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BIOLOGY

Genotypic selection of pre-cultivars of carioca and early carioca beans for the Agreste-Sertão of Pernambuco, Brazil

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ABSTRACT: Genotype x environment interactions represent a major challenge in identifying and selecting genotypes responsive to different climate and soil conditions. This research evaluated and selected pre-cultivars of carioca bean and early carioca bean based on adaptability, stability, and grain yield. In the 2014 crop season, two regional competition trials were conducted in the state of Pernambuco: carioca beans (14 genotypes in Arcoverde, Belém de São Francisco, Caruaru and São João) and early carioca beans (11 genotypes in Araripina, Arcoverde, and Caruaru) and, in the 2015 crop season, with early carioca beans (11 genotypes in Araripina, Arcoverde, and Brejão). Parameters were estimated by mixed models, and the selection was performed using the Harmonic Mean of Relative Performance of Genetic Values (HMRPGV) method following three strategies: i) selection based on predicted genetic value with no interaction; ii) selection according to predicted genetic value considering each location; and iii) simultaneous selection for grain yield, adaptability, and stability. The environments influenced the phenotypic expression of the carioca and early carioca bean genotypes, representing a specific adaptation. The genotypes BRS Notável, BRS Estilo and BRS Pérola, of carioca beans, and CNFC 15875, BRS Notável and CNFC 15630, of early carioca beans, had the best results in the environments tested, regarding, simultaneously, adaptability to different soil and climate conditions, performance stability, and grain yield.
Key words: *Phaseolus vulgaris*, REML/BLUP, heritability, genotype x environment interaction, HMRPGV.

Seleção genotípica de pré-cultivares de feijão carioca e carioca precoce para o Agreste-Sertão de Pernambuco, Brasil

RESUMO: A interação genótipo x ambiente representa um grande desafio na identificação e seleção de genótipos responsivos às diversas condições de clima e solo. O objetivo deste trabalho foi avaliar e selecionar pré-cultivares de feijão carioca e feijão carioca precoce com base na adaptabilidade, estabilidade e produtividade de grãos. Na safra 2014 foram conduzidos dois ensaios regionais de competição no estado de Pernambuco: feijão carioca (14 genótipos em Arcoverde, Belém de São Francisco, Caruaru e São João) e feijão carioca precoce (11 genótipos em Araripina, Arcoverde e Caruaru) e na safra de 2015 com feijão carioca precoce (11 genótipos, em Araripina, Arcoverde e Brejão). Os parâmetros foram estimados por meio de modelos mistos e a seleção foi realizada pelo método da Média Harmônica do Desempenho Relativo dos Valores Genéticos (MHPRVG), adotando-se três estratégias: i) seleção com base no valor genético predito, sem interação; ii) seleção com base no valor genético predito, considerando cada local; iii) seleção simultânea quanto à produtividade de grãos, adaptabilidade e estabilidade. Observou-se que os ambientes influenciaram na expressão fenotípica dos genótipos de feijão carioca e carioca precoce, configurando adaptação específica. Os genótipos BRS Notável, BRS Estilo e BRS Pérola, de feijão carioca, e CNFC 15875, BRS Notável e CNFC 15630, de feijão carioca precoce, apresentaram os melhores desempenhos nos ambientes testados, considerando-se, simultaneamente, a adaptabilidade a diferentes condições edafoclimáticas, estabilidade de desempenho e produtividade de grãos.
Palavras-chave: *Phaseolus vulgaris*, REML/BLUP, herdabilidade, interação genótipo x ambiente, MHPRVG.

INTRODUCTION

In bean-breeding programs, the development of new cultivars should associate high yield, adaptability to various environments, and production stability with desirable agronomic traits, such as plant architecture, resistance or tolerance to major diseases or both, and grain quality, such as cooking time, tegument darkening, grain size, protein content, among others. Studies on selection

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gain; however, are hampered by the effect of each environment where the inbred lines are tested due to the genotype x environment (G x E) interaction (CARVALHO et al., 2016).

At present, the production of the state of Pernambuco is not enough to meet the state demand, being necessary to import a little more than 31 thousand tons of beans (CONAB, 2021). The growth of beans in the state is located in two regions, Agreste and Sertão, with common characteristics, such as low rainfall index and poor distribution of rainfall that limit the growth of a variety of crops. Using cultivars adapted to these regions becomes an alternative to eliminate the dependence on beans from other states and countries and to develop regional agriculture.

In the existence of G x E interactions, the study of adaptability and stability provides support for a selection process in which adaptability refers to the ability of a genotype to achieve maximum yield in relation to environmental changes, and stability means the predictability of genotypes as a result of environmental variations (CRUZ et al., 2014). The selected inbred lines should; therefore, associate high grain yield, predictability, and adaptability to various edaphoclimatic conditions.

A number of statistical methodologies may be used to evaluate the genotypic adaptability and stability, among them, the Restricted Maximum Likelihood (REML) / Best Linear Unbiased Prediction (BLUP), which is currently largely used for this type of study, given that genetic evaluation is performed by predicting the genotypic values of the genotypes for selection (RESENDE, 2007). Within this scenario, the simultaneous selection for productivity, stability and adaptability, in the context of mixed models, can be performed by the method of harmonic mean of the relative performance of the predicted genetic values (HMRPGV) that gather the values of the harmonic mean of the genotypes (HMGV), which simultaneously implies in the selection for productivity and stability, and also in terms of adaptability, referring to relative performance of genetic values (RPGV), across environments (RESENDE, 2007).

According to RESENDE (2007), the REML/BLUP methodology allows selecting superior genotypes simultaneously according to the three attributes already mentioned, presenting the following advantages: (a) it considers genotypic effects as random; and, therefore provides genotypic and non-phenotypic stability and adaptability; (b) it allows handling unbalanced data; (c) it enables handling non-orthogonal designs; (d) it supports heterogeneity of variances; (e) it considers errors correlated within environments; (f) it provides genetic values already discounted (penalized) of environmental effects; (g) it may be applied to any number of environments; (h) does not depend on the estimation of other parameters, such as regression coefficients; (i) it eliminates the noise of the genotype x environment interaction, as it considers the heritability of these effects; (j) it generates results in the magnitude or scale of the evaluated character, and (k) it allows computing the genetic gain with the selection by the three attributes simultaneously.

This research determined the efficiency of simultaneous selection of pre-cultivars of carioca and early carioca beans for yield, adaptability, and stability for the state of Pernambuco by using univariate mixed models and the harmonic mean method of the relative performance of predicted genetic values.

MATERIALS AND METHODS

The experiments were conducted in 2014 and 2015 at the experimental stations of the Instituto Agronômico de Pernambuco (IPA) (Agronomic Institute of Pernambuco) in seven municipalities in the Agreste and Sertão macro-regions of Pernambuco: Araripina, Arcoverde and Belém de São Francisco, located in the Sertão, and Brejão, Caruaru and São João, in the Agreste.

In the 2014 crop year, 14 carioca bean genotypes were evaluated, being ten inbred lines (identified with the prefix ‘CNFC’) developed by Embrapa Arroz e Feijão and four control cultivars in four municipalities: Arcoverde, Belém de São Francisco, Caruaru and São João, and 11 early carioca bean genotypes, comprising eight inbred lines (identified with the prefix ‘CNFC’) and three control cultivars in three municipalities: Araripina, Arcoverde, and Caruaru. In the 2015 crop year, 11 early carioca bean genotypes were evaluated in three municipalities: Araripina, Arcoverde, and Brejão. The control ‘BRS Notável’, developed by Embrapa Arroz e Feijão, was used in both tests because it was defined as a semi-early cycle.

The sertão and the agreste are characterized by being regions with low rainfall, generally less than 1,000 mm year^{-1}. All environments where the bean genotypes were evaluated had a sprinkler irrigation system, which was activated whenever necessary. However, the Araripina and Caruaru environments, both from 2014, where the early carioca bean genotypes were evaluated, did not use an irrigation system and had grain yields below 1,000 kg ha^{-1}.

A randomized block design with three replicates was utilized, totaling 408 experimental plots, with 210 plots from the trial network of carioca beans and 198 plots from the trial network of early carioca beans. Each experimental unit was composed of four rows of 4 m, spaced 0.50 m apart, totaling a population of 300,000 plants ha^{-1}. The grain yield was evaluated based on the two central rows, adjusted to 13% moisture content, and converted to kg ha^{-1}.

Using the phenotypic data, the genetic parameters and the effect of the G x E interaction were estimated, via mixed modeling, by means of the SELEGEN - REML/BLUP program developed by RESENDE (2016).

For evaluating the G x E interaction of data of carioca beans in the 2014 crop year and early carioca beans in the 2014 and 2015 crop years, it was adopted the statistical model corresponding to y = Xb+ Zg+ Wc + e, in which *y* is vector of values observed; *b*, effects of blocks within different environments (fixed); *g*, effects of genotypes (random); *c*, effects of G x E interaction (random); *e*, random errors; and X, Z, and W are the incidence matrices for *b*, *g*, and *c*, respectively. The distributions and structures of means (E) and variances (Var) assumed were

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

The model adjustment was determined from the mixed model equations:

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

in which $\lambda_1 = \frac{\sigma_e^2}{\sigma_g^2} = \frac{(1-h_g^2-c^2)}{h_g^2}$; $\lambda_2 = \frac{\sigma_e^2}{\sigma_c^2} = \frac{(1-h_g^2-c^2)}{c_g^2}$, in which

$h_g^2 = \frac{\sigma_g^2}{\sigma_g^2 + \sigma_c^2 + \sigma_e^2}$ is the individual heritability in a broad sense at block level;

$h_{mg}^2 = \frac{\sigma_g^2}{(\sigma_g^2 + \sigma_e^2/J)}$

refers to the genotype mean heritabilit;

$c^2 = \frac{\sigma_c^2}{(\sigma_g^2+\sigma_c^2+\sigma_e^2)}$ is the coefficient of determination of the effects of the G x E interaction; σ_g^2 is the genotypic variance; σ_c^2 G x E interaction variance; σ_e^2 is the residual variance among plots; $\hat{r}_{gloc} = \frac{\sigma_c^2}{(\sigma_g^2+\sigma_c^2)} = \frac{h_g^2}{(h_g^2+c^2)}$ corresponds to the genotypic correlation of genotypes by means of environments;

$\hat{r}_{gg} = \sqrt{h_{mg}^2}$ is the accuracy in selecting genotypes; $CVg\% = \frac{\sqrt{\sigma_g^2}}{\mu}$ corresponds to the genotypic coefficient of variation;

$CVe\% = \frac{\sqrt{\sigma_e^2}}{\mu}$, is the experimental coefficient of variation.

The significance tests of the statistical effects should not be estimated by the F test, as in the analysis of variance method, when employing the mixed model methodology for genotype selection. The recommended test for random effects is the likelihood ratio test (LRT) using the analysis of deviance. This analysis recommended by RESENDE (2007) generalizes the classical analysis of variance, both for balanced and unbalanced data, indicating the quality of adjustment of the statistical model used, with the deviance being a statistic derived from the ratio between the likelihoods of the complete model and the model without effect expected to be tested.

Statistical models 54 of the SELEGEN – REML/BLUP computer application were used to select the superior genotypes on the basis of yield, adaptability, and stability (RESENDE, 2016).

RESULTS AND DISCUSSION

The analysis of deviance (Table 1) was used to identify significant differences between the effects and their interactions. Significant differences by the chi-squared test was seen in the two types beans in the interaction G x E ($P < 0.05$), indicating a difference in genotypic behavior in the different environments evaluated. The difference in response in contrasting environments causes difficulty when selecting the ideal genotype and its recommendation, since

Table 1 - Analysis of deviance and estimates of genetic parameters (individual REML) for grain of carioca and early carioca bean genotypes cultivated in seven municipalities in the Agreste and Sertão macro-regions of Pernambuco, Brazil.

Effect	LRT Chi-Square Carioca Bean	LRT Chi-Square Early Carioca Bean
Genotype	1.82^{ns}	0.25^{ns}
G x E interaction	52.09^{*}	3.84^{*}
Complete Deviance Model	2,648.37	2,329.14
Components of variance (REML Individual)	Carioca Bean (kg ha^{-1})	Early Carioca Bean (kg ha^{-1})
Genotypic variance	32,582.84	2,365.61
Variance of G x E interaction	171,558.20	19,140.16
Residual variance	135,783.36	102,605.90
Individual phenotypic variance	339,924.41	124,111.68
Individual broad sense heritability free from interaction	0.10 0.0604	0.02 0.03
Average heritability	0.43	0.21
Selective accuracy	0.65	0.46
Genotype x environment interaction R^2	0.50	0.15
Genotypic correlation of performance in different environments	0.16	0.11
Genotypic coefficient of variation (%)	10.02	3.25
Coefficient of experimental variation (%)	20.45	21.40
Relative coefficient of variation	0.49	0.15
Overall mean	1,801.83	1,496.89

[+]Deviance of adjusted model without the effects cited; distribution for 1 degree of freedom. LRT, likelihood; *,**significant by chi-square, test at 5% (3.84) and 1% (6.63) probability, respectively.

the productivity ranking of the genotypes may change according to their interaction with the environment.

When it comes to yield, a character greatly influenced by the environment, the results of the experimental coefficient of variation were high and ranged from 20.45 to 21.40% for carioca and early carioca beans, respectively, exceeding the results estimated from the genetic coefficient of variation (Table 1). Considering this, it is clear that, in both trials, there was a strong influence of environment on the performance of the genotypes.

As for the genotypic coefficient of variation, high values should be aimed, since it quantifies the magnitude of the genetic variation available for selection (CARVALHO et al., 2016). The values for the genotypic coefficient of variation were 10.02% for carioca beans, and 3.25% for early carioca bean, showing, respectively, the low and very low fraction of genetic variances from the total phenotypic variation (Table 1). This way the selection of superior genotypes is possible, but more costly.

According to RESENDE & DUARTE (2007), the joint evaluation of the genetic and experimental coefficients of variation is shown in the statistics of selective accuracy. The accuracy obtained for the carioca bean genotypes (65.50%) and early carioca bean (45.84%) (Table 1) was considered of high and medium accuracy, respectively, by the classification of the same authors. For the carioca bean genotypes, this indicated a high correspondence between the phenotypic values observed and the genotypic values predicted; consequently, an excellent selective efficiency of superior genotypes, while for the early carioca bean genotypes, the selection of superior genotypes is possible, but more difficult because of the low correspondence between the phenotypic values observed and the genotypic values predicted.

Heritability is one of the most important genetic parameters as it measures the fraction of phenotypic variation, of heritable nature, which can be used in selection (SILVA et al., 2013). The average heritability of genotypes is estimated when using averages as evaluation or selection criteria or both. In this way, given the heritability value found for the carioca bean (0.43) and early carioca bean (0.21) genotypes (Table 1), based on the predicted genotypic values, the selection of superior genotypes is possible for both carioca and early carioca beans, but, for the latter group, this selection is more costly. SANTOS et al. (2018) found similar results.

Individual heritability, in the broad sense, free of interaction, considers the total genetic dispersion and allows exploiting all the genetic variance among genotypes (SANTOS et al., 2018). For the carioca bean and early carioca bean genotypes, the variance of the effects of G x E interaction has extremely high magnitude to the variance of genotypic effects, consisting of 9.59% and 1.91% of the individual phenotypic variance, represented by the individual plot heritability (0.10 and 0.02, respectively, carioca bean and early carioca bean) (Table 1). LIMA et al. (2020) and SOUZA et al. (2018) reported similar results.

The variance of the G x E interaction may increase the phenotypic expression of a character. This measure quantifies the fraction of the total variation because of the G x E interaction. Estimates of small magnitude of this variance may suggest that the G x E interaction has little influence on the phenotypic value. Based on this, a genotype with higher productivity in one environment tends to maintain similar levels in other ones, as it will respond positively to environmental changes and will have acceptable predictability regarding environmental variations. The variance estimates of the G x E interaction may be considered of moderate and low magnitudes, corresponding to 50.47 and 15.42% of the individual phenotypic variance of the carioca and early carioca bean genotypes, respectively, expressed by the coefficient of determination of the G x E interaction (Table 1). Such fact helped the genotype correlation to be low (0.16 and 0.11 for carioca bean genotypes and early carioca bean, respectively), suggesting high levels of complex interactions (Table 1). From these estimates, it may be predicted that genotypes with higher productivity in an environment will tend to perform differently in others results.

The variance of the residual effects of the early carioca bean genotypes accounted for 82.67% of the individual phenotypic variance; however, significant genetic progress was achieved (Table 2). SANTOS et al. (2018), reported similar result for

Table 2 - Estimate of predicted genetic gain for grain productivity (kg ha^{-1}) of carioca and early carioca bean genotypes in nine environments in the Agreste and Sertão macro-regions of Pernambuco.

Early Carioca Bean			---Carioca Bean---		
Genotype	Gain	New Mean	Genotype	Gain	New Mean
---Araripina 2014---			---Arcoverde---		
BRS Notável	111.20	648.40	CNFC 15475	801.17	3,032.42
CNFC 15875	81.21	618.41	CNFC 15458	644.57	2,875.82
CNFC 15874	68.73	605.92	BRS Notável	516.73	2,747.98
---Araripina 2015---			---Belém de São Francisco I---		
Carioca Precoce	102.08	1,770.04	BRS Notável	673.68	2,946.78
CNFC 15875	91.17	1,759.12	BRS Estilo	597.29	2,870.38
CNFC 15630	86.78	1,754.73	CNFC 15475	551.35	2,824.44
---Arcoverde 2014---			---Belém de São Francisco II---		
CNFC 15874	109.64	2,092.37	BRS Pérola	1,211.75	3,079.07
CNFC 15626	108.59	2,091.31	BRS Notável	1,071.93	2,939.25
CNFC 15875	100.07	2,082.79	BRS Estilo	930.44	2,797.76
---Arcoverde 2015---			---Caruaru---		
CNFC 15625	138.38	1,916.79	BRS Estilo	113.21	1,316.54
Carioca Precoce	117.16	1,895.57	IPR 139	111.97	1,315.31
CNFC 15630	99.96	1,878.37	CNFC 15504	109.74	1,313.07
---Brejão---			---São João---		
CNFC 15875	175.36	2,360.74	CNFC15534	435.21	1,869.38
CNFC 15630	154.35	2,339.73	BRS Estilo	312.12	1,746.29
Carioca Precoce	137.23	2,322.61	CNFC 15497	241.42	1,675.58
---Caruaru---				-	
BRS Notável	109.44	939.06	-	-	-
CNFC 15502	100.94	930.56	-	-	-
CNFC 15875	84.88	914.50	-	-	-

black bean genotypes. For carioca bean genotypes, conversely, the variance of the residual effects represented 39.94% of the individual phenotypic variance (Table 1). High values of residual variance among plots occur because grain yield is a quantitative trait, thus being highly influenced by the environment.

The selection of the best genotypes was made by the three different strategies (Tables 2, 3 and 4). In the selection based on the average performance in all environments, the three best carioca bean genotypes that presented the highest predicted genetic gains were BRS Notável (10.94%), BRS Estilo (9.83%) and BRS Pérola (8.98%). Conversely, the best early carioca bean genotypes showed gains lower than 1.0%, which were CNFC 15875, CNFC 15630 and CNFC 15625 (Table 3). This result was expected, as the genotypic variance compared with individual phenotypic variance, represented by the individual heritability in the broad sense, had a very small value (Table 1). The magnitudes of the genetic gain

Table 3 - Estimates of predicted genetic gain for grain productivity (kg ha^{-1}) of carioca and early carioca bean genotypes, considering the average performance in all environments in the Agreste and Sertão macro-regions of Pernambuco, Brazil.

Order	Genotype	g(1)	u + g	Gain	New Mean	u+g+gem
----------Carioca Bean----------						
1	BRS Notável	197.15	1,998.98	197.15	1,998.98	2,206.59
2	BRS Estilo	156.96	1,958.79	177.05	1,978.89	2,124.08
3	BRS Pérola	131.15	1,932.98	161.75	1,963.58	2,071.08
4	CNFC 15475	124.92	1,926.76	152.54	1,954.38	2,058.31
5	CNFC 15497	68.43	1,870.27	135.72	1,937.56	1,942.33
6	CNFC 15458	17.52	1,819.35	116.02	1,917.86	1,837.80
7	CNFC 15460	-14.30	1,787.53	97.40	1,899.24	1,772.47
8	CNFC 15513	-41.05	1,760.79	80.10	1,881.93	1,717.56
9	IPR 139	-44.41	1,757.43	66.26	1,868.10	1,710.66
10	CNFC 15462	-63.43	1,738.41	53.29	1,855.13	1,671.61
11	CNFC 15480	-102.18	1,699.65	39.16	1,840.99	1,592.04
12	CNFC 15507	-136.01	1,665.83	24.56	1,826.40	1,522.60
13	CNFC15534	-138.87	1,662.96	11.99	1,813.82	1,516.73
14	CNFC 15504	-155.89	1,645.95	0.00	1,801.83	1,481.79
Order	Genotype	g(1)	u + g	Gain	New Mean	u+g+gem
----------Early Carioca Bean----------						
1	CNFC 15875	27.49	1,524.37	27.49	1,524.37	1,561.44
2	CNFC 15630	24.89	1,521.77	26.19	1,523.07	1,555.34
3	CNFC 15625	12.54	1,509.42	21.64	1,518.52	1,526.33
4	CNFC 15874	11.63	1,508.52	19.14	1,516.02	1,524.21
5	Carioca Precoce	11.63	1,508.52	17.64	1,514.52	1,524.21
6	BRS Notável	6.32	1,503.20	15.75	1,512.63	1,511.72
7	IPR Colibri	0.54	1,497.42	13.58	1,510.46	1,498.15
8	CNFC 15626	-14.03	1,482.85	10.13	1,507.01	1,463.93
9	CNFC 15873	-14.97	1,481.92	7.34	1,504.22	1,461.73
10	CNFC 15502	-16.92	1,479.96	4.91	1,501.79	1,457.14
11	CNFC 15629	-49.13	1,447.75	0.00	1,496.88	1,381.50

(1)Estimates: g. genotypic effect; u + g. predicted genotypic value; and u+g+gem. mean genotypic value in the environments.

Table 4 - Stability and adaptability (MHPRVG and MHPRVG * MG) of the genotypic values of carioca and early carioca bean genotypes for grain productivity (kg ha^{-1}) in all environments in the Agreste and Sertão macro-regions of Pernambuco. Brazil.

Carioca Bean			-----------------------Early Carioca Bean-------------------------		
Genotype	MHPRVG	MHPRVG*MG	Genotype	MHPRVG	MHPRVG*MG
BRS Notável	1.18	2,133.45	CNFC 15875	1.05	1,568.81
BRS Estilo	1.16	2,097.89	BRS Notável	1.04	1,555.31
BRS Pérola	1.09	1,963.91	CNFC 15630	1.03	1,548.07
CNFC 15475	1.08	1,952.27	CNFC 15874	1.03	1,534.58
CNFC 15497	1.07	1,921.38	CNFC 15625	1.01	1,512.11
CNFC 15458	0.98	1,760.85	Carioca Precoce	1.00	1,504.12
CNFC 15460	0.97	1,754.54	CNFC 15873	0.99	1,484.58
CNFC 15513	0.95	1,709.49	CNFC 15502	0.99	1,481.55
IPR 139	0.92	1,661.13	IPR Colibri	0.99	1,479.18
CNFC 15462	0.89	1,611.80	CNFC 15626	0.93	1,395.95
CNFC 15480	0.89	1,602.42	CNFC 15629	0.89	1,337.83
CNFC 15504	0.81	1,452.24	-	-	-
CNFC15534	0.80	1,449.68	-	-	-
CNFC 15507	0.80	1,441.70	-	-	-

values may be considered for the recommendation of superior bean genotypes, aiming the selection of genetic material with average performance in the different environments evaluated.

Considering the selection of the carioca bean genotypes in all environments evaluated (Table 3), the six best genotypes are the same that were selected based on the genotypes with the best agronomic response, using the HMRPGV method for grain yield (Table 4). The results of adaptability and stability (Table 4) are not in accordance with the results of the selection conducted for each environment (Table 2). It is observed in table 3 that, for each environment, a different genotypic order was obtained, differing even from the order obtained in the selection based on the best agronomic response, using the HMRPGV method for grain yield (Table 4). In the productive scenario, the genotypes CNFC 15475 and BRS Pérola stood out with the highest yields in the municipalities of Arcoverde and Belém de São Francisco II, respectively.

The adaptability and stability results for early carioca bean genotypes using HMRPGV method (Table 4) were not in accordance with the selection practiced in all environments (Table 3). Regarding the selection of the early carioca bean genotypes for each environment (Table 2), the same situation was observed for the carioca bean genotypes. This fact is due to the low estimate of the genotypic correlation observed in both beans, which provided a complex G x A interaction. In this case, a selection of genotypes for high productivity, predictability, and adaptation is specific to each environment. In the productive scenario, the Arcoverde 2014 and Brejão environments stood out for having presented yields above 2,000 kg ha^{-1}.

The carioca bean genotypes BRS Notável, BRS Estilo and BRS Pérola and early carioca bean genotypes CNFC CNFC 15875, BRS Notável and CNFC 15630 presented the best performances, considering, simultaneously, productivity, adaptability, and stability by the HMRPGV method (Table 4).

The overall mean yield of the carioca (1,801.83 kg ha^{-1}), and early carioca bean (1,496.89 kg ha^{-1}) genotypes exceeded by 3.88 and 3.22 times the bean yield of the state of Pernambuco. It surpassed 80.11 and 52.12% the national average, respectively, according to data from the last harvest surveyed by the National Supply Company (Companhia Nacional de Abastecimento, in Portuguese) (CONAB, 2021).

CONCLUSION

The genotypes BRS Notável, BRS Estilo and BRS Pérola of carioca beans and the early carioca beans CNFC 15875, BRS Notável and CNFC 15630 exhibited the best performances in all environments tested in the state of Pernambuco when considering grain yield, adaptability, and stability, simultaneously.

The harmonic mean of relative performance of genetic values (HMRPGV) method enabled an optimized selection of genotypes for productivity, adaptability, and stability simultaneously and should be used as a strategy for the selection of carioca and early carioca bean genotypes for commercial plantings in the Agreste and Sertão regions of Pernambuco.

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DECLARATION OF CONFLICT OF INTEREST

The authors declared that there is no conflict of interest that could constitute an impediment to the publication of this article.

AUTHORS' CONTRIBUTIONS

All authors contributed effectively to the conception of the manuscript idea, in the installation and conduction of experimental essays and data collection, in data analysis, writing and final review of the manuscript.

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