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Strategies for the selection of common bean lines for yield and commercial grain quality

Abstract – The objective of this work was to evaluate common bean lines for yield and commercial grain quality in multi-environments, and to maximize the efficiency of selection using complementary methods. Over three crop years, 79 trials using carioca common bean lines were carried out in the dry, winter, and rainy crop seasons, in the Southern, Southeastern, Midwestern, and Northeastern regions of Brazil. The experimental design was a randomized complete block with three replicates and 17 genotypes. The evaluated traits were: grain yield (GY), grain appearance (GA), sieve yield (SY), and 100-seed weight (100SW). Adaptability and stability analyses were carried out using models that consider the genotype effect as fixed or as random, in a mixed-model perspective. A significant interaction between genotypes and environments was observed for all traits evaluated. The CNFC 15086 line presented the highest GY and 100SW, besides a high adaptability and stability. The most prominent line for GA was CNFC 15038. The CNFC 15097 line is recommended as a cultivar (BRS FC406) because it shows, simultaneously, favorable performances for GY, GA, SY, and 100SW, as well as for adaptability and stability.

Index terms: *Phaseolus vulgaris*, adaptability, multi-environments, stability.

Estratégias de seleção de linhagens de feijão-comum quanto à produtividade e à qualidade comercial de grãos

Resumo – O objetivo deste trabalho foi avaliar linhagens de feijão-comum quanto à produtividade e à qualidade comercial de grãos em multiambientes, e maximizar a eficiência da seleção por meio de métodos complementares. Ao longo de três anos agrícolas, 79 ensaios com linhagens de feijão-comum do tipo carioca foram conduzidos nas safras da seca, do inverno e do verão, nas regiões Sul, Sudeste, Centro-Oeste e Nordeste do Brasil. O delineamento experimental foi em blocos ao acaso, com três repetições e 17 genótipos. Os caracteres avaliados foram: produtividade de grãos (GY), aparência de grãos (GA), rendimento de peneira (SY) e massa de 100 grãos (100SW). As análises de adaptabilidade e estabilidade foram realizadas por meio de modelos que consideram o efeito de genótipo como fixo ou aleatório, em uma perspectiva de modelo misto. Observou-se interação significativa entre genótipos e ambientes para todos os caracteres avaliados. A linhagem CNFC 15086 apresentou as maiores GY e 100SW, além de alta adaptabilidade e estabilidade. A linhagem de maior destaque quanto à GA foi a CNFC 15038. A linhagem CNFC 15097 é a recomendada como cultivar (BRS FC406), por apresentar, simultaneamente, desempenhos favoráveis para GY, GA, SY e 100SW, bem como para adaptabilidade e estabilidade.

Termos para indexação: *Phaseolus vulgaris*, adaptabilidade, multiambientes, estabilidade.

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Introduction

High grain yield is one of the main aims of common bean breeding programs. However, to associate this trait with grain quality, plant architecture suitable for mechanized harvest, and yield stability, is essential to expand the approval of the cultivar (Pereira et al., 2017). In recent years, the increasing requirements of consumers and industry have imposed new demands in relation to grain traits, especially commercial traits.

Some studies have shown favorable genetic gains for yield in common bean breeding programs (Faria et al., 2013, 2014), and for grain appearance (Faria et al., 2013) in cultivars of the carioca commercial group. Nevertheless, the response of the genotypes has not coincided in different environments, which is a result of the genotype by environment (G×E) interaction for the agronomic and grain quality traits (Carbonell et al., 2010; Arns et al., 2018; Amaral et al., 2022). In this regard, studies on the adaptability and phenotypic stability of agronomic traits may provide a greater reliability in ranking new cultivars of common bean, by contributing both to the reduction of limiting factors of production and to the management of this crop. For the commercial grain quality traits, these parameters may be useful for making available the cultivars with high commercial added value (Carbonell et al., 2010; Pereira et al., 2017; Vakali et al., 2017).

The method of Nunes et al. (2005) for adaptability and stability analyses has stood out in these studies, and it uses a modeling that considers the genotype effect as fixed. The method of Resende (2007) is also prominent; it uses modeling that considers the genotype effect as random, in a perspective of mixed modeling, which allows of the possible estimation of genetic parameters via residual or restricted maximum likelihood (REML), obtaining the genotypic mean via best linear unbiased prediction (BLUP). For direct application in plant breeding programs, we could not find in the literature that use the two methods as a strategy for selection of promising lines.

In addition, studies on common bean that evaluate the estimates of adaptability and stability for traits related to grain quality are still in an initial phase (Carbonell et al., 2010; Pereira et al., 2017), which shows the need for broader and more consistent studies, to better capitalize on the effect of the genotype by environment interaction. This information is necessary for common bean because of the great diversity of environmental conditions in which the crop is grown in Brazil (Ramalho et al., 2012). According to studies performed up to now, most of the estimates were obtained in few locations within the same state.

The objective of this work was to evaluate common bean lines for yield and commercial grain quality in multi-environments, and to maximize the efficiency of selection using complementary methods.

Materials and Methods

Seventeen common bean genotypes of the carioca group were evaluated for their value of cultivation and use (VCU). The trials were composed of 13 elite lines of the Embrapa Arroz e Feijão breeding program and 4 checks ('BRS Estilo', 'Pérola', 'BRS Sublime', and CNFC 10762), chosen for their agronomic traits and grain quality.

Seventy-nine (79) experiments were carried out in the states of Goiás, Distrito Federal, Mato Grosso, Mato Grosso do Sul, Paraná, Santa Catarina, São Paulo, Pernambuco, Bahia, Alagoas, and Sergipe. These experiments were conducted from 2011 to 2013 in the dry season, winter, and rainy crop season in a randomized complete block design, with three replicates, and plots of four 4 m length rows spaced at 0.50 m between rows, with 15 seed m^{-1} sowing. The two center rows were used for data collection. The crop treatments followed those recommended for the crop (Del Peloso & Melo, 2005), except for disease control, which was not performed.

Phenotype evaluations were performed for grain yield and for traits related to commercial grain quality. Measured grain yield (GY) – in g/plot converted to kg ha^{-1} – was adjusted to 13% grain moisture in all 79 experiments. The traits related to grain quality were visual grain appearance (GA), sieve yield (SY), and 100-seed weight (100SW). Evaluations were performed for SY in 48 experiments, 100SW in 61 experiments, and GA in 8 experiments, using a scale proposed by Faria et al. (2013) that takes into account grain color, shape, and weight. SY was estimated in each plot with 300 g grain samples, with 13% moisture. Each sample was classified in a sieve with oblong openings of 0.45 cm (sieve 12). The grain retained in the sieve was weighed and SY was estimated in percentage. The determination of 100SW was performed through counting out 100 grains in random samples, in each plot, followed by weighing on a precision balance.

Individual and joint analyses of variance were performed on the phenotypic data. The mean values were compared by the Scott-Knott′s test at 10% probability. This level of significance was used to reduce the likelihood of lack of discrimination between genotypes due to type II errors (Zimmermann, 2014). This procedure is recommended when small differences occur between treatments, as is the case of trials with elite genotypes.

Two methods of stability and adaptability analysis were used. In the method of Nunes et al. (2005), the adjusted mean values of the genotypes were obtained considering the genotype effect as fixed, and the other model effects as random. The mean values of the environments were standardized for each environment (experiment), through the following expression:

$$Z_{ij} = \frac{\left(\bar{y}_{ij} - \bar{y}_{.j}\right)}{s_{.j}},$$

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

$$s_{.j} = \sqrt{\sum_{i=t}^{t} \frac{(\bar{y}_{ij} - \bar{y}_{.j})^2}{t-1}}.$$

Then, the constant 4 was added to the values, to eliminate negative values. The mean of the Z_i values for a line is a measure of adaptation of the line; and the coefficient of variation of the CV_{Zi} for each line is a measure of stability.

Combined analyses of variance were used on the estimates of Z_i per trait, and the means were grouped by the cluster analysis of Scott-Knott. To facilitate the interpretation of the results and to adjust the inferences to the methodology used, the mean value of each treatment was inverted for GA. This arises from the fact that for GA, the lowest mean values are associated with the best phenotypes.

In analyses by the method of Resende (2007), the prediction of the genotypic value is based on a model that considers the genotype effect as random, and the other effects, as fixed. The measure of stability is the harmonic mean of the genotypic values (HMGV), obtained by following equation:

$$V = \frac{n}{\sum_{j}^{n} \frac{1}{V_{gij}}},$$

where: n is the number of environments in which the genotype i was evaluated, and V_{gij} is the genotypic value of genotype i in environment j, expressed by the ratio of the mean in this environment. The measure of adaptability is the relative performance of the genotypic value (RPGV), obtained according to the following expression:

$$RPGVi = \frac{1}{n} \frac{\sum_{j-1}^{n} V_{gij}}{M_j},$$

where: M_j is the mean of the trait evaluated in environment j. The combined selection for the evaluated trait e, stability, and adaptability can be given by the statistics of the harmonic mean of the relative performance of the predicted genotypic values (HMRPGV), as follows:

$$HMRPGV_i = \frac{1}{\sum_{j-1}^{n} 1/RPVG_{ij}},$$

The Spearman’s correlations coefficients for stability and adaptability were estimated between the two methods for all variables. Statistical analyses were carried out using the R Software (R Core Team, 2021).

Results and Discussion

In the joint analysis for grain yield, significant effects were observed for environments and for the genotype by environment interaction (G×E) (Table 1), characterizing a differential response of the lines under different environmental conditions. The significance of the G×E interaction for yield has been found in various studies; however, the lack of detection of genetic variability among the genotypes contrasts with most of the results in final trials of evaluation of common bean lines for this trait (Domingues et al., 2013; Carloni et al., 2022). This can be explained by the fact that 12 of the 17 evaluated genotypes were obtained from the same population, in a recurrent selection program that

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was designed to increase the grain yield and disease resistance to improve plant architecture, and to adapt the genotypes to low soil fertility and water deficit (Del Peloso & Melo, 2005).

The trend of modern cultivars, with increasingly upright plant architecture and a smaller number of branches, has limited the increase of yield potential of the cultivars (Del Peloso & Melo, 2005). However, it was expected that selecting genotypes under different stress conditions, in various locations, would highlight existing differences among them. In the present study, the genotypes were selected in multiple locations, under different environmental conditions and for various traits, which contributed to the development of lines with good mean yield values, even in heterogeneous growing regions.

Significant differences were detected among the genotypes, environments, and genotype by environment for all quality traits of commercial grain (Table 1). These differences suggest the existence of genetic variability among the genotypes, and the presence of differential response of the genotypes under environmental variations. When the genotype by environment interaction is confirmed, it is important to identify the genotypes that combine a high mean for commercial grain quality with adaptability and phenotypic stability.

There is a limited number of studies that assess adaptability and stability in common bean for commercial grain traits (Carbonell et al., 2010; Pereira et al., 2017; Vakali et al., 2017). In addition, in all these studies, the estimates were obtained in few locations within the same state. Thus, from the wide diversity of environmental and technological conditions under which common bean is grown in Brazil, the marked effect of the G×E interaction is observed, as it can interfere in the recommendation of cultivars.

The lines CNFC 10762 and CNFC 15086 had the highest adaptability (Zi) and the greatest relative performances of genotypic value RPGV (2466 and 2485

Table 1. Joint analyses of variance, mean values, and estimates of stability (CV_{Zi}) (%) and adaptability (Z_i) of 14 elite lines and 3 cultivars, evaluated in 79 environments for grain yield, grain appearance, sieve yield, and 100-seed weight, in 2011, 2012, and 2013 by the method of Nunes et al. (2005).

Genotype	Grain yield (kg ha^{-1})			Grain appearance (1-5)			Sieve yield (%)			100-seed weight (g)		
	Mean	Zi[(1)]	CV_{Zi}	Mean	Zi	CV_{Zi}	Mean	Zi	CV_{Zi}	Mean	Zi	CV_{Zi}
Pérola	2,330	3.81d	28.9^{17*}	1.4a	4.52a	18.0^{9}	65.3e	3.97e	25.1^{16}	26.3e	3.89e	20.9^{11}
BRS Estilo	2,377	4.02c	25.5^{13}	1.3a	4.76a	10.8^{1}	71.1c	4.60b	20.3^{9}	25.5g	3.39g	21.5^{12}
BRS Sublime	2,306	3.72d	24.6^{11}	1.4a	4.58a	10.9^{2}	70.6c	4.35c	21.7^{10}	24.9h	2.98i	29.3^{15}
CNFC 10762	2,483	4.34a	26.9^{16}	1.6b	4.26a	13.4^{7}	68.5d	4.14d	23.2^{12}	25.6g	3.38g	23.6^{14}
CNFC 15003	2,349	3.77d	26.5^{15}	1.5a	4.31a	24.6^{12}	61.3g	3.39h	24.1^{14}	26.1f	3.75f	18.8^{8}
CNFC 15010	2,314	3.73d	24.5^{10}	1.7b	4.23a	13.0^{5}	65.1e	3.96e	18.9^{6}	26.3e	3.95e	15.7^{1}
CNFC 15018	2,437	4.16b	23.9^{9}	2.3c	3.26c	31.3^{15}	60.9g	3.32h	26.9^{17}	27.2c	4.43c	17.6^{7}
CNFC 15023	2,358	3.87d	22.5^{6}	1.7b	4.08a	32.6^{16}	62.4g	3.53g	16.9^{4}	26.1f	3.72f	16.6^{4}
CNFC 15025	2,411	4.06c	21.2^{2}	1.8b	3.95b	20.4^{11}	62.0g	3.57g	20.0^{8}	27.0c	4.42c	16.4^{3}
CNFC 15033	2,400	3.97c	21.8^{4}	1.7b	4.10a	17.4^{8}	65.5e	3.95e	15.8^{3}	26.9d	4.31d	17.2^{6}
CNFC 15035	2,380	4.00c	24.9^{12}	1.9b	3.85b	25.0^{13}	59.4h	3.27h	24.1^{15}	25.9f	3.60f	16.6^{4}
CNFC 15038	2,404	4.06c	23.1^{8}	1.4a	4.55a	11.8^{4}	63.7f	3.80f	17.1^{5}	26.8d	4.23d	19.3^{9}
CNFC 15049	2,400	4.00c	22.8^{7}	1.9b	3.77b	11.0^{3}	71.4c	4.65b	11.8^{1}	25.4g	3.24h	20.0^{10}
CNFC 15070	2,450	4.14b	21.5^{3}	1.9b	3.92b	13.0^{6}	62.6g	3.73f	19.2^{7}	26.8d	4.21d	16.9^{5}
CNFC 15082	2,375	3.96c	20.6^{1}	2.8d	2.31d	38.2^{17}	75.4b	4.94a	15.2^{2}	26.6d	3.97e	22.3^{13}
CNFC 15086	2,495	4.26a	21.8^{5}	2.4c	3.01c	29.1^{14}	66.4e	3.82f	23.3^{13}	28.8a	5.48a	15.8^{2}
CNFC 15097	2,414	4.12b	25.8^{14}	1.4a	4.54a	19.6^{10}	78.1a	5.04a	22.3^{11}	28.1b	5.04b	15.7^{1}
Mean	2,393			1.79			66.5			26.5		
CV (%)	23.7			36.4			11.1			6.4		
MS (G)	684,442^{ns}			2.56**			4,108.77**			172.93**		
MS (G × E)	610,459**			0.60*			280.09**			7.07**		

[(1)]Mean values followed by equal letters, in the columns, do not differ from each other, by Scott-Knott's test, at 10% probability. For grain appearance, the analyses of stability and adaptability were carried out with inverted values. *Classification of genotypes regarding stability. MS (G): genotype mean square. MS (GXE): interaction mean square.

kg ha^{-1}) for GY, respectively, differing significantly from the other genotypes (Tables 1 and 2), and they were considered as the most adapted genotypes. The lowest estimated coefficient of variation (CV_{Zi}) was obtained by the line CNFC 15082 (20.6%), indicating that this line had the lowest variation in the different environments and was considered the most stable line by the Nunes´ method. However, the most stable line by the Resende´s method was CNFC 15086, which ranked in the fifth place by the Nunes´ method, standing out as stable by both methods (Table 2 and 3). Although each method has a specialized classification pattern for stability parameters, they can be complementary and useful in the breeding program and select superior genotypes based on their performance and stability (Pour-Aboughadareh et al., 2022).

The line CNFC 15086 had the highest yield, associated with the best stability and adaptability, producing an average of 4% more than the other lines. In the Nunes´ method, the line that was most stable was CNFC 15082, and the most adaptable was CNFC 10762, which contrasts with the other method. In the Resende´s method, by the harmonic mean of genotypic values (HMGV) statistics, the values are computed already penalizing the lines by instability through the environments (Pour-Aboughadareh et al., 2022). In the relative performance of the genotypic value (RPGV) statistics, capitalization is provided, that is, the ability to respond (adaptability) to improvement in the environment; and in the harmonic mean of the relative performance of genetic values (HMRPGV) all properties are encompassed in a single measurement. Simultaneously considering the estimates of adaptability and stability in both methods, the lines CNFC 15086 and CNFC 10762 were those that had the best performances for GY (Table 2).

In the GA evaluation, the scores of the genotypes ranged from 1.3 for 'BRS Estilo' to 2.8 for CNFC 15082 (Tables 1 and 2), forming four groups by the cluster analysis of the means. The first group was formed by three lines and the cultivars BRS Estilo, BRS Sublime, and Pérola. Similarly to Pérola, the cultivars BRS Estilo and BRS Sublime had excellent GA. These values are considered a reference for selecting genotypes that meet market requirements, such as for carioca beans, for which farmers and wholesalers are very demanding regarding the appearance of grains, which should be close to to that of the standard considered by the market.

Table 2. Arithmetic mean (AM), stability of genotypic values (HMGV), adaptability of genotypic values (RPGV), and stability and adaptability of genotypic values (HMRPGV) for grain yield and grain appearance, from the evaluation of 14 elite lines and 4 cultivars in final trials.

Genotype	Grain yield							Grain appearance						
	AM	HMGV	HMGV_R[1]	RPGV	RPGV_R	HMRPGV	HMRPGV_R	AM	HMGV	HMGV_R[1]	RPGV	RPGV_R	HMRPGV	HMRPGV_R
Pérola	2,330	1,969	17	2,335	15	2,314	17	1.44	1.41	4	1.49	4	1.47	4
BRS Estilo	2,377	2,028	11	2,381	11	2,368	11	1.31	1.30	1	1.37	1	1.37	1
BRS Sublime	2,306	1,993	14	2,333	16	2,323	15	1.44	1.42	5	1.49	5	1.48	5
CNFC 10762	2,483	2,104	2	2,466	2	2,449	2	1.62	1.56	7	1.65	7	1.64	7
CNFC 15003	2,349	1,979	16	2,344	14	2,329	14	1.56	1.49	6	1.59	6	1.57	6
CNFC 15010	2,314	1,986	15	2,328	17	2,319	16	1.69	1.61	8	1.70	8	1.69	8
CNFC 15018	2,437	2,093	4	2,438	3	2,429	3	2.31	2.14	15	2.24	15	2.23	15
CNFC 15023	2,358	2,014	13	2,360	13	2,351	13	1.75	1.63	9	1.74	9	1.72	9
CNFC 15025	2,411	2,039	9	2,396	8	2,389	7	1.81	1.69	11	1.79	11	1.79	11
CNFC 15033	2,400	2,039	10	2,393	9	2,384	9	1.75	1.66	10	1.75	10	1.74	10
CNFC 15035	2,380	2,014	12	2,373	12	2,361	12	1.88	1.78	13	1.87	13	1.86	13
CNFC 15038	2,404	2,050	6	2,402	6	2,392	6	1.44	1.39	3	1.47	3	1.47	3
CNFC 15049	2,400	2,047	7	2,397	7	2,386	8	1.94	1.82	14	1.91	14	1.91	14
CNFC 15070	2,450	2,072	5	2,431	5	2,423	4	1.88	1.75	12	1.85	12	1.84	12
CNFC 15082	2,375	2,045	8	2,388	10	2,380	10	2.81	2.61	17	2.71	17	2.68	17
CNFC 15086	2,495	2,129	1	2,485	1	2,473	1	2.38	2.23	16	2.32	16	2.30	16
CNFC 15097	2,414	2,094	3	2,434	4	2,416	5	1.38	1.37	2	1.44	2	1.43	2

[1]R, ranking of the line based on the respective statistics.

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The check 'BRS Estilo' had the best response for GA, with lower mean values associated with stability and adaptability, also by the Resende´s method. Comparing the lines, CNFC 15097 and CNFC 15038 stood out (only behind 'BRS Estilo'), occupying the second and third place, respectively, with a high grain standard (Table 2). The CNFC 15097 line by the Nunes' method ranked 4th in adaptability and 10th in stability, confirming its good performance. In this case, using these two methodologies makes the selection of some lines safer more robust and, as the methods complement each other.

It should be emphasized that 14 genotypes had mean scores lower than 2.0 that is acceptable for the requirements of industry and for the consumer (Tables 1 and 2). 'BRS Estilo', 'BRS Sublime', 'Pérola', CNFC 15003, CNFC 15038, and CNFC 15097 are the genotypes that combined good adaptation and stability for the two methods in evaluation, and that were associated with mean values considered standards for the carioca commercial group.

For SY, the CNFC 15097 line had the best mean value (Tables 1 and 3), differing significantly from the others, followed by the CNFC 15082 line, which suggests excellent SY and superiority in relation to the check cultivars. Other good performances were observed in CNFC 15049 and in 'BRS Estilo' and 'BRS Sublime'; the suitable size of the grain of these last two cultivars was reported in other studies (Melo et al., 2010; Faria et al., 2013). Therefore, those lines that had responses similar to or better than the cultivars used as standards will consequently have high commercial acceptance, since the consumer market prefers large beans with high grain weight and high SY (Carbonell et al., 2010).

'Pérola' is considered a standard by companies (Del Peloso & Melo, 2005), both for GA and for its excellent SY during processing; it was clustered in the fifth of the eight groups formed by the comparison test

Table 3. Arithmetic mean (AM), stability of genotypic values (HMGV), adaptability of genotypic values (RPGV), and stability and adaptability of genotypic values (HMRPGV) for sieve yield and100-seed weight from the evaluation of 14 elite lines and 3 cultivars in final trials.

Genotype	Sieve yield							100-seed weight						
	AM	HMGV	HM-GV_R[1]	RPGV	RP-GV_R	HM-RP-GV	HM-RP-GV_R	AM	HMGV	HM-GV_R[1]	RPGV	RP-GV_R	HMRP-GV	HMRP-GV_R
Pérola	65.4	49.8	9	64.5	8	62.1	9	26.3	25.9	10	26.3	10	26.3	10
BRS Estilo	71	61.4	5	72.3	5	70.5	5	25.5	25.2	14	25.6	14	25.5	14
BRS Sublime	70.6	63.3	3	72.9	4	71.4	4	24.9	24.6	17	24.9	17	24.9	17
CNFC 10762	68.6	60.9	6	70.3	6	68.8	6	25.5	25.2	15	25.5	15	25.5	15
CNFC 15003	61.3	43.5	15	59.3	16	56.4	16	26.0	25.7	12	26.0	12	26.0	12
CNFC 15010	65.1	49.3	10	63.4	10	61.6	10	26.4	26.1	9	26.4	9	26.4	9
CNFC 15018	60.9	46.5	13	59.5	15	57.6	14	27.2	26.9	3	27.2	3	27.2	3
CNFC 15023	62.3	48	12	60.8	12	59.7	12	26.1	25.7	11	26.1	11	26.1	11
CNFC 15025	61.9	46.2	14	59.9	14	58.1	13	27.0	26.7	4	27.0	4	27.0	4
CNFC 15033	65.6	52.1	8	64.5	9	63.7	8	26.8	26.5	5	26.8	5	26.8	5
CNFC 15035	59.3	40.6	17	56.6	17	53.4	17	25.9	25.5	13	25.9	13	25.8	13
CNFC 15038	63.7	48.9	11	61.9	11	60.7	11	26.8	26.4	6	26.8	6	26.8	6
CNFC 15049	71.4	63.1	4	72.9	3	71.9	3	25.4	25.1	16	25.4	16	25.4	16
CNFC 15070	62.5	43.4	16	60.0	13	56.8	15	26.7	26.3	7	26.7	7	26.7	7
CNFC 15082	75.5	68.2	2	78.8	2	76.3	2	26.6	26.2	8	26.5	8	26.5	8
CNFC 15086	66.3	58.3	7	67.8	7	66.4	7	28.8	28.4	1	28.7	1	28.7	1
CNFC 15097	78.1	74.1	1	84.3	1	79.4	1	28.1	27.8	2	28.1	2	28.1	2

[1]R, ranking of the line based on the respective statistics.

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of means, with 65.3% (Tables 1 and 4). Higher values (84.6%) have already been found for 'Pérola' (Pereira et al., 2017), as well as lower values (59.8%) (Carbonell et al., 2010). Lines with superior SY indicate that the breeding programs have exhibited efficiency in developing lines with bean grain size superior to that of 'Pérola', meeting demands for large bean grain.

The estimates of adaptability for SY show that the best lines were CNFC 15097 and CNFC 15082 (Tables 1 and 3), which differed significantly from the other genotypes. Other good responses were observed in the line CNFC 15049 and in the cultivar BRS Estilo. The line with the most stable response was CNFC 15049, by the Nunes' method. The most stable line by the Resende´s method was CNFC 15097 (Tables 1 and 3). In contrast, the line CNFC 15018 had the worst stability by the Nunes' method; and CNFC 15035 showed the worst stability by the Resende's method. The line CNFC 15082 had superiority in relation to the mean in 90% of the environments, followed by CNFC 15097, CNFC 15049, and 'BRS Estilo', which had superiority in 85, 83, and 77% of the environments, respectively. These results reinforce what was previously said, that is, both methodologies make the selection safer, as they complement each other.

It is known that the consumer market values the bean grain form of a semi-flattened profile and elliptical shape; other shapes are considered outside the commercial standard (Pereira et al., 2017). The selection of lines with large bean grains and greater 100SW is an important requirement for the success of a common bean cultivar. Although a large number of groups were formed (Table 1), most of the genotypes (94.2%) had values that fit within the market preference range, that is, 100SW greater than 25 g/100 beans (Table 3), as reported by Pereira et al. (2021). The line CNFC 15086 (28.8 g) stood out for this property, differing significantly from the others. The standard for bean size, 'Pérola' was in the fifth group, with a 26.3 g mean value, which is similar to that described by Faria et al. (2013). 'BRS Estilo' – considered as having bean size similar to that of 'Pérola'– had 25.5 g (Melo et al., 2010). That cultivar and the checks CNFC 10762 (25.6 g) and 'BRS Sublime' (24.9 g) were in the groups of lower mean values (Table 1).

These estimates were confirmed, as the line CNFC 15086 and the line CNFC 15097 were the most adapted genotypes and had the best stability estimates (Tables 1 and 3). In addition, they had 100SW above the mean in 93% and 89% of the environments. The lines CNFC 15018 and CNFC 15025 also had favorable adaptability and stability estimates, as well as a good performance in 67% and 75% of the environments, respectively. The check 'BRS Sublime' was the least adapted and stable genotype. It is noteworthy that, in general, the checks had responses inferior to most of the lines for 100SW, thus emphasizing the high genetic potential of the common bean lines of Embrapa. Four notable lines for 100SW based on the three estimates are CNFC 15086, CNFC 15097, CNFC 15025, and CNFC 15018.

From the above discussed results, the allocation of the line CNFC 15097 agrees with its good performance for all individual traits (Tables 1 to 3). For the other genotypes cited, the individual performances were compatible with the classifications, although each one of them has shown low mean performance for one of the traits related to grain size (SY or 100SW). In general, the parameter of adaptability of Nunes allows for the same lines to be selected, when selection is made by the RPGV statistic. This can be verified by the high magnitude of the Spearman´s correlation coefficients between the two methods for all variables (0.94**, 0.98**, 0.97**, and 1.00**, for GY, GA, SY and 100SW, respectively) (Table 4).

There was a significant Sperman's correlation between the stability parameters of the two methods only for GA (0.56*) and 100SW (0.63*). However, the correlations ranged from low to moderate, suggesting that the methods do not select the same stable lines.

Table 4. Spearman's correlation coefficients for the parameters of stability and adaptability between the methods by Resende (2007) and Nunes et al. (2005) for grain yield, grain appearance, sieve yield, and 100-seed weight.

Value	Grain yield	Grain appearance	Sieve yield	100-seed weight
	Stability parameter by Nunes (Cvi)			
HMGV	0.30 ^{ns}	0.56*	0.30^{ns}	0.63**
	Adaptability parameter by Nunes (Zij)			
RPGV	0.94**	0.98**	0.97**	1.00**

*, ** Significant at 5% and 1%, respectively, by the t-test. ^{ns}Nonsignificant. Adaptability of genotypic values (RPGV), and stability and adaptability of genotypic values (HMRPGV). Parameters of stability (CV_{Zi}) (%) and adaptability (Z_i).

The Nunes' method uses the concept of biological stability (Pour-Aboughadareh et al., 2022), and refers to the constant performance of the genotype over the environmental oscillations, that is, the lower is the variance of a line, within the different environmental conditions, the greater will be its stability. In contrast, the concept of stability by the Resende's method is based on the definition of the agronomic sense, according to which stability occurs when the cultivar shows minimum interactions with the environment, presupposing that the most stable line accompanies the mean performance (of all lines) obtained in the environments (Becker, 1981). This methodology allows of the identification of stable cultivars with potential to maintain their position among the best ones in all environments (Ramalho et al., 2012).

In the perspective of recommendation, the line CNFC 15086 stood out for its good phenotypic mean values, wide adaptation, and good stability for most traits, which is a relevant aspect when considering that common bean breeding programs give priority to cultivars with wide adaptation. However, CNFC 15086 had a low performance for GA, extrapolating the mean value considered as standard for the carioca group (2.0), a condition that may result in direct restriction for its acceptance by consumers. Alternatively, the line CNFC 15097 showed a good performance for this property and for the others (Tables 2 and 3). It aggregated yield and commercial grain quality, together with high stability and genotypic adaptability.

Although the results for GY mean values among the genotypes are not statistically different, studies show that the genetic progress for GY has been continuous over the years (Faria et al., 2013, 2014). Furthermore, regarding mean performance, for most of the traits the elite lines were superior to the checks; they also had a greater adaptation and phenotypic stability under conditions of environmental oscillations. This wide adaptation exhibited by the lines is of great importance for the cultivation of common bean, which has characteristics of low use of certified seed and of responsibility taken on by the public sector in supplying the market with cultivars, due to the limited interest of private companies in producing seed. Thus, the identification of lines for this crop for specific regions is still a restricted reality.

For commercial grain quality, four lines with high 100SW (CNFC 15086, CNFC 15097, CNFC 15018, and CNFC 15025) and two lines with excellent SY (CNFC 15097 and CNFC 15082) stood out. 'BRS Estilo' and 'BRS Sublime' should also be considered, which, together with the line CNFC 15038, had excellent GA. This characterization is very important for breeding programs because, in addition to indicating lines with potential for recommendation as cultivars, it contributes to choosing parents in the formation of segregating populations.

It is necessary to highlight that the Nunes' method presupposes the concept of stability in the biological sense, which corresponds to the cultivar that shows constant performance, regardless of the variation in the environment. The method of Resende presupposes stability in the agronomic sense, by which the performance of the genotype accompanies the mean performance of the materials in tested environments. Although the two methods are divergent in conceptual terms, they indicated the line CNFC 15097 as superior for grain yield and commercial grain quality. This line is also the most stable and shows wide adaptability for all the traits under evaluation. Based on its agronomic performance and commercial grain quality, the line CNFC 15097 was released as a new common bean cultivar of Embrapa, under the trade name 'BRS FC406' (Pereira et al., 2021). This cultivar was registered in the Brazilian Ministry of Agriculture (Ministério da Agricultura Pecuária e Abastecimento) for growing in the Adaptation Region I (South region of Brazil) for the rainy and dry crop seasons. It was registered in the Region II (Central region of Brazil) for the rainy, dry, and winter crop seasons, and in the Region III (Northeast region of Brazil), for the rainy crop season.

Conclusions

1. Although the Nunes' method and the Resende's method are divergent in conceptual terms, the use of both methods is a good strategy for the identification of bean lines with stability and wide adaptability.
2. The cultivar BRS FC406 is recommended by both methods and released for the common bean production chain in Brazil.

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