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Research Article

Adaptability and stability of black and purple bean genotypes[1]

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ABSTRACT

Selecting the best genotypes is difficult, due to the genotype × environment interaction effect. When this interaction is present, the study of adaptability and stability can provide the selection of the best genotypes. Thus, the selected genotypes should associate high yield, adaptability to different environmental conditions, as well as production stability. This study aimed to evaluate and select black and purple bean pre-cultivars based on adaptability, stability and grain yield. The parameters were estimated via mixed models and the selection using the Harmonic Mean of the Relative Performance of Predicted Genetic Values (HMRPGV) method. The environments influenced the phenotypic expression of the black and purple bean genotypes, characterizing a specific adaptability. The black bean genotypes BRS Esteio, BRS FP 403, CNFP 15681 and CNFP 16459 and the purple bean inbred lines CNFRx 16340, CNFRx 16346 and CNFRx 16353 showed the best performance, when considering, simultaneously, grain yield, adaptability and stability. The HMRPGV method provided an optimized selection of genotypes with high grain yield, predictability and responsiveness to environmental improvements, and should be used as a selection strategy for common bean genotypes for commercial growing.

KEYWORDS: *Phaseolus vulgaris* L., genotype × environment interaction, genotypic values prediction.

RESUMO

Adaptabilidade e estabilidade de genótipos de feijão preto e roxo

A seleção dos melhores genótipos é dificultada devido ao efeito da interação genótipos x ambientes. Na existência dessa interação, o estudo de adaptabilidade e estabilidade fornece subsídios para a seleção dos melhores genótipos. Sendo assim, os genótipos selecionados deverão associar alta produtividade, adaptabilidade às diversas condições ambientais e estabilidade de produção. Objetivou-se avaliar e selecionar pré-cultivares de feijão preto e roxo com base na adaptabilidade, estabilidade e produtividade de grãos. Os parâmetros foram estimados por meio de modelos mistos e a seleção pela Média Harmônica da Performance Relativa dos Valores Genotípicos (MHPRVG). Os ambientes influenciaram na expressão fenotípica dos genótipos de feijão preto e roxo, configurando adaptação específica. Os genótipos de feijão preto BRS Esteio, BRS FP 403, CNFP 15681 e CNFP 16459 e as linhagens de feijão roxo CNFRx 16340, CNFRx 16346 e CNFRx 16353 apresentaram as melhores performances, considerando-se, simultaneamente, a produtividade de grãos, adaptabilidade e estabilidade. O método MHPRVG proporcionou seleção otimizada de genótipos com elevada produtividade de grãos, previsibilidade e responsividade à melhoria do ambiente, e deve ser utilizado como estratégia de seleção de genótipos de feijão para plantios comerciais.

PALAVRAS-CHAVE: *Phaseolus vulgaris* L., interação genótipos x ambientes, predição de valores genéticos.

INTRODUCTION

Common bean (*Phaseolus vulgaris* L.) is cultivated by small and large farmers in different production systems and all regions of Brazil. According to Carneiro et al. (2014), depending on the genotype and soil-climatic conditions, the common bean cycle may range from 65 to 100 days. This characteristic makes it a suitable crop for adoption from intensive, highly technological, irrigated agricultural systems to those with low use of technology, particularly those of the subsistence type. Additionally, it is a very nutritious crop, constituting an important source of proteins, carbohydrates, vitamins, minerals and fibers (Silva et al. 2013).

Given the importance and tradition of this crop in Brazil, the national production is still not sufficient to supply the domestic market, resulting in the importation of 100 thousand tons of the product, mainly from Argentina and Bolivia (Conab 2022). In this scenario, breeding is an efficient strategy aimed at the release of new cultivars that are increasingly

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productive, adapted to different growing conditions and with excellent nutritional quality.

Studies of selection gain are difficult because of the effect of each environment where common bean genotypes are tested, due to the interaction between genotypes and environments (G × E). In the presence of this interaction, the study of adaptability and stability associates selection with adaptability, indicating the ability of a genotype to gain from environmental changes and stability, representing the predictability of a genotype response to environmental variations (Rosado et al. 2012).

Several statistical methodologies may be used to evaluate the adaptability and stability of genotypes; however, only the Restricted Maximum Likelihood/ Best Linear Unbiased Prediction (REML/BLUP) methodology can estimate the variance components and also the predicted genotypic values for selection purposes (Resende 2016). In this context, the Harmonic Mean of the Relative Performance of Predicted Genetic Values (HMRPGV) method proposed by Resende (2007) stands out, allowing the simultaneous selection of genotypes based on three parameters that substantially influence the genotype performance: productivity, adaptability and stability.

The univariate mixed model for the G × E interaction considers genotypic effects as random and, therefore, provides genotypic stability and adaptability, allowing the analysis of unbalanced data and non-orthogonal designs with heterogeneity of variances. This model also allows additional inferences such as the selection of specific genotypes for each location; selection of stable genotypes in different environments; selection of genotypes responsive (with high adaptability) to environmental improvement; and simultaneous selection for yield, adaptability and stability (Gonçalves et al. 2014).

This study aimed to determine the efficiency of the simultaneous selection of black and purple bean genotypes for yield, adaptability and stability, using univariate mixed models and the HMRPGV method.

MATERIAL AND METHODS

The evaluations were carried out in Campos dos Goytacazes (21º44'47"S, 41º18'27"W and 11 m of altitude), Italva (21º25'41"S, 41º40'44"W and 34 m of altitude) and Macaé (22º17'15"S, 41º87'17"W and 9 m of altitude), all in the Rio de Janeiro State, Brazil, from 2016 to 2019.

The experiment involved 12 black bean genotypes grown in 2016 and 2017, which included eight inbred lines (identified by the prefix CNFP) developed by the Embrapa Arroz e Feijão and four cultivars designated as controls (BRS Esteio, BRS FP 403, IPR Tuiuiú and IPR Uirapuru); 11 black bean genotypes cultivated in 2018 and 2019, including seven inbred lines (identified by the prefix CNFP) developed by the Embrapa Arroz e Feijão and four cultivars designated as controls (BRS Esteio, BRS FP 403, IPR Tuiuiú and IPR Uirapuru); and 12 purple bean genotypes grown in 2018 and 2019, consisting of nine inbred lines (identified by the prefixes CNFR and CNFRx) developed by the Embrapa Arroz e Feijão and three cultivars designated as controls (BRS CNFRx 15595, BRS Pitanga and BRSMG Tesouro). The experiment was carried out in a randomized-blocks design, with three replications. Each experimental unit consisted of four 4-m rows spaced 0.5 m apart.

The harvest was carried out at the R9 stage, from 90 days after sowing. The data were collected from the two central rows, disregarding the border rows. The material was weighed in grams and moisture was adjusted to 13 %, with results expressed in kg ha^{-1}.

Based on the data obtained for each commercial group of common bean, the genetic parameters were estimated using the REML/BLUP procedure, considering the following statistical model: y = Xb + Zg + Wc + e, where y is the vector of the observed values; b the effect of blocks within different environments (fixed); g the effect of genotypes (random); c the effect of the G × E interaction (random); e the random errors; and X, Z and W the incidence matrices for b, g and c, respectively. The distributions and structures of means (E) and assumed variances (Var) were as it follows:

$$E\begin{bmatrix} y \\ g \\ c \\ e \end{bmatrix} = \begin{bmatrix} Xb \\ 0 \\ 0 \\ 0 \end{bmatrix}; \text{Var}\begin{bmatrix} g \\ c \\ \text{e} \end{bmatrix} = \begin{bmatrix} I\sigma_g^2 & 0 & 0 \\ 0 & I\sigma_c^2 & 0 \\ 0 & 0 & I\sigma_e^2 \end{bmatrix}.$$

The fit of the model was obtained with the following mixed model equations:

$$\begin{bmatrix} X'X & X'Z & X'W \\ Z'X & Z'Z + I\lambda_1 & Z'W \\ W'X & W'Z & W'W + I\lambda_2 \end{bmatrix} \text{x} \begin{bmatrix} \hat{b} \\ \hat{g} \\ \hat{c} \end{bmatrix} = \begin{bmatrix} X'y \\ Z'y \\ W'y \end{bmatrix}$$

where: $\lambda_1 = \sigma^2_e/\sigma^2_g = (1 - h^2_g - c^2)/h^2_g$; $\lambda_2 = \sigma^2_e/\sigma^2_c = (1 - h^2_g - c^2)/c^2_g$; h^2_g is the individual broad-sense heritability at the block level; $c^2 = \sigma^2_c/(\sigma^2_g + \sigma^2_c + \sigma^2_e)$ the coefficient of determination of the G × E interaction effects; σ^2_g the genotypic variance; σ^2_c the variance of the G × E interaction; σ^2_e the residual variance between plots; $\hat{r}_{gloc} = \sigma^2_c/(\sigma^2_g + \sigma^2_c) = h^2_g/(h^2_g + c^2)$ the genotypic correlation of the genotypes through the environments; $h^2_{mg} = \sigma^2_g/[\sigma^2_g + (\sigma^2_e/J)]$ the mean heritability of the genotypes; and $\hat{r}^2_{gg} = \sqrt{\hat{h}^2_{mg}}$ the genotype selection accuracy.

According to Resende (2016), when using the mixed-model methodology in unbalanced data for the purpose of selecting agronomically superior genotypes, the effects of the model used should not be tested by the F test, as in the analysis of variance method. Therefore, the recommended test for random effects is the Likelihood Ratio Test (LRT), using deviance analysis. This analysis generalizes the classic analysis of variance, both for balanced and unbalanced data, indicating the goodness-of-fit of the model used. Thus, deviance is a statistics derived from the ratio between the likelihoods of the full model relative to the model without the effect to be tested.

The simultaneous selection for yield, adaptability and stability is given by the HMRPGV statistics, according to the following expression: $HMRPGV_i = n/(\sum^{n}_{j=1} x\ 1)/Gv_{ij}$, where n is the number of locations where genotypes i will be evaluated; and Gv_{ij} the genotypic value of genotype i in location j, expressed as a proportion of the mean in that location.

The statistical model 54 (HMRPGV method, black and purple bean genotypes, several locations and one observation per plot) of the Selegen - REML/BLUP software was used to rank and select the superior genotypes based on yield, adaptability and stability (Resende 2016).

RESULTS AND DISCUSSION

Deviance analysis (Table 1) was performed to test the main effects and their interactions. In the black (2016-2017) and purple bean genotype groups, the chi-square test revealed significant effects ($p < 0.05$) on genotype × environment interactions, indicating a difference in genotypic behavior between the evaluated environments. Regarding the group of black bean genotypes (2018-2019), a significant difference ($p < 0.05$) was observed by the chi-square test for genotype effects and for genotype × environment interaction, which indicated the existence of genetic variability between genotypes and a difference in genotypic behavior between environments. The difference in the response in contrasting environments generates difficulties in choosing the ideal genotype and its recommendation, since the ranking of genotypes by yield may change according to their interaction with the environment.

Yield is a trait greatly influenced by the environment, and, in the present study, the experimental coefficient of variation for this trait ranged from 8.52 to 14.10 %, exceeding the genotypic coefficients of variation (Table 2). Given this scenario, it is possible to state that there was an influence of the environment on the performance of the genotypes. Although high, these values were lower than those observed by Lima et al. (2020), who obtained results above 20 and 30 % for early-developing carioca bean genotypes in 2016 and 2015, respectively.

High values are desired for the genotypic coefficient of variation, since this parameter quantifies the magnitude of genetic variation available for selection (Carvalho et al. 2016). The genotypic coefficients of variation found ranged from 0.87 to 4.51 %, indicating that the very low fractions of genetic variances were extracted from the total phenotypic variation (Table 2). Under these conditions, the selection of superior genotypes is possible, although more costly. Cruz et al. (2018) and Souza et al. (2018) observed similar results, estimating values of low magnitude and lower than the experimental coefficient of variation for green bean and black bean genotypes, respectively.

Table 1. Deviance analysis for yield of black and purple bean genotypes evaluated in the Rio de Janeiro State, from 2016 to 2019.

Effect	Black bean (2016-2017)		Black bean (2018-2019)		Purple bean (2018-2019)	
	Deviance	LRT	Deviance	LRT	Deviance	LRT
Genotype	759.76	0.00^{ns}	1,861.74	4.73*	832.09	0.00^{ns}
Genotype × environment	778.58	18.82**	1,866.56	9.55**	838.28	6.19*
Full model	759.76	-	1,857.01	-	832.09	-

* and ** significant by the chi-square test at 5 % (3.84) and 1 % (6.63) of probability, respectively. LRT: likelihood ratio test.

Table 2. Estimates of genetic parameters (individual Restricted Maximum Likelihood - REML) for grain yield of black and purple bean genotypes evaluated in the Rio de Janeiro State, from 2016 to 2019.

Component of variance (individual REML)	Black bean		Purple bean
	2016-2017	2018-2019	
Genotypic variance	176.99	12,347.69	439.00
Genotype × environment interaction variance	23,553.14	19,610.21	34,016
Residual variance	16,913.64	49,688.15	63,591
Individual phenotypic variance	40,643.76	81,646.06	98,046
Individual broad-sense heritability, free of interaction	0.004 ± 0.022	0.151 ± 0.086	0.004 ± 0.022
Coefficient of determination for genotype × environment effects	0.58	0.24	0.35
Mean heritability	0.01	0.63	0.02
Selection accuracy	0.11	0.79	0.13
Genotypic correlation of performance in various environments	0.01	0.39	0.01
Genotypic coefficient of variation (%)	0.87	4.51	1.17
Experimental coefficient of variation (%)	8.52	9.05	14.1
Coefficient of relative variation	0.10	0.50	0.08
Overall mean	1,527.14	2,462.42	1,788.58

The variation index (VI) is expressed by the ratio between the genetic coefficient of variation and the experimental coefficient of variation (GCV/ECV). In plant breeding programs, estimates higher than the unity (VI > 1) are desirable, as they allow the breeder to devise more appropriate selection strategies, as well as succeed in genotypic prediction. In the present study, the variation index of the two types of common bean was lower than the unity, what provides a more restrictive selection (Table 2). In this respect, it is possible to affirm that the influence of the environment on the performance of the genotypes was high, since the genotypic coefficient of variation showed very low values, in relation to the experimental coefficient of variation (Table 2).

The accuracy obtained for the 2018-2019 black bean genotypes (0.79) was considered high, whereas the 2016-2017 black (0.11) and purple (0.13) bean genotypes were considered to be of low precision, according to the classification proposed by Resende & Duarte (2007), indicating a high correspondence between the observed phenotypic and the predicted genotypic values and, consequently, great efficiency of selection of superior genotypes for the 2018-2019 black bean. For the 2016-2017 black bean and the 2018-2019 purple bean genotypes, on the other hand, due to the low correspondence between the observed phenotypic and predicted genotypic values, the selection of superior genotypes is possible, but more difficult. Similar findings were reported by Santos et al. (2018), who estimated accuracy at 75.91 and 15.72 % for black and carioca bean genotypes, respectively, under the same conditions as in the present study.

Heritability is one of the most important genetic parameters, as it measures the fraction of phenotypic variation that is heritable in nature and that can be exploited in genotypic selection. When means are used as a selection criterion, the mean heritability of the genotypes is estimated. In the present study, the estimated mean heritability values for the 2018-2019 black bean genotypes (0.63) were of high magnitude; whereas, for the 2016-2017 black (0.01) and purple (0.02) bean genotypes, low-magnitude estimates were obtained, implying that the selection of superior genotypes based on predicted genotypic values is more costly due to the strong influence of the environment on the performance of genotypic values. These results corroborate those obtained by Santos et al. (2018), who estimated low-magnitude values for carioca bean genotypes (0.02).

Individual broad-sense heritability, free of the interaction, considers the total genetic dispersal and allows exploiting all the genetic variance between genotypes (Torres et al. 2015). This parameter is calculated as the ratio of the genotypic variance to individual phenotypic variance. For the 2016-2017 and 2018-2019 black and purple bean genotypes, the variance of the G × E interaction effects showed a high magnitude to the variance of the genotypic effects, constituting 0.43, 15.12 and 0.45 % of the individual phenotypic variance, represented by the heritability of individual plots (0.0043, 0.1512 and

0.0043, respectively for the 2016-2017 and 2018-2019 black and purple beans) (Table 2). Similar results were obtained by Santos et al. (2018) and Souza et al. (2018).

The variance estimate for the G × E interaction was considered of medium to high magnitude, corresponding to 34.69 and 57.95 % of the individual phenotypic variance of purple bean and 2016-2017 black bean genotypes, as expressed by the coefficient of determination of the G × E interaction (Table 2), which favored a low genotypic correlation (0.01). In the 2018-2019 black bean genotypes, however, the variance of the G × E interaction was of low magnitude, corresponding to 24.02 % of the individual phenotypic variance of the genotypes, as expressed by the coefficient of determination of the G × E interaction (Table 2). Based on the genotypic correlation results, it is possible to state that the predominance of the G × E interaction is of the complex type (Table 2), which leads to changes in the ranking of genotypes in different environments (Cruz & Castoldi 1991).

Genotypic correlation indicates the reliability of the ranking of the best genotypes in the evaluated environments (Cruz et al. 2012). Overall, significant changes were observed in the ranking of black and purple bean genotypes due to the low and medium magnitudes detected in the genotypic correlations (Table 2). This indicates the occurrence of the complex fraction of genotypes × environments and genotypes × years interactions, which favors the selection of genotypes with a more specific adaptation behavior.

The best genotypes were selected using three different adaptability and stability strategies (Tables 3, 4 and 5). In the selection of the three best genotypes based on the average performance in all environments, the black bean inbred lines CNFP 15681 and CNFP 16459 showed the highest selection gains, exceeding the controls IPR Tuiuiú and IPR Uirapuru (Table 3). In addition, these inbred lines exhibited yields above the overall mean: 1,527.14 and 2,462.42 kg ha^{-1} for the 2016-2017 and 2018-2019 black bean genotypes, respectively (Table 3). The three best 2018-2019 black bean genotypes obtained based on the average performance in all environments (Table 3) were also the most predictable and responsive, based on the HMRPGV method (Table 5). Furthermore, the two best 2016-2017 black bean genotypes, BRS Esteio and BRS FP 403, were also the same for the 2018-2019 black bean genotypes (Table 3).

Regarding the same selection strategy for the three best purple bean genotypes, the inbred lines CNFRX 16340, CNFRX 16346 and CNFR16997 showed the highest yields, surpassing the controls BRS CNFRX 15595, BRS Pitanga and BRSMG Tesouro (Table 3). In addition, these genotypes showed yields higher than the overall mean (1,788.58 kg ha^{-1}) (Tables 2 and 3). The genotypic ranking based on the average performance in all environments was not similar to that observed based on the HMRPGV method (Table 5). Due to the conservative nature of the method, which penalizes the predicted genotypic values ($u + g$), the same behavior of the genetic means ($u + g + mge$) of the trait is expected when the chosen genotypes are subjected to different environments (Maia et al. 2009).

The recommendation of the most stable genotypes with high adaptability becomes inherent to the capitalization of the G × E interaction. Among the adaptability and stability methods evaluated, this is one of those that least penalizes the predicted genotypic values, as it capitalizes on the effects of the G × E interaction of each environment (Carvalho et al. 2016).

For the black and purple bean genotypes, each environment (Table 4) resulted in a different pattern in the ranking of genotypes, differing even from the ranking obtained based on the average performance in all environments (Table 3) and that based simultaneously on yield, adaptability and stability (Table 5). This indicates the occurrence of the complex fraction of the G × E interaction, which makes the selection of superior genotypes more costly. This finding was already expected due to the higher values of the variances of the G × E interaction and residual variances relative to the genotypic variance (Table 2).

The BRS Esteio cultivar had the highest yield in all the environments evaluated with black bean genotypes, except for the environment of the year 2016, where it was outperformed by the inbred lines CNFP 15676 and CNFP 15681 (Table 4). The purple bean inbred line CNFR 16340 showed the highest yield in the 2018 crop (1,247.57 kg ha^{-1}); however, in the following crop, it was outperformed by the BRSMG Tesouro cultivar, whose yield was 2,787.01 kg ha^{-1} (Table 4).

In view of the foregoing, it may be inferred that the three best genotypes of black and purple beans interacted in a complex way with the environment,

Table 3. Estimates of predicted genetic gain for grain yield of black and purple bean genotypes, considering the average performance in the evaluated environments, in the Rio de Janeiro State, from 2016 to 2019.

Ranking	Genotype	*g*	*u* + *g*	Gain	New mean	*u* + *g* + *mge*
			Black bean (2016-2017)			
1	BRS Esteio	2.39	1,529.53	2.39	1,529.53	1,688.55
2	BRS FP 403	1.60	1,528.74	1.99	1,529.13	1,635.16
3	CNFP 15681	0.95	1,528.09	1.65	1,528.79	1,591.50
4	CNFP 15678	0.30	1,527.44	1.31	1,528.45	1,547.30
5	CNFP 15684	0.16	1,527.30	1.08	1,528.22	1,537.84
6	CNFP 15697	0.14	1,527.28	0.92	1,528.06	1,536.89
7	CNFP 15685	0.05	1,527.19	0.80	1,527.94	1,530.41
8	CNFP 15670	-0.27	1,526.87	0.66	1,527.80	1,508.64
9	CNFP 15676	-0.28	1,526.86	0.56	1,527.70	1,508.37
10	IPR Tuiuiú	-1.04	1,526.10	0.40	1,527.54	1,456.74
11	IPR Uirapuru	-1.92	1,525.22	0.19	1,527.33	1,397.53
12	CNFP 15695	-2.08	1,525.06	0.00	1,527.14	1,386.72
			Black bean (2018-2019)			
1	BRS Esteio	225.47	2,687.90	225.47	2,687.90	2,759.52
2	BRS FP403	96.84	2,559.26	161.16	2,623.58	2,590.02
3	CNFP 16459	7.51	2,469.93	109.94	2,572.37	2,472.32
4	CNFP 16416	-13.09	2,449.34	79.18	2,541.61	2,445.18
5	CNFP 16383	-26.23	2,436.20	58.10	2,520.53	2,427.87
6	CNFP 16384	-27.07	2,435.36	43.91	2,506.33	2,426.76
7	CNFP 16404	-33.37	2,429.05	32.87	2,495.29	2,418.45
8	CNFP 16380	-38.31	2,424.11	23.97	2,486.39	2,411.94
9	CNFP 16379	-42.09	2,420.33	16.63	2,479.05	2,406.96
10	IPR Tuiuiú	-59.96	2,402.46	8.97	2,471.39	2,383.42
11	IPR Uirapuru	-89.70	2,372.72	0.00	2,462.42	2,344.23
			Purple bean			
1	CNFRX 16340	4.69	1,793.26	4.69	1,793.26	1,974.69
2	CNFRX 16346	1.74	1,790.32	3.21	1,791.79	1,857.79
3	CNFR16997	1.62	1,790.19	2.68	1,791.26	1,852.85
4	BRSMG Tesouro	1.39	1,789.97	2.36	1,790.94	1,843.76
5	CNFRX 16352	1.15	1,789.73	2.12	1,790.69	1,834.41
6	CNFRX 16353	1.11	1,789.69	1.95	1,790.53	1,832.85
7	BRS Pitanga	-1.03	1,787.55	1.53	1,790.10	1,747.64
8	BRS CNFRX 15595	-1.08	1,787.50	1.20	1,789.78	1,745.82
9	CNFRX 16360	-1.17	1,787.41	0.94	1,789.51	1,742.18
10	CNFR 17014	-1.32	1,787.26	0.71	1,789.29	1,736.21
11	CNFR 16932	-2.68	1,785.90	0.40	1,788.98	1,682.18
12	CNFRX 16998	-4.43	1,784.14	0.00	1,788.58	1,612.55

Estimates: *g*: genotypic effect; *u* + *g*: predicted genotypic value; *u* + *g* + *mge*: mean genotypic value in the environments.

what was confirmed by the inconsistency in their ranking based on the average performance in all the environments (Table 3) and by the HMRPGV method (Table 5).

In the selection of the three best black and purple bean genotypes for all the environments, the predicted genetic gain (Table 3) was much lower than that obtained with the selection by environment (Table 4). This may be attributed to the better capitalization of the G × E interaction effects in the strategy of selection by environment, when compared with the selection for all the environments based on genetic value (Carvalho et al. 2016).

According to Carvalho et al. (2016), the estimation of adaptability and stability complements the study of the G × E interaction, that is, it determines the genotypes' level of response to the environmental stimulus and the predictability of yield in the face of environmental variations. In this way, it allows the selection of genotypes with greater yield potential, more responsive to environmental variations and with predictable behavior.

Table 4. Estimates of predicted genetic gain for grain yield of the three best genotypes of black and purple beans evaluated in the Rio de Janeiro State, from 2016 to 2019.

Ranking	Genotype	*g + ge*	*u + g + ge*	Gain	New mean
		Black bean (2016-2017)			
		2016			
1	CNFP 15676	219.03	1,747.50	219.03	1,747.50
2	CNFP 15681	158.75	1,687.23	188.89	1,717.37
3	BRS Esteio	78.35	1,606.82	152.04	1,680.52
		2017			
1	BRS Esteio	243.75	1,769.56	243.75	1,769.56
2	BRS FP 403	231.50	1,757.30	237.62	1,763.43
3	CNFP 15697	149.99	1,675.80	208.41	1,734.22
		Black bean (2018-2019)			
		Campos dos Goytacazes 2018			
1	BRS Esteio	183.04	1,592.51	183.04	1,592.51
2	CNFP 16404	142.67	1,552.14	162.86	1,572.32
3	CNFP 16383	128.32	1,537.79	151.34	1,560.81
		Campos dos Goytacazes 2019			
1	BRS Esteio	279.43	2,633.59	279.43	2,633.59
2	BRS FP403	100.81	2,454.98	190.12	2,544.29
3	CNFP 16379	62.04	2,416.21	147.43	2,501.59
		Macaé 2018			
1	BRS Esteio	313.47	3,259.84	313.47	3,259.84
2	BRS FP403	222.05	3,168.41	267.76	3,214.12
3	CNFP 16383	111.03	3,057.40	215.52	3,161.88
		Macaé 2019			
1	BRS Esteio	398.12	3,009.18	398.12	3,009.18
2	BRS FP403	106.11	2,717.17	252.11	2,863.17
3	CNFP 16416	97.79	2,708.85	200.67	2,811.73
		Italva 2019			
1	BRS Esteio	311.38	3,302.44	311.38	3,302.44
2	BRS FP403	135.02	3,126.08	223.20	3,214.26
3	CNFP 16384	87.32	3,078.38	177.91	3,168.97
		Purple bean			
		2018			
1	CNFRX 16340	161.04	1,247.57	161.04	1,247.57
2	CNFRX 16353	156.59	1,243.11	158.81	1,245.34
3	CNFRX 16346	103.43	1,189.96	140.35	1,226.88
		2019			
1	BRSMG Tesouro	296.38	2,787.01	296.38	2,787.01
2	CNFRX 16340	210.37	2,700.99	253.37	2,744.00
3	CNFRX 16352	142.27	2,632.89	216.34	2,706.96

Estimates: *g + ge*: genotypic effect of each environment; *u + g + ge*: genotypic value predicted with the capitalization of the interaction with environments.

The ranking of the three best black bean genotypes based on the average performance in all the environments (Table 3) was found to be the same obtained based simultaneously on yield, adaptability and stability (Table 5). In contrast, the ranking of the three best purple bean genotypes based on the average performance in each environment (Table 4) differed from that observed based on the HMRPGV method (Table 5). However, only the inbred lines CNFRx 16340 and CNFRx 16346 are concordant with each other.

The results obtained using the HMRPGV method (Table 5) for the black and purple bean genotypes are not in agreement with the results of selection practiced for each environment (Table 4). This is because the G × E interaction was of the complex type, i.e., the superiority of genotypes with the change of environment was inconsistent. In other words, a genotype with superior performance in one environment may not display the same performance in other environments (Cruz & Castoldi 1991). In such cases, it may be inferred that the selection

Table 5. Adaptability and stability (HMRPGV and HMRPGV * OM) of predicted genetic values for grain yield of black and purple bean genotypes evaluated in the Rio de Janeiro State, from 2016 to 2019.

Ranking	Genotype	HMRPGV	HMRPGV * OM
Black bean (2016-2017)			
1	BRS FP403	1.10	1,684.20
2	BRS Esteio	1.06	1,625.65
3	CNFP 15681	1.04	1,585.66
4	CNFP 15678	1.01	1,546.31
5	CNFP 15684	1.01	1,537.78
6	CNFP 15685	1.00	1,530.17
7	CNFP 15697	1.00	1,524.19
8	CNFP 15670	0.99	1,508.61
9	CNFP 15676	0.96	1,470.72
10	IPR Tuiuiú	0.95	1,455.33
11	IPR Uirapuru	0.91	1,395.28
12	CNFP 15695	0.90	1,379.18
Black bean (2018-2019)			
1	BRS Esteio	1.12	2,762.91
2	BRS FP403	1.05	2,588.36
3	CNFP 16459	1.00	2,471.10
4	CNFP 16404	0.99	2,444.43
5	CNFP 16383	0.99	2,441.46
6	CNFP 16416	0.99	2,425.93
7	CNFP 16379	0.98	2,411.69
8	CNFP 16384	0.98	2,401.34
9	CNFP 16380	0.97	2,396.35
10	IPR Tuiuiú	0.97	2,379.44
11	IPR Uirapuru	0.94	2,321.20
Purple bean			
1	CNFRx 16340	1.12	1,995.03
2	CNFRx 16346	1.05	1,883.36
3	CNFRx 16353	1.05	1,880.53
4	CNFR 16997	1.03	1,848.23
5	CNFRx 16352	1.00	1,793.04
6	CNFR 17014	1.00	1,781.39
7	BRS Pitanga	0.99	1,776.80
8	CNFRx 16360	0.96	1,722.96
9	CNFR 16932	0.96	1,715.52
10	BRSMG Tesouro	0.95	1,702.96
11	BRS CNFRx 15595	0.95	1,697.24
12	CNFRx 16998	0.88	1,570.61

HMRPGV: harmonic mean of the relative performance of predicted genetic values; HMRPGV * OM: product of HMRPGV and the overall mean.

of genotypes for high yield, predictability and adaptability is specific for each location, making the selection of the best genotypes more costly.

The different rankings of the genotypes selected by the three selection methods used (Tables 3, 4 and 5) were due to the low and medium magnitudes of genotypic correlations, indicating G × E interaction levels that ranged from moderate to high. This was due to the predominance of complex interactions (Cruz & Castoldi 1991). Based on these results, the HMRPGV method is recommended for the selection of genotypes with high yield, predictability and adaptability.

CONCLUSION

The black bean genotypes BRS Esteio, BRS FP 403, CNFP 15681 and CNFP 16459 and purple bean inbred lines CNFRx 16340, CNFRx 16346 and CNFRx 16353 showed the best performances, considering grain yield, adaptability and stability simultaneously.

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