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Genetic potential of fusarium wilt-resistant elite common bean lines assessed in multiple environments

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ABSTRACT. Fusarium wilt is a serious soil disease affecting common bean cultivation, especially crops under a central pivot irrigation system. Our objective was to identify bean lines that combine resistance to Fusarium wilt in the field with other desirable traits. Twenty-eight randomized block trials with three replicates were conducted in the rainy, winter, and dry seasons from 2009 to 2012 in the states of Goiás, Federal District, and Paraná. The trials were composed of six elite lines (one carioca and five black grain type) selected in a previous study as resistant to Fusarium wilt under controlled conditions and five cultivars (three carioca two black grain type). Variance analysis demonstrated variability for reaction to Fusarium wilt and anthracnose, yield, architecture, and lodging tolerance. The interaction among the lines/cultivars and environments was significant for all traits. Five black bean lines were resistant to Fusarium wilt (grades <3.0) in the field; however, none of these lines outperformed the best controls in other traits, especially anthracnose resistance (grades >4.0). The Carioca line (CNFC 15872) was susceptible to fusarium wilt (5.6). Thus, these lines should not be indicated as suitable cultivars. Cultivars BRS Esplendor and BRS Notável exhibited excellent yield (2144 and 2200 $kg.ha^{-1}$, respectively), high stability, erect architecture (3.4 and 4.1), lodging tolerance (3.3 and 4.0), anthracnose resistance (1.0 and 1.7), and high fusarium wilt resistance (2.0 and 2.6). These cultivars are still excellent options for planting in areas with Fusarium wilt.

Key words: *Fusarium oxysporum* f. sp. *Phaseoli*; AMMI; Stability; Anthracnose; *Phaseolus vulgaris*

INTRODUCTION

Common beans are grown throughout Brazil by small and large farmers, with different levels of technology and agricultural input (Embrapa Arroz e Feijão, 2019). Because of the diversity of the environments where they are cultivated, and because the crops have three sowing seasons during the year (rainy, winter, and dry season), common beans are exposed to diseases that reduce grain yield and quality. Fusarium wilt, whose causal agent is the fungus *Fusarium oxysporum* f. sp. *phaseoli*, is one of the most serious diseases, mainly in crops under central pivot irrigation systems in the winter season in areas where beans are grown annually (Pereira et al., 2009a). The best and most adequate control of this disease is by using resistant cultivars and by rotating the common bean with non-host crops (Pereira et al., 2008).

The genetic resistance of common bean to *Fusarium oxysporum* f. sp. *phaseoli* is not well known; thus, few studies report information on genetic control (Cross et al., 2000; Brick et al., 2004; Pereira et al., 2008; 2009c; Cândida et al., 2009; Musoni et al., 2010). Currently, of the common bean cultivars available to growers, few have adequate levels of resistance to Fusarium wilt (Pereira et al., 2011; 2016; 2018). Thus, efforts should be directed toward obtaining new cultivars resistant to this disease. Most studies related to breeding resistance to the disease have been conducted with inoculations under controlled conditions (Pereira et al., 2008; Cândida et al., 2009). However, after this stage of research, the genotypes should be evaluated in the field to confirm their resistance. Few studies have evaluated the resistance of genotypes in the field (Pereira et al., 2016). In addition, the genotypes should be evaluated regarding other traits of agronomic importance because, to become new cultivars, the genotypes should combine a set of favorable phenotypes for several important traits.

Another important disease for common bean is anthracnose, caused by the fungus *Colletotrichum lindemuthianum*, which is widespread throughout the country and frequent in crops in the winter season, causing losses that can reach 100% (Singh and Schwartz, 2010). Plant architecture and lodging tolerance are also highly important traits, since erect plants with less lodging, which have reduced contact of the pods with the soil, are associated with a lower disease occurrence, less loss during mechanized harvesting, and grains with better commercial quality (Pereira et al., 2012a).

Another important trait is grain yield. Because beans are grown in very diverse environments, the lines should be evaluated using a set of trials representative of the real cultivation conditions to determine the effects of the interaction of genotypes with the environments on the different traits and to select those lines with greater adaptability and stability to each type of environment where grown. The interaction between genotypes and environments has been reported in several studies for several traits, especially for grain yield (Pereira et al., 2013; 2018; Melo et al., 2018;). Among the methods for analyzing stability and adaptability, the method of Nunes et al., (2005) assesses adaptability and stability by standardizing the means of the genotypes in different environments using the adaptability parameter (Zi) for each cultivar and the coefficient of variation for each cultivar (CVi) based on the values of Z_{ij} (CVij). This method has been used recently in common bean (Pereira et al., 2018). Cruz et al. (1989) and AMMI (Gauch and Zobel, 1996) are methods to evaluate the stability and adaptability widely used. Considering the above, the objective of our study was to identify elite lines that combine field resistance to Fusarium wilt, erect plant architecture, lodging tolerance, and resistance to anthracnose with good adaptability and stability for grain yield for the recommendation of new cultivars.

MATERIAL AND METHODS

Six elite common bean lines were evaluated, including one of the *carioca* market class (cream with brown stripes) (CNFC 15872) and five of the black market class (CNFP 15870, CNFP 15867, CNFP 15871, CNFP 15868, and CNFP 15869) obtained previously and selected as resistant to Fusarium wilt (isolate FOP 46) under controlled conditions, together with five cultivars that were used as controls (Table 1).

The cultivar BRS Cometa, of *carioca* type (Faria et al., 2008) and the cultivar BRS Supremo (Costa et al., 2006) of black type were used because they are susceptible to Fusarium wilt. The cultivar BRS Notável (Pereira et al., 2012b), of *carioca* type, and the cultivar BRS Esplendor (Costa et al., 2011), a black type, both resistant to fusarium wilt, were also used. The cultivar Pérola (*carioca* type) was included because it is one of the most frequently planted cultivars in Brazil, especially during the winter season, under central pivot irrigation, when Fusarium wilt is more severe. A total of 28 experiments were conducted with these 11 lines/cultivars at different locations (Brasília-Distrito Federal, Santo Antônio de Goiás-Goiás, Anápolis-Goiás, Ponta Grossa-Paraná, and Inhumas-Goiás) between 2009 and 2012, during dry, winter, and rainy seasons. Some of the trials installed in Santo Antônio de Goiás were conducted in an area with a history of occurrence of Fusarium wilt that is routinely used to test genotypes for the reaction to this disease (Pereira et al., 2016).

All trials were installed in randomized blocks with three replicates, and the plots consisted of four rows that were 4 m in length, with spacing of 0.45 meters. In these experiments, the yield, plant architecture, lodging tolerance, reaction to Fusarium wilt, and reaction to anthracnose were evaluated. The evaluations of each trait were made in different numbers of trials. Yield was measured in grams per plot, converted to kilograms per hectare, and adjusted to 13% moisture. Plant architecture and lodging tolerance were evaluated using score scales ranging from 1 to 9, with 1 being the most desired phenotype (fully adapted to mechanized harvest) and 9 being the undesired phenotype (inadequate for mechanized harvest). Reaction to diseases was evaluated using a descriptive scale of scores with values ranging from 1 (an absence of symptoms) to 9 (most plants are dead) (Melo, 2009). The evaluations were conducted by two evaluators.

After the data were obtained, analyses of variance were performed for each trait in each of the experiments. The homogeneity of the residual variances was tested by the ratio between the largest and the smallest mean square of the residuals. The variances were considered homogeneous when this ratio was less than seven, as described by Pimentel-

Gomes (1990). When a lack of homogeneity of residual variances was observed, an adjustment was made in the degrees of freedom of the mean error and of the genotype by environment interaction (Cochran, 1954).

Table 1. Description of the common bean cultivars and elite lines evaluated.

Cultivar/Line	Grain type	Genealogy
BRS Notável	Carioca	A769 /5/ A774 /4/ A429 / XAN252 // V8025 / G4449 /// WAF2 / A55 // GN31 / XAN170
BRS Esplendor	Black	CB911863 / AN9123293
Pérola	Carioca	Selected from the cultivar Aporé
BRS Supremo	Black	W22-34 x VAN163
BRS Cometa	Carioca	A769 /5/ EMP250 /4/ A429 / XAN252 // V8025 / G4449 /// WAF2 / A55 // GN31 / XAN170
CNFP 15867	Black	FT Tarumã / Diamante Negro
CNFP 15868	Black	FT Tarumã / Macanudo
CNFP 15869	Black	Milionário 1732 / Xamego
CNFP 15870	Black	Milionário 1732 / Diamante Negro
CNFP 15871	Black	Milionário 1732 / Macanudo
CNFC 15872	Carioca	São José / Goytacazes

After the homogeneity of the residual variances test was considered, joint analyses of the experiments were performed for each trait. For yield, the effect of the environments was considered random, and for the other traits, the effect of the environments was considered fixed due to the smaller number of environments. Selective accuracy was determined to evaluate the informativeness of the experiments, as proposed by Rezende and Duarte (2007).

Next, parameters of phenotypic adaptability and stability for yield were estimated, according to the method of Nunes et al. (2005). Initially, the means of the lines/cultivars in the different environments were standardized for each environment (experiment) according to the following expression:

$$z_{ij} = \frac{\left(\bar{y}_{ij} - \bar{y}._j\right)}{s._j} \quad \text{(Eq. 1)}$$

where z_{ij} is the value of the standardized variable corresponding to cultivar i in environment j; $\bar{y}_{ij}$ is the mean of cultivar i in environment j; $\bar{y}._j$ is the mean of environment j; and $s._j$ is the phenotypic standard deviation among the means of the cultivars in environment j, given

$$s._j = \sqrt{\sum_{i-1}^{t} \frac{\left(\bar{y}_{ij} - \bar{y}._j\right)^2}{t-1}} \quad \text{(Eq. 2)}$$

The method of Nunes et al. (2005) provides information on the adaptability of a line via the z_{ij} statistic and on the stability of the line via the coefficient of variation of the Zij estimates (CV_{Zi}). The standardized values (z_{ij}) were used to construct graphs for each genotype, with the dimensions of the axes (environments) being equivalent to the values of each genotype i in environment j. The most adapted genotype is the one with the highest Z_i estimate, and the most stable genotype is the one with the lowest coefficient of variation (CV_{Zi}), that is, with the lowest variation among the environments.

In the bisegmented linear regression of Cruz et al. (1989) the response to unfavorable environments is given by the parameter β_{1i}, and the response to the favorable environments by $\beta_{1i} + \beta_{2i}$. The genotype stability is evaluated by the deviations from the regression $\left(\sigma^2_{\delta i}\right)$ and the coefficient of determination (R^2_i). These parameters were estimated.

The AMMI analysis (Gauch and Zobel, 1996), which uses the additive model to examine the main effects and multiplicative model to study the interaction, was performed. The Gollob test was used to select the model. To identify the most stable genotypes by AMMI, for each genotype, the mean of the absolute scores was obtained for the significative components, weighted by the percentage of explanation of each component (weighted mean of absolute scores – WMAS) (Pereira et al., 2009a; 2009b). Statistical analyses were performed using the computational applications GENES (Cruz, 2013) and SAS.

RESULTS AND DISCUSSION

Regarding Fusarium wilt, the experimental coefficient of variation (CV) estimates among the environments ranged from 19.0 to 22.1% (Table 2), indicating good experimental precision, considering that *Fusarium oxysporum* is a soil pathogen and that the severity of the disease was evaluated in the field and under natural occurrence (Costa et al, 2007; Cândida et al., 2009; Pereira et al., 2019). Estimates of selective accuracy were considered high (SA >0.90) for all trials, similar to those obtained by Pereira et al. (2019), indicating high informativeness of the trials. In the four trials, the lines/cultivars presented significant genetic variability. The means of reaction to Fusarium wilt in the different environments ranged from 2.82 to 4.59, indicating variability of the disease incidence in the different environments.

The coefficient of variation for grain yield ranged from 10.4 to 23.2% (Table 2), indicating good experimental precision (Pereira et al., 2013; 2019). The experimental quality was confirmed by the selective accuracy estimates, which were considered high or very high (above 0.70) for 23 of the 28 trials. Significant difference among the lines in 75% of the trials showed genetic variability among the lines/cultivars. The general mean for grain yield among the environments varied from 935 to 3636 $kg.ha^{-1}$, indicating considerable environmental variation, which can be confirmed by the geographic data of the experimental sites, at altitudes varying from 770 to 1,171 m, in addition to the three years and three different sowing seasons evaluated.

For plant architecture, lodging tolerance, and reaction to anthracnose, the CVs also indicated good experimental accuracy, compatible with other studies (Pereira et al., 2018; Marques Júnior et al., 1997), which was confirmed by the selective accuracy estimates. The means of the environments also showed great variation, confirming the occurrence of distinct environmental conditions (1.5 to 1.91 for plant architecture, 3.00 to 4.68 for lodging tolerance, and 3.00 to 4.27 for anthracnose reaction).

Table 2. Geographical information of locations (altitude[1] in meters, sowing season[2] [dry (D), rainy (R) and winter (W)], and years) of field trials used in evaluation of the common bean lines/cultivars, and summary of individual analysis of variance for yield (kg ha^{-1}).

Site	Alt[1]	Season[2]	Year	MSg[3]	P[4]	Mean	CV (%)[5]	SA[6]
Brasília-DF	1171	R	2009	224837	0.045	1717	17.8	0.77
SAG-GO[7]	823	D	2010	350688	0.001	935	21.0	0.94
SAG-GO	823	W	2010	391842	0.001	1446	16.7	0.92
SAG-GO	823	W	2010	265590	0.001	1148	17.0	0.93
Brasília-DF	1171	R	2010	177957	0.333	1720	22.2	0.43
SAG-GO	823	R	2010	432523	0.048	2992	14.3	0.76
Anápolis-GO	1017	R	2010	1258618	0.001	3068	11.5	0.95
Ponta Grossa-PR	969	D	2011	244866	0.008	2538	10.4	0.85
SAG-GO	823	D	2011	183939	0.084	1853	16.2	0.71
Anápolis-GO	1017	D	2011	818283	0.001	2002	12.9	0.96
Brasília-DF	1171	D	2011	206782	0.034	2386	11.9	0.78
SAG-GO	823	W	2011	495423	0.001	2348	12.5	0.91
Anápolis-GO	1017	W	2011	748158	0.001	2302	15.7	0.91
Ponta Grossa-PR	969	R	2011	538072	0.024	3636	12.1	0.80
Brasília-DF	969	W	2011	72598	0.080	1053	17.8	0.72
SAG-GO	823	W	2011	481427	0.001	1556	20.2	0.89
Anápolis-GO	1017	R	2011	107364	0.351	1871	16.0	0.40
Brasília-DF	1171	R	2012	308795	0.105	2097	19.2	0.69
SAG-GO	823	R	2012	568283	0.001	1407	16.5	0.95
Inhumas-GO	770	R	2012	583666	0.001	1552	15.1	0.95
SAG-GO	823	D	2012	229014	0.002	1300	17.3	0.88
Brasília-DF	1171	D	2012	362070	0.001	1043	16.4	0.96
Ponta Grossa-PR	969	D	2012	195161	0.024	2313	11.4	0.80
Brasília-DF	1171	W	2012	273331	1.000	2285	23.2	0.00
Brasília-DF	1171	W	2012	114781	0.368	1633	19.2	0.38
Anápolis-GO	1017	W	2012	1983221	0.001	3469	17.7	0.90
SAG-GO	823	W	2012	1440233	0.001	2120	17.6	0.95
SAG-GO	823	W	2012	744201	0.001	2155	15.2	0.92

[3]Mean square of lines; [4]P-value for lines; [5]Coefficient of variation (%); [6]Selective accuracy; [7]SAG- Santo Antônio de Goiás.

Considering the joint analyses, for all traits evaluated, a significant effect of lines was observed, confirming the genetic differences observed in the individual analyses (Table 3). Differences also existed among the environments, indicating variability among sites, years, and growing seasons. Because of the significance of the interaction between genotypes and environments, the performance of the lines was not coincident in the different environments for all the traits.

Grain yield is strongly influenced by the environment, has polygenic inheritance, is complex, and is fundamental in the selection and recommendation of cultivars. The significant interaction for grain yield was observed in other studies (Pereira et al., 2013; Torga et al., 2013; Melo et al., 2018), confirming the need for more detailed analyses of the cultivars according to the particularity of each environment, thus making analysis of the adaptability and stability necessary to obtain greater confidence in the recommendation of cultivars.

Regarding the reaction to Fusarium wilt and anthracnose, the presence of genotype by environment interaction may also be due to the presence of variability in pathogen races, indicating that a genotype identified as resistant in a given region may not present the same response in other regions (Sala et al., 2006). Thus, part of the interaction between genotypes and environments observed in this study may have occurred due to the incidence and severity of the diseases in the environments, caused by variations in climatic conditions and the occurrence of different pathogen races, as observed by Pereira et al. (2018). For fusarium wilt, some research carried out in this same infected area did not detect this type of interaction, such as that of Pereira et al. (2019), which evaluated segregant populations in three years (2012, 2013 and 2014).

Table 3. Summary of joint analyses of variance for reaction to fusarium wilt (FOP), yield (kg ha^{-1}), plant architecture (ARQ), lodging tolerance (LOD), and reaction to anthracnose (ANT) of common beans.

Source of variation	DF[1]	FOP		DF	Yield		DF	ARQ		DF	LOD		DF	ANT	
		MS[2]	P[3]		MS[2]	P[3]		MS[2]	P[3]		MS[2]	P[3]		MS[2]	P[3]
Blocks/Environments	4	0.34		56	272624		16	9.50		14	1.54		3	6.07	
Lines (L)	10	37.84	0.01	10	1759663	0.01	10	142.76	0.01	10	16.55	0.00	10	22.70	0.01
Environments (E)	3	13.05	0.01	27	16362171	0.01	15	227.63	0.01	13	9.13	0.00	2	10.13	0.06
L X E	30	1.98	0.01	184	654460	0.01	114	74.34	0.01	95	1.51	0.01	20	5.18	0.01
Residue	40	0.47		377	161369		119	50.00		100	0.92		30	2.14	
Total	87			923			351	504.22		307			65		
Mean		3.61			1998			3.88			3.93			3.77	
CV (%)[4]		18.89			20.11			16.69			24.38			38.80	
SA[5]		0.99			0.79			0.99			0.97			0.95	

[1]Degrees of freedom; [2]Mean Square; [3]P-value; [4]Coeficient of variation (%); [5]Selective accuracy.

When the means of the lines/cultivars for reaction to Fusarium wilt were considered, four lines with black grain type (CNFP 15867, CNFP 15868, CNFP 15869, and CNFP 15870) showed excellent resistance and were in the first group of means, together with the controls BRS Esplendor (2.0) and BRS Notável (2.6), which showed high resistance to Fusarium wilt (Table 4). These lines were already considered resistant based on a study conducted by Costa et al. (2007) in which the lines were evaluated for the incidence of Fusarium wilt in the greenhouse using isolate FOP 46. Pereira et al. (2016; 2018) also had reported that these two cultivars are highly resistant to Fusarium wilt in the field in evaluations conducted in different years.

The resistance of the CNFP 15867, CNFP 15868, CNFP 15869, and CNFP 15870 lines is apparently due to the FT Tarumã and Milionário 1732 parents of the original crosses, which were resistant to four *Fusarium oxysporum* f. sp. *phaseoli* isolates (Sala et al., 2006) (Tables 1 and 4).

Table 4. Means for reaction to fusarium wilt (FOP), yield (kg ha^{-1}), plant architecture (ARQ), lodging tolerance (LOD), and reaction to anthracnose (ANT), for 11 common bean lines evaluated in 28 environments.

Line	Group	FOP		Yield		ARQ		LOD		ANT	
CNFP 15867	Black	1.8	a	2077	b	3.4	B	3.4	b	5.8	c
CNFP 15870	Black	2.0	a	2152	a	3.8	C	3.9	c	5.2	c
CNFP 15869	Black	2.0	a	1828	c	4.1	D	4.5	d	4.2	b
BRS Esplendor	Black	2.0	a	2144	a	3.4	B	3.3	b	1.0	a
CNFP 15868	Black	2.1	a	1977	b	3.8	C	4.1	c	4.0	b
BRS Notável	*Carioca*	2.6	a	2202	a	4.1	D	4.0	c	1.7	a
CNFP 15871	Black	3.0	b	2050	b	3.8	C	3.6	c	6.7	c
Pérola	*Carioca*	3.9	c	2045	b	5.6	E	5.6	e	5.8	c
CNFC 15872	*Carioca*	5.6	d	1796	c	3.5	B	3.8	c	2.2	a
BRS Cometa	*Carioca*	7.3	e	1850	c	4.3	D	4.4	d	1.8	a
BRS Supremo	Black	7.5	e	1857	c	3.0	A	2.6	a	3.2	a

In columns, mean values followed by the same letter do not differ from each other by the Scott-Knott mean clustering method at the 10% level of significance.

The line CNFC 15872, with *carioca* type, considered resistant by Costa et al., (2007) in greenhouse studies, was moderately susceptible to Fusarium wilt when evaluated in the field (5.6), and was less resistant than the cultivar BRS Notável (2.6). High susceptibility to fusarium wilt was confirmed for the cultivars BRS Cometa (7.3) and BRS Supremo (7.5), confirming the strong selection pressure in the field trials and the discrimination efficiency of the lines/cultivars relative to the occurrence of this disease. The cultivar Pérola showed an intermediate reaction to Fusarium wilt (3.9), which is consistent with the behavior of this cultivar in production areas—occurrence of disease symptoms but high productive capacity—and may be related to the root system of this cultivar. This trait, coupled with the excellent commercial quality of the grains, makes this cultivar one of the most used, especially in cultivation under central pivot irrigation, despite its poor plant architecture and lodging tolerance (5.59 and 5.61, respectively).

The mean grain yield ranged from 1796 to 2202 kg ha^{-1} among the lines, and CNFP 15870, BRS Esplendor, and BRS Notável were the most productive (Table 4). Three other lines (CNFP 15867, CNFP 15868, and CNFP 15871) presented yields similar to that of the Pérola cultivar. The CNFP 15869 and CNFC 15872 lines presented grain yield similar to the BRS Cometa and BRS Supremo controls, which are susceptible to Fusarium wilt and exhibit lower productive potential.

The adaptability analysis for grain yield by the method of Nunes et al. (2005) identified six genotypes with an adaptability parameter estimate (Zi) greater than 3: BRS Notável, CNFP 15870, BRS Esplendor, CNFP 15867, CNFP 15871, and Pérola. In general, the lines with the highest means presented the highest Zi values, indicating a strong relation between these estimates. Differences in lines stability were also observed, as measured by the coefficient of variation of Zij (CVi). The identification of lines with high means and that are stable and adapted is important. According to the Zi values, the most adapted genotypes were BRS Notável (3.49), CNFP 15867 (3.42), CNFC 15870 (3.39), BRS Esplendor (3.38), CNFP 15871 (3.03), and Pérola (3.01) (Table 4). Among these, the most stable genotypes (lower CVi) were BRS Notável (16.8%), BRS Esplendor (21.4%), CNFP 15867 (25.9%), and CNFP 15870 (26.0%). The use of cultivars with phenotypic stability is an alternative that mitigates the interaction between genotypes and environments. No line presented CVi estimates lower than those of the controls BRS Notável and BRS Esplendor. However, the CNFP 15870 and CNFP 15867 lines presented lower CVi estimates than those obtained for the controls Pérola, BRS Supremo, and BRS Cometa. Considering the mean, the adaptability, and the stability, the lines/cultivars that had notable grain yields were BRS Notável, BRS Esplendor, CNFP 15867, and CNFP 15870 (Figure 1). The BRS Notável cultivar presented above-average grain yield in 24 of the 28 environments; the BRS Esplendor cultivar, in 22 environments, with both showing great stability. Among the lines, CNFP 15867 presented above-average yield in 19 environments and CNFP 15870 in 20 environments.

For the Cruz et al. (1989) method, the ideal genotype presents high mean, low sensitivity to unfavorable environments ($\hat{\beta}_{1i}<1$), responsiveness to environmental improvement ($\hat{\beta}_{1i}+\hat{\beta}_{2i}>1$) and high or tolerable predictability. None of the genotypes presented this performance (Tabela 5), as reported in several other publications (Oliveira et al., 2006; Pereira et al., 2009a; 2009b), in different regions and with different genotypes.

The genotypes CNFP 15867 e CNFP 15869 presented low sensitivity to unfavorable environments ($\hat{\beta}_{1i}$ <1), but not did not show responsivity to environmental improvement (Table 5). CNFP 15867 and CNFP 15869, presented high and low predictability, respectively. BRS Supremo was the only genotype responsive to environmental improvement ($\hat{\beta}_{1i}+\hat{\beta}_{2i}$ >1), but it was sensitive to unfavorable environments and presented low predictability. The genotypes with highest yield, BRS Notável, BRS Esplendor and CNFP 15870 were sensitive to unfavorable environments ($\hat{\beta}_{1i}$=1), not responsive to environmental improvement ($\hat{\beta}_{1i}+\hat{\beta}_{2i}$=1), and highly predictable.

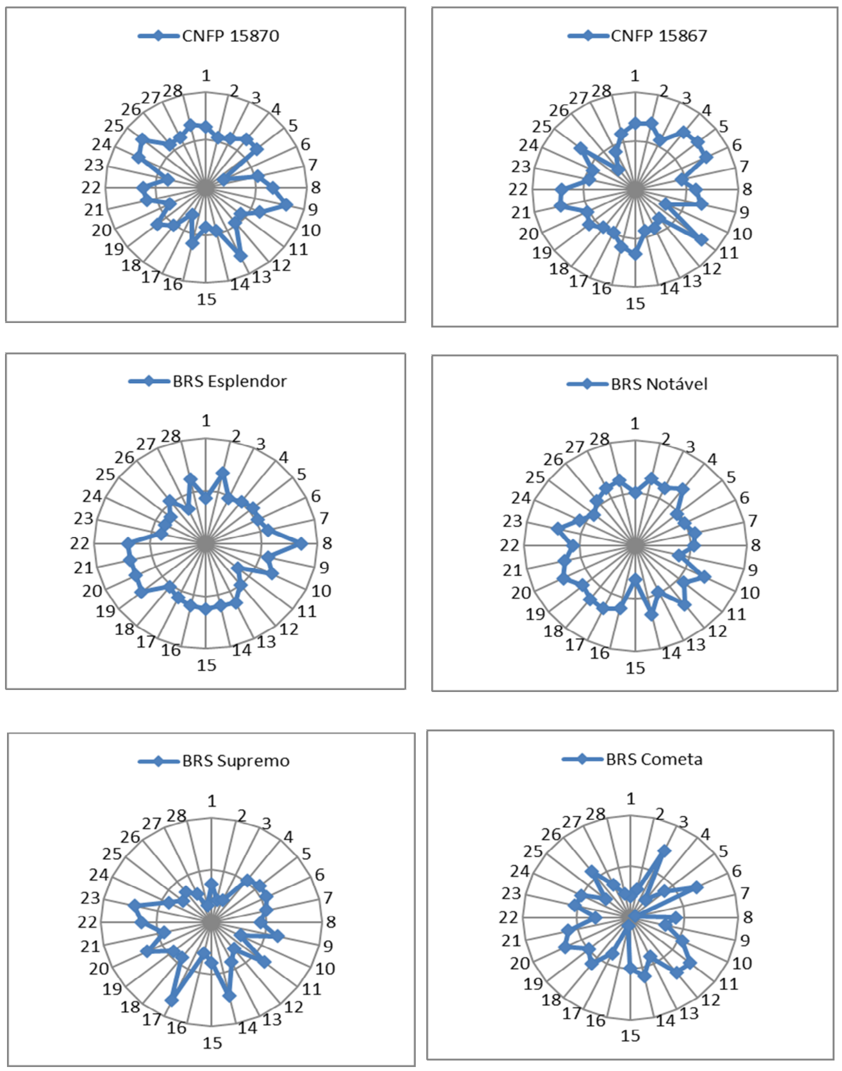

Figure 1. Graphical representation of the adaptability (Z_{ij}) of six common bean lines/cultivars in the environments, for yield, according to the method of Nunes et al. (2005). The circle represents the average of environments (constant value associated with the variable Z), and the axes represent each of the environments evaluated.

In the AMMI analysis the first five principal components and the residue were significant, at 1% probability, indicating that AMMI 5 is an appropriate model. These components together amounted to a total of 87% of the variation. To identify the most stable genotypes by AMMI, the mean of the absolute scores was obtained for the first five components, weighted by the percentage of explanation of each component (weighted mean of absolute scores – WMAS) for each genotype (Table 5). Thus, the lower the WMAS value, the lower the contribution of a genotype to the interaction and, consequently, the more stable is the genotype. The most stable genotypes were BRS Notável, BRS Esplendor e CNFP 15868 (Table 5; Figure 2) Among these, BRS Notável and BRS Esplendor (G2) presented high seed yield too (Figure 1B).

Different genotypes were identified as stable and adapted by the different methods. None of the genotypes presented the performance required by the Cruz et al. (1989) method. The Nunes et al. (2005) and AMMI methods identified the same three genotypes as the most stable (BRS Notável, BRS Esplendor and CNFP 15868). Among these genotypes, BRS Notável and BRS Esplendor presented high seed yield.

Regarding the architecture and lodging tolerance of the plants, lines with mean scores equal to or better than that of the BRS Cometa cultivar, which has an erect plant architecture and good lodging tolerance, were considered erect (Faria et al., 2008). All lines showed erect architecture and high lodging tolerance (Table 4). The line with the best architecture and lodging tolerance was CNFP 15867 (black type), with performance similar to that of the BRS Esplendor but lower than that of the best control (BRS Supremo). In general, lines/cultivars with black grains present better plant architecture than those of the carioca type market class (Pereira et al., 2018). The cultivars BRS Esplendor and BRS Supremo presented high tolerance to lodging, similar to evaluations conducted in the low-altitude Cerrado region in the state of Mato Grosso (Pereira et al., 2012a).

Resistance to anthracnose is also important, as this disease is widespread throughout Brazil, causing yield losses of up to 100%. The cultivars BRS Esplendor (1.0), BRS Notável (1.7), BRS Cometa (1.8), and BRS Supremo (3.2) showed high resistance to anthracnose, as did the CNFC 15872 line (2.2) (Table 4). Among these cultivars, BRS Notável and BRS Cometa are notable for their high resistance to anthracnose in other field studies (Faria et al., 2008; Pereira et al., 2012a; 2018). However, the lines with black grains, resistant to Fusarium wilt were susceptible to anthracnose.

None of the lines were simultaneously superior for all the evaluated traits. So, these lines do not have potential to be indicated as new cultivars. However, the line CNFP 15870 can be used in crosses in breeding programs to obtain new cultivars, because it gave good performance in reaction to Fusarium wilt, grain yield, adaptability and stability, plant architecture, and lodging tolerance. The *carioca* cultivar BRS Notável and the black cultivar BRS Esplendor presented resistance to Fusarium wilt and anthracnose, good stability, high productive potential, and intermediate plant architecture and lodging tolerance, confirming the results of Pereira et al. (2012).

CONCLUSIONS

Considering seed yield, adaptability, stability, plant architecture, lodging tolerance, anthracnose and fusarium wilt resistance, none of the lines was superior to the cultivars BRS Esplendor and BRS Notável; therefore, none of these lines have the potential to replace these two cultivars. These two cultivars are still excellent options for cultivation in areas where Fusarium wilt is a problem.

Table 5. Mean values for seed yield (kg ha^{-1}), adaptability and stability parameters, using Nunes et al. (2005), Cruz et al., (1989) and AMMI methods, for 11 common bean genotypes evaluated in 28 environments.

Line	Mean [1]	Nunes	Cruz				AMMI					
		Z_{ij} [2]	CV_i [3]	ß1 [4]	ß1 + ß2 [5]	δ_{di} [6]	IPCA1 (36%) [7]	IPCA2 (23%) [7]	IPCA3 (12%) [7]	IPCA4 (8%) [7]	IPCA5 (8%) [7]	WMAS [8]
CNFP 15867	2077 b	3.4	25.9	0.68*	0.81	1.92	25.0	11.6	9.0	14.7	-0.3	16.0
CNFP 15870	2152 a	3.4	26.0	0.99	0.78	1.74	-10.6	10.6	-16.0	0.9	-9.2	10.3
CNFP 15869	1828 c	2.6	32.5	0.71*	1.03	2.73*	27.3	16.4	-2.6	-12.0	-3.0	17.4
BRS Esplendor	2144 a	3.4	21.4	0.93	1.10	1.50	7.5	-1.6	-23.9	0.5	-5.7	7.4
CNFP 15868	1977 b	2.8	24.8	1.02	0.99	1.18	-9.8	4.5	-10.1	7.6	-7.1	8.0
BRS Notável	2202 a	3.5	16.8	1.08	0.93	0.80	-3.5	-3.6	-5.7	1.3	-4.2	3.7
CNFP 15871	2050 b	3.0	37.5	1.25*	1.22	3.13*	-20.5	14.0	27.9	-16.9	-16.0	19.1
Pérola	2045 b	3.0	35.2	1.34*	0.98	3.57*	-35.0	-5.3	-7.9	-7.3	19.8	19.5
CNFC 15872	1796 c	2.4	30.9	0.98	0.70	1.78	-5.7	10.2	15.2	24.6	17.3	11.0
BRS Cometa	1850 c	2.7	42.2	1.11	1.06	4.91*	3.5	-44.6	10.1	6.9	-12.6	16.4
BRS Supremo	1857 c	2.8	36.6	0.91	1.38*	2.63*	21.8	-12.1	3.9	-20.3	21.0	16.5

(1) Means followed by the same letter are equal (Scott-Knott. α=0.10); [2] Z_{ij}- value of the standardized variable; [3] CV_i - coeficiente of variation for each genotype; [4] H_0: $\beta_{1i} = 1$; [5] H_0: $\sigma_{di} = 0$; [6] H_0: $\beta_{1i} + \beta_{2i} = 1$; * and **, significant at 5% and 1% error probability, by the t test, respectively; [7] Percentage of the variation explained by each principal component (CP) in the AMMI analysis; [8] Weighted mean of the absolute scores

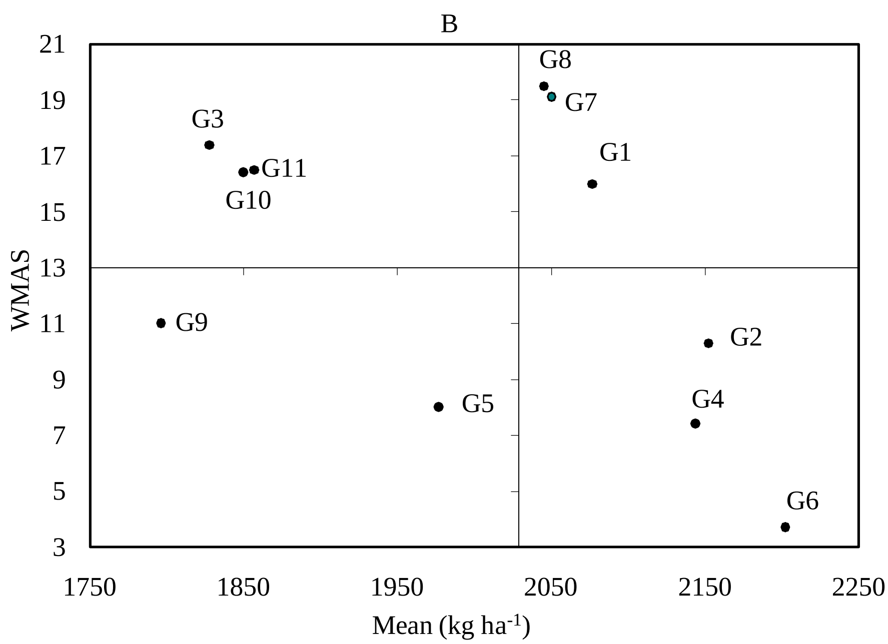

Figure 2. Graphical AMMI analysis for 11 common bean lines/cultivars (G1- CNFP 15867; G2- CNFP 15870; G3- CNFP 15869; G4- BRS Esplendor; G5- CNFP 15868; G6- BRS Notável; G7- CNFP 15871; G8- Pérola; G9- CNFC 15872; G10- BRS Cometa; G11- BRS Supremo), evaluated in 28 environments. WMAS (weighted mean of absolute scores).

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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