	IPA2592	3.79	A9735R	2.19
AG1040	3.40	BRS373	3.78	BRS332	2.17
BRS330	3.39	FOX	3.75	1G220	2.16
90G45	3.38	IPA2583	3.68	80G20	2.09
AGN8040	3.38	BRS330	3.66	80G80	2.06
BM737	3.36	80G20	3.61	90G45	2.04
Buster	3.34	1105661	3.60	Buster	2.03
80G80	3.34	BRS332	3.59	Nugrain4	2.00
Nugrain4	3.33	AG1040	3.53	70G15	1.95
ADV123	3.28	ADV123	3.50	BM737	1.95
BRS332	3.25	70G15	3.47	Jade	1.86
IPA2583	3.24	Bravo	3.18	-	-
80G20	3.17	-	-	-	-
70G15	3.00	-	-	-	-
Bravo	2.97	-	-	-	-

remarkable when this comparison is made in relation to unfavorable environments. This result shows that this hybrid has a high phenotypic plasticity, that is, it has high productive stability in unfavorable environments; however, when favorable environmental stimuli occur, there is a response in the same proportion.

The favorable environment is characterized by low stress and high mean yield, and the unfavorable environment is characterized by high stress and low yield (Ceccarelli, 1989). This difference is explained by the variation of the weather conditions during the evaluation (Table 1). Water stress is a major cause of crop losses, which was the case for Nova Porteirinha, in the harvests of 2017 and 2018. Droughts are frequent due to the irregular rainfall distribution, which accumulated around 650 mm. Subregions may be defined for hybrids recommendation, and each subregion should coincide with a recommendation domain, grouping those environments with the same best-performing genotypes (Gauch Jr. & Zobel, 1997). The definition of subregions is not just geographical, but may also encompass farming practices (Coan et al., 2018).

Considering the results, it is necessary to use more accurate methods to recommend sorghum genotypes. The HMRPGV method analyzes the genotypic stability and adaptability simultaneously. The results of its application to experimental data were highly consistent in the ranking of genotypes. This method penalizes genotypes that show high mean variation over the replicates within an environment. This situation also occurs if there are variations across the environments regarding the overall mean of the environments. Due to its advantages, HMRPGV has been increasingly used to recommend different crop genotypes in Brazil (Almeida Filho et al., 2014; Coan et al., 2018). However, in these researches, the authors did not separate the environments into favorable and unfavorable ones.

The cultivation of sorghum in Brazil occurs mainly in the second crop. This period is defined by the high climatic instability of Brazilian environments, especially in the Cerrado. Thus, the separation of the entire group of environments into favorable and unfavorable, carried out in the present research, is advantageous for growers. Thus, the recommendation of genotypes can be made based on the technological

level used (that is, seed sowing, level of fertilization, irrigation, among others).

## Conclusions

1. The hybrids that stand out considering all environments are 1G282, A9904, 50A50, A9902, and XB6022.
2. The A9904 hybrid stands out for favorable environments with above average grain yield.
3. The hybrid 1G282 is among the five best hybrids for each group of environments, and it is the best hybrid grain for yield performance, adaptability, and stability.
4. The predicted genotypic values based on genotypic means can be used in relation to the environments with the same pattern of genotype x environment (GxE) interaction because they are free of the GxE interaction.

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