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ARTICLE

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Genotype-environment interaction in common bean cultivars with carioca grain cultivated in Brazil in the last 40 years

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Abstract – *The purpose of this study was to analyze the effect of genotype-environment interaction (GE) on common bean cultivars with carioca grain (cream-colored beans with light brown stripes), recommended for cultivation by different Brazilian research institutions in the last 40 years. The experiments were carried out with 40 cultivars in four different environments (Coimbra and Viçosa, in the dry and winter seasons of 2013) using a randomized block design with three replications. The results showed an effective increase in grain yield resulting from the use of new cultivars from different Brazilian breeding programs in the past four decades. In addition, the analysis of the GE interaction indicated that the cultivars recommended after 2005 combined high mean grain yield, wide adaptability and high or stability*

Key words: Phaseolus vulgaris *L., breeding, grain yield.*

INTRODUCTION

Socioeconomically, common bean is an essential staple crop in Brazil. The country is a major producer and consumer of this legume, with a production of 2.83 million tons in the 2012/2013 growing season (CONAB 2013). The mean grain yield lingered around 550 kg ha^{-1} for many years (Backes et al. 2005). This scenario was significantly optimized in recent decades, in response to the evolution of cultural practices and planting of improved cultivars, which led to a 73% increase in grain yield between 1985 and 2011 (Feijão 2014). Among the common bean types grown in Brazil, most breeding programs have focused mainly on carioca-grain lines, due to the high market demand, since these cultivars are planted on more than 70% of the common bean production area in the country (Souza et al. 2013).

The development of superior lines in terms of grain yield, plant architecture, grain-processing quality, stress resistance, wide adaptation, and yield stability is an unchanging goal in plant breeding programs (Moda Cirino et al. 2012). However, the influence of the genotype – environment (GE) interaction hampers breeding, for inducing variations in genotype performance in different environments and jeopardizing selection (Cargnin et al. 2006). Since common bean is a crop sensitive to environmental variations, the development of genotypes with wide adaptation, high stability and high mean yield has become one of the alternatives to mitigate the effects of GE interaction and make the recommendation of cultivars more reliable (Melo et al. 2007). Thus, the estimation of adaptability and stability parameters contributes to the description of the response of these genotypes to environmental variations, solidifying the recommendation of new cultivars (Silva et al. 2013).

Different methodologies have been proposed for the analysis of adaptability and stability, and the choice of one of them depends on factors such as the number of evaluated genotypes and environments and the way in which the results are interpreted. In common bean, Dalla Corte et al. (2002), Carbonell et al. (2004), Oliveira et al. (2006), Pereira et al. (2009), and Silva et al. (2013), among others, carried out research of this nature. However in these studies, most genotypes tested were lines of a particular breeding program, which were often not released on the market. In addition, these studies addressing cultivars evaluated few

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genotypes, which usually only represent a particular stage of breeding in Brazil.

Given the above, it would be interesting to compile the cultivars recommended throughout the history of common bean breeding in Brazil by different research institutions in a single review/paper, estimating their adaptability and stability parameters, and thus investigating the contribution of breeding to increases in grain yield, adaptability and performance stability of these cultivars. Thus, we investigated the relationship between the increase in grain yield and adaptability and phenotypic stability parameters in common bean cultivars with carioca grain recommended by various Brazilian institutions in the last 40 years.

MATERIAL AND METHODS

The experiments were carried out at experimental stations of the Federal University of Viçosa, i.e., in the municipalities of Viçosa/MG (lat 20º 45’ 14” S, long 42º 52’ 55” W, alt 648m asl) and in Coimbra/MG (lat 20º 51’ 24” S, long 42º 48’ 10” W, alt 720 m asl), in the dry and winter seasons of 2013.

Forty common bean cultivars with carioca grain (Table 1), recommended by different research institutions in Brazil between 1970 and 2013 were planted. The varieties considered in this study were selected based on scientific records, as well as on reports of breeders participating in different bean breeding programs. Initially, a seed sample of the cultivars was obtained from the breeding institutions and multiplied, to standardize germination and for the experiment.

The experimental design was a randomized block design with three replications. The experimental plots consisted of four 3-m long rows, spaced 0.5 m apart. The trait used for the study was grain yield (in g), by weighing the beans harvested from the two center rows of each plot, adjusted to 13% moisture and extrapolated to kg ha^{-1}.

The data were subjected to individual and combined analysis of variance. Combined analysis of variance was performed assuming environmental effects as fixed, and effects of genotype and GE interaction as random. The model in question is given by:

$$Y_{ijk} = m + G_i + A_j + B_k + GA_{ij} + E_{ijk}$$

where: Y_{ijk} is the measured value of genotype i in block k in environment j; m the general mean; G_i the random effect of genotype i, with $i = 1, 2, 3, ..., 40$; A_j the random effect of environment j, where $j = 1, 2, 3, 4$; B_k the random effect of block k ($k = 1, 2, 3$); $GA_{(ij)}$ the random effect of the interaction of genotype i with environment j and E_{ijk} is the experimental error.

To assess the homogeneity of residual variance in this model, the ratio between the largest and smallest mean residual square of the tests was used. By the F_{max} test, variances are considered homogeneous when this ratio is

Table 1. Name of cultivars, year of release and research institution in charge of the 40 bean cultivars with carioca grain evaluated in this study

Cultivars	Release	Institution	Cultivars	Release	Institution
Carioca 1030	1970	IAC	SCS Guará	2004	EPAGRI
Carioca 80	1980	IAC	IPR Colibri	2004	IAPAR
IAPAR 16	1986	IAPAR	IPR Saracura	2004	IAPAR
Rio doce	1987	EMCAPA	BRSMG Pioneiro	2005	Embrapa
IAC Carioca	1987	IAC	IAC Votuporanga	2005	IAC
Carioca 1070	1989	IAC	IAC-Ybaté	2005	IAC
IAPAR 31	1991	IAPAR	IAC-Apuã	2005	IAC
Aporé	1992	Embrapa	BRS Cometa	2006	Embrapa
FT bonito	1992	FT- sementes	IPR Eldorado	2006	IAPAR
IAPAR 57	1992	IAPAR	IAC Alvorada	2007	IAC
Pérola	1996	Embrapa	IPR 139	2007	IAPAR
Rudá	1994	CIAT	IPR Tangará	2008	IAPAR
IAC - Carioca Pyatã	1994	IAC	BRS Estilo	2010	Embrapa
BR- IPA 11-Brígida	1994	IPA/PE	BRS Notável	2011	Embrapa
IAC - Carioca Akytá	1996	IAC	IAC Formoso	2011	IAC
IAPAR 81	1997	IAPAR	IPR Campos Gerais	2011	IAPAR
BRSMG Talismã	2002	UFLA	BRSMG Madrepérola	2012	UFV
BRS Requinte	2003	Embrapa	IAC Imperador	2013	IAC
BRS Pontal	2003	Embrapa	IPR Andorinha	2013	IAPAR
BRS Majestoso	2004	Embrapa	VC 15	2013	UFV

lower than 7.0 (Pimentel-Gomes 1990). After checking the significance of the interaction, the mean grain yields of the cultivars in each environment were subjected to the Scott-Knott (1974) grouping test, at 5% error probability.

To study adaptability and stability, we used the methodology proposed by Eberhart and Russell (1966), based on linear regression analysis, in which genotypes with general or wide adaptability are those with $\beta_{1i} = 1$; with specific adaptability to favorable environment those with $\beta_{1i} > 1$ and genotypes with specific adaptability to harsh environments those with $\beta_{1i} < 1$. Stability is assessed by regression deviations (σ^2_{di}), and genotypes with $\sigma^2_{di} = 0$ were considered stable and those with $\sigma^2_{di} \neq 0$ unstable. All analyses were processed by software Genes (Cruz 2006).

RESULTS AND DISCUSSION

Individual analyses of variance detected significant differences among genotypes in all evaluated environments, demonstrating genetic variability among cultivars (Table 2). The coefficients of variation (CVs) were low (7.5 ~ 14.1%), indicating good experimental accuracy and reliability of results. In studies with common bean, Oliveira et al. (2006), Silva et al. (2013), Menezes Júnior et al. (2013) and Domingues et al. (2013), found CVs between 6-23% for grain yield. The grain yield varied between experiments and means were highest in the dry and winter seasons in Coimbra (3571 and 3153 kg ha^{-1}, respectively). These results corroborate Oliveira et al. (2006), who evaluated common bean lines in Viçosa and Coimbra/MG and observed higher means in Coimbra. This indicates that this site is more favorable than Viçosa for common bean cultivation. In addition, the estimate based on the ratio between the highest and lowest residual mean squares was below seven, indicating homogeneity of residual variances, enabling combined analysis without restrictions.

The analysis of variance showed significance (p <0.01) of all tested effects, indicating a differentiated response of the common bean cultivars to environmental changes (Table 3). These results corroborate those of Oliveira et al. (2006), Melo et al. (2007), Ribeiro et al. (2009), Rocha et al. (2013) and Moura et al. (2013) who studied common bean and also found significant effects of genotypes, environments and of GE interaction. The mean grain yield in both environments was 3100 kg ha^{-1} and the coefficient of variation 10.91%, which is within the standard range for common bean.

Once the significance of the GE interaction was confirmed, the results of comparisons of phenotypic means were presented separately per environment. The genetic variability among cultivars was significant (Table 4), since the Scott and Knott test (5% probability) formed different groups. Note that the cultivars recommended after 2005 achieved the highest grain yields in the four environments, demonstrating the success of breeding for high-yielding cultivars in the last decades. In contrast, the mean yield of the cultivars recommended until 2000 (e.g., the cultivars IAPAR 16, IAPAR 57, Carioca 1070, IAC Carioca and Rudá) were lowest in the four environments.

The most significant increases in recent decades can be ascribed to breeding (Ramalho et al. 2012). This reflects the intensified activity of research institutions in Brazil focused on common bean breeding, involving different areas of knowledge (genetics, statistics, plant pathology, entomology, biotechnology, and others). Cultivars resistant to biotic and abiotic stresses, adapted to different cultivation sites,

Table 3. Summary of analysis of variance for grain yield (in kg ha^{-1}) of 40 common bean cultivars with carioca grain. Coimbra and Viçosa, Minas Gerais, dry and winter growing seasons

Source of variation	df	MS	P-value
Blocks/Environments	8	378642.17	
Cultivars	39	4469931.13**	< 0.001
Environments	3	25911360. 68**	< 0.001
Cultivars x Environments	117	181329.57**	< 0.001
Error	312	114378.06	
Mean	-	3100	
CV (%)	-	10.91	

* and ** significant a 5% and 1% probability, respectively.

Table 2. Summary of individual variance analysis for grain yield (kg ha^{-1}) of 40 common bean cultivars with carioca grain. Coimbra (dry and winter growing seasons) and Viçosa (dry and winter growing seasons), Minas Gerais

Environments	Mean squares			CV (%)	Mean
	Block	Genotype	Error		
	df=2	df=39	df=78		
Coimbra/Dry 2013	227459.11	1631061.85**	139305.96	10.45	3571
Viçosa/Dry 2013	108486.81	1144568.92**	196464.83	14.06	3153
Coimbra/Winter 2013	179204.28	1455445.81**	87357.82	9.18	3219
Viçosa/Winter 2013	23043.47	782843.27**	34383.65	7.53	2461
Relation between highest and lowest mean square residues			5.71		

* and ** significant at 5% and 1% probability, respectively.

with high yield stability and responsive to environmental improvements are the predominant factors in the increase in grain yield observed in recent decades.

The use of improved cultivars contributes to raise yields and yield stability without additional costs for farmers (Polizel et al. 2013). The reason is that breeders try to combine high yields, wide adaptability and high stability of performance in one genotype. According to the classification of Eberhart and Russell (1966), around 90% of the cultivars have wide adaptability ($\beta 1i = 1$) (Table 5). Line VC15 was the only one with adaptability to favorable environments, i.e., it responded positively to environmental improvements. In contrast, the

Table 4. Mean grain yield (kg ha^{-1}) per environment and overall, and mean grouping test for 40 common bean cultivars with carioca grain, evaluated in Coimbra and Viçosa/Minas Gerais

Cultivars	Release	Coimbra Dry/13	Viçosa Dry/13	Coimbra Winter/13	Viçosa Winter/13	Overall mean
VC 15	2013	5083 a	3435 a	4619 a	3305 a	4111 a
BRS Notável	2013	4767 a	3960 a	3817 b	3171 a	3929 a
IAC Formoso	2011	4689 a	4055 a	4489 a	3189 a	4106 a
IPR Campos Gerais	2011	4560 a	3741 a	4163 b	3071 a	3884 a
BRS Estilo	2010	4511 a	4053 a	3939 b	3194 a	3924 a
BRSMG Madrepérola	2012	4205 b	4130 a	4089 b	3390 a	3954 a
IPR Andorinha	2013	4203 b	3913 a	3743 b	2972 a	3708 a
IAC Imperador	2013	4185 b	3722 a	3977 b	3083 a	3742 a
IPR Tangará	2008	4183 b	3598 a	3819 b	2845 b	3611 a
BRSMG Pioneiro	2005	4100 b	3399 a	3224 c	2617 b	3335 b
BRS Majestoso	2005	4021 c	3730 a	3256 c	2534 b	3385 b
IPR139	2007	4017 c	3589 a	3975 b	3047 a	3657 a
BRS Requinte	2003	4007 c	2656 b	3420 c	2448 b	3133 b
IAC - Apuã	2005	3948 c	3591 a	3895 b	2743 b	3544 a
IPR Eldourado	2006	3926 c	2948 b	3399 c	2508 b	3195 b
BRS Pontal	2003	3822 c	3530 a	3398 c	2739 b	3373 b
IAC - Ybaté	2005	3770 c	3691 a	3146 c	2731 b	3335 b
IAC Alvorada	2007	3765 c	3338 a	3913 b	2889 a	3476 b
IPR Colibri	2004	3753 c	2637 b	3176 c	2494 b	3015 b
IAPAR 81	1997	3723 c	2743 b	3272 c	2160 c	2975 b
BRSMG Talismã	2002	3694 c	3090 b	3159 c	2596 b	3135 b
SCS Guará	2004	3564 c	3090 b	3425 c	2285 c	3091 b
IAC Votuporanga	2005	3547 c	3775 a	3651 c	2470 b	3361 b
BRS Cometa	2006	3512 c	3400 a	3306 c	1637 c	2964 b
Pérola	1994	3476 c	3189 a	2922 d	2356 c	2986 b
IAC - Carioca Akytã	1996	3437 c	3228 a	3218 c	2185 c	3017 b
IAC - Carioca Pyatã	1994	3430 c	3036 b	2835 d	2048 c	2838 c
IPR Saracura	2004	3360 c	3528 a	3230 c	2724 b	3210 b
FT bonito	1992	3033 d	2634 b	2214 e	1830 c	2428 c
IAPAR 31	1991	2928 d	2540 b	2590 d	1923 c	2495 c
Carioca 80	1980	2816 d	2674 b	2515 d	1822 c	2457 c
Aporé	1992	2803 d	2714 b	2476 d	1833 c	2457 c
IAPAR16	1986	2794 d	2039 c	2038 e	1748 c	2155 c
BR-IPA11-Brígida	1994	2729 d	3037 b	2378 d	1717 c	2465 c
IAPAR 57	1992	2726 d	2254 c	2292 e	1952 c	2306 c
Carioca 1030	1970	2476 d	2541 b	2446 d	1800 c	2316 c
Rio doce	1987	2408 d	2735 b	2448 d	1933 c	2381 c
Carioca 1070	1989	2374 d	1885 c	1849 e	1758 c	1967 c
IAC Carioca	1987	2366 d	2425 b	2453 d	1935 c	2295 c
Rudá	1994	2140 d	1838 c	2552 d	1906 c	2109 c
Overall mean	-	3571	3153	3219	2440	3100

* Means followed by the same letter in a column belong to the same group, according to the grouping criterion of Scott-Knott (1974), at 5% probability.

cultivars Rio Doce, IAC Carioca, Rudá, and Carioca 1070 proved adaptable to harsh environments and are suitable for areas with a low level of management technology, for being irresponsive to improvement of the environment.

For the parameter yield stability, the performance of all cultivars was high, except for line VC 15 and cultivars BRS Requinte, IAC Votuporanga, BR-IPA 11-Brígida, IPR Colibri, and Rudá, which had low yield stability.

According to the criteria of Eberhart and Russell (1966), a genotype considered ideal combines high yield, regression coefficient equal to 1 (wide adaptability) and deviation from regression zero (high stability). So, the cultivars that contribute to the desired ideotype are: IAC Formoso, BRSMG Madrepérola, BRS Notável, BRS Estilo, IPR Campos Gerais,

Table 5. Adaptability and stability parameters of 40 common bean cultivars with carioca grain evaluated in four environments in Minas Gerais, in 2013, based on the criterion of Eberhart and Russell (1966)

Cultivars	Release	Mean (kg ha^{-1})	β_{1i}	R²	δ_{1j}
VC15	2013	4111 a	1.54*	67	347690**
IAC Formoso	2011	4106 a	1.39	95	-3540.03
BRSMG Madrepérola	2012	3954 a	0.78	91	-19218.6
BRS Notável	2013	3929 a	1.34	90	25571.73
BRS Estilo	2010	3924 a	1.16	98	-27495
IPR Campos Gerais	2011	3884 a	1.33	95	-5978.05
IAC Imperador	2013	3742 a	1.01	97	-28123.5
IPR Andorinha	2013	3708 a	1.11	96	-22133.5
IPR 139	2007	3657 a	0.92	90	-6483.34
IPR Tangará	2008	3611 a	1.20	99	-33025.8
IAC-Apuã	2005	3544 a	1.15	93	-3323.57
IAC Alvorada	2007	3476 b	0.86	75	42148.96
BRS Majestoso	2005	3385 b	1.31	88	40363.12
BRS Pontal	2003	3373 b	0.97	97	-28387.6
IAC Votuporanga	2005	3361 b	1.10	73	110628.7*
BRSMG Pioneiro	2005	3335 b	1.25	91	13975.12
IAC-Ybaté	2005	3335 b	0.91	74	53334.93
IPR Saracura	2004	3210 b	0.61	70	18133.06
IPR Eldourado	2006	3195 b	1.23	88	28449.12
BRS Cometa	2006	3172 b	0.98	92	-11962.4
BRSMG Talismã	2002	3135 b	0.94	94	-21176.6
BRS Requinte	2003	3133 b	1.32	74	164527.2**
SCS Guará	2004	3091 b	1.20	95	-12669.8
IAC - Carioca Akytã	1996	3017 b	1.18	95	-12845.5
IAC Colibri	2004	3015 b	1.05	73	97196.61*
Pérola	1994	2986 b	0.98	92	-10238.9
IAPAR 81	1997	2975 b	1.38	91	24250.86
IAC - Carioca Pyatã	1994	2838 c	1.22	96	-18197.2
IAPAR 31	1991	2495 c	0.90	100	-38012
BR-IPA 11-Brígida	1994	2465 c	0.96	62	144496.9**
Aporé	1992	2457 c	0.89	90	-8121.85
Carioca 80	1980	2457 c	0.92	93	-18730.2
FT bonito	1992	2428 c	1.01	81	38576.72
Rio doce	1987	2381 c	0.50*	49	45565.32
Carioca 1030	1970	2316 c	0.66	80	-3035.07
IAPAR 57	1992	2306 c	0.65	89	-21899.7
IAC Carioca	1987	2295 c	0.45*	73	-14491.7
IAPAR 16	1986	2155 c	0.83	75	36071.96
Rudá	1994	2109 c	0.28*	16	92186.25*
Carioca 1070	1989	1967 c	0.47*	63	4081.803

* and **: significant at 5 and 1%, by the t test (h_0: β_{1i} = 1.0) and the F test (h_0: σ^2_{di} = 0).

IAC Imperador, IPR Andorinha, IPR 139, IPR Tangará, IAC-Apuã, IAC Alvorada, BRS Majestoso, BRS Pontal, BRSMG Pioneiro, IAC-Ybaté, IPR Saracura, IPR Eldourado, BRS Cometa, and BRSMG Talismã, for having means above the overall mean, wide adaptation and high performance stability. In addition, the correlation coefficients of these genotypes were high (R^2 > 70%), indicating that much of their total variation can be explained by the adopted model. Regarding this value, Nascimento et al. (2010) found that genotypes with R^2 > 70% were highly stable.

It is noteworthy that the above cultivars were released after 2005, again showing the commitment of the breeders to recommend high-yielding cultivars, adaptable to a variety of environmental conditions and with a stable performance, crowned by significant genetic gain in common bean. The fact that the best-adapted and stable are also the highest-yielding genotypes (Pereira et al. 2009), confirms the hypothesis of the relentless efforts in bean breeding programs to achieve the plant ideotype proposed by Eberhart and Russel (1966).

The common bean breeding programs have contributed effectively to the increase in grain yield, leading to the release of cultivars with carioca grain and high yield potential. The cultivars with the best combinations of high grain yield, phenotype, wide adaptability, and high performance stability were recommended for cultivation in the past 15 years.

Interação genótipos x ambientes em cultivares de feijão carioca recomendadas no Brasil nos últimos 40 anos

Resumo – *Nosso objetivo foi investigar a interação genótipos por ambiente (GxA) em cultivares de feijão do grupo carioca recomendadas por diferentes instituições de pesquisa do Brasil nos últimos 40 anos. Os experimentos foram realizados considerando 40 cultivares em quatro ambientes (Coimbra e Viçosa nas safras da seca e de inverno de 2013), usando um delineamento em blocos casualizados com três repetições. Os resultados mostraram o incremente efetivo na produtividade de grãos proporcionado pela recomendação de novas cultivares pelos programas de melhoramento de feijão do Brasil nas últimas quatro décadas. Além disso, a análise da GxA indicou que as cultivares recomendadas após o ano de 2005 foram as que apresentaram conjuntamente altas produtividades de grãos, ampla adaptabilidade e alta previsibilidade.*

Palavras-chave: *Feijeiro comum, melhoramento genético, produtividade de grãos.*

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