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CROP PRODUCTION

Analysis of the adaptability of black bean cultivars by means of quantile regression

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ABSTRACT: *The aim of this study was to use quantile regression (QR) to characterize the effect of the adaptability parameter throughout the distribution of the productivity variable on black bean cultivars launched by different national research institutes (research centers) over the last 50 years. For this purpose, 40 cultivars developed by Brazilian genetic improvement programs between 1959 and 2013 were used. Initially, QR models were adjusted considering three quantiles (τ = 0.2, 0.5 and 0.8). Subsequently, with the confidence intervals, quantile models τ = 0.2 and 0.8 ($QR_{0.2}$ and $QR_{0.8}$) showed differences regarding the parameter of adaptability and average productivity. Finally, by grouping the cultivars into one of the two groups defined from $QR_{0.2}$ and $QR_{0.8}$, it was reported that the younger cultivars were associated to the quantile τ = 0.8, i.e., those with higher yields and more responsive conditions indicating that genetic improvement over the last 50 years resulted in an increase in both the productivity and the adaptability of cultivars.*
Key words: *gene-environment (GxE) interaction, Phaseolus vulgaris L., genetic improvement, quantiles, regression models.*

Análise da adaptabilidade de cultivares de feijão preto por meio de regressão quantílica

RESUMO: *Neste estudo objetivou-se utilizar a regressão quantílica (RQ) para caracterizar o efeito do parâmetro de adaptabilidade ao longo de toda a distribuição da variável produtividade em cultivares de feijão preto lançadas por diferentes instituições nacionais de pesquisa nos últimos 50 anos. Para tanto utilizou-se 40 cultivares desenvolvidas pelos programas brasileiros de melhoramento genético entre os anos de 1959 a 2013. Inicialmente foram ajustados modelos de RQ considerando três quantis (τ=0,2, 0,5, 0,8). Posteriormente, com os intervalos de confiança verificou-se que os modelos quantílicos τ=0,2 e 0,8 ($RQ_{0,2}$ e $RQ_{0,8}$) apresentaram diferenças quanto ao parâmetro de adaptabilidade e produtividade média. Finalmente, por meio do agrupamento das cultivares em um dos dois grupos definidos a partir de $RQ_{0,2}$ e $RQ_{0,8}$, constatou-se que as cultivares mais novas foram associadas ao quantil τ = 0,8, ou seja, aquelas com maiores produtividades e mais responsivas as condições ambientais indicando que o melhoramento ao longo dos últimos 50 anos possibilitou o incremento tanto na produtividade quanto na adaptabilidade das cultivares.*
Palavras-chave: *Interação GE, Phaseolus vulgaris L., melhoramento genético, quantis, modelos de regressão.*

INTRODUCTION

Brazil is the world's largest producer and consumer of beans (*Phaseolusvulgaris* L.) and reached 3.39 million tons in the 2016/2017 harvest (CONAB, 2017).Genetic improvement has contributed significantly to this production (or productivity) growth over the last decades.

In a genetic improvement program, when the objective is to recommend genotypes for cultivation, it is necessary to consider the interaction between genotype and environment (GxE). The GxE interaction is defined as the differential of the genotype response in connection with the environmental variation (COUTO et al., 2015). Effect of the GE interaction can be reduced by recommending more stable and well-adapted genotypes to be used in different environments through adaptability and phenotypic stability analyses.

In order to recommend genotypes with wide adaptation, there are a large number of studies on the adaptability and stability of bean cultivars (PEREIRA et al., 2009; SILVA et al., 2013). Recently, aiming to evaluate the increase in productivity and the adaptation and predictability of black bean cultivars, BARILI et al. (2015) estimated the average grain yield as well as the adaptability and phenotypic stability parameters of genotypes developed by the main Brazilian genetic improvement programs between 1959 and 2013. According to these

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researchers, genetic improvement programs have contributed to an increase of productivity as new cultivars are recommended.

Although interesting, such studies evaluate the adaptability in average terms, i.e., the correlation between environmental variation (X) and phenotypic response (Y) is explained by conditional expectation E(Y|X). In order to obtain information on different levels of the productivity variable, BARROSO et al. (2015) proposed the use of quantile regression (KOENKER & BASSET, 1978) for adaptability and stability studies considering 92 genotypes of alfalfa (*Medicago sativa L.*) assessed in 20 different environmental conditions. In order to explain the functional relationship between the environmental variation (X) and the phenotypic response (Y), this method, unlike the methods based on linear regression (EBERHART & RUSSELL, 1966) provides a generalized explanation for any quantile of phenotypic values. Therefore, the quantile regression (QR) may be used in all situations that the usual regression methods can be applied. However, it allows that more detailed information about the phenomenon under study is gathered (NASCIMENTO et al., 2018; PUIATTI et al., 2018). Specifically, unlike the study carried out by BARILI et al. (2015), if we consider the entire set of genotypes under study for the adjustment, they were able to characterize the effect of the adaptability parameter along the entire distribution of observed productivity values.

In view of the above mentioned, the present study aimed to characterize the adaptability of black bean cultivars recommended by different national research institutes over the last 50 years (from 1959 to 2013), according to the distribution of the observed values of grain yield, from of the quantile regression analysis (QR).

MATERIALS AND METHODS

We used data from experimental trials conducted at the Experimental Stations of the Universidade Federal de Viçosa (UFV) in the municipalities of Viçosa (latitude: 20º 45‘ 14“ S, longitude: 42º 52’ 55” W and altitude: 648m) and Coimbra, state of Minas Gerais (MG), southeast Brazil (latitude 20º 51’ 24” S, longitude 42º48’10”W, and altitude of 720m) during the drought crop and winter crops of 2013 characterizing 4 different environments. In these experiments, which consisted of a randomized blocks with three replicates, the grain yield (kg.ha^{-1}) of 40 black bean cultivars developed by the Brazilian genetic improvement programs between 1959 and 2013 was evaluated (Table 1).

Initially, the analysis of joint variance was performed to detect any GxE interaction. Once a GxE interaction was detected, we used the QR (KOENKER & BASSET, 1978) to characterize the adaptability of 40 black bean cultivars as suggested by BARROSO et al. (2015) for adaptability and stability studies. It should be emphasized that the concept of adaptability used in QR models is similar to the one described by EBERHART & RUSSELL (1966); i.e., adaptability refers to the ability of cultivars to benefit from the environment.

BARROSO et al., (2015) suggested that the following model of quantile regression is used in studies of adaptability and phenotypic stability:

$$Y_{ij} = \beta_{0i}(\tau) + \beta_{1i}(\tau)I_j + \varepsilon_{ij} \tag{1}$$

in which Y_{ij} are the grain yield values of the cultivar evaluated in j environments; I_j are the values of the coded environmental index; $\beta_{0i}(\tau)$ refers to the intercept of each cultivar (average productivity); $\beta_{1i}(\tau)$ is the coefficient of regression of each cultivar (parameter of adaptability), and is the same indicator of the effect of environmental improvement in quantiles of the distribution of productivity; and τ indicates the quantile of interest.

In the present study, unlike the study carried out by BARROSO et al. (2015), quantile models are adjusted considering all cultivars simultaneously; i.e., the adjusted model is given by:

$$Y_k = \beta_0(\tau) + \beta_1(\tau)I_k + \varepsilon_k \tag{2}$$

in which are the grain yield values of all cultivars evaluated in the k environments; I_k are the values of the coded environmental index; $\beta_0(\tau)$ refers to the intercept (average productivity); $\beta_1(\tau)$ is the regression coefficient (parameter of adaptability), and is the same indicator of the effect of environmental improvement on the quantiles of productivity distribution; and indicates the quantile of interest. Therefore, we are able to study the effect of the adaptability parameter along the distribution of the phenotypic values. Three quantiles, $\tau = 0.1, 0.5$ and 0.8, were considered.

Adjusted quantile regression for this study consisted of obtaining the estimates of the parameters $\beta(\tau) = [\beta_0(\tau), \beta_1(\tau),]^T$ of the 40 cultivars assessed in 4 differents environments (160 observations in total) by means of the solution of the following optimization problem:

$$\beta(\tau) = argmin_{\beta}\left\{\sum_{k=1}^{160} \rho_{\tau}[Y_k - \beta_0(\tau) - \beta_1(\tau)I_k]\right\}$$

The check function (KOENKER & BASSETT, 1978), ρ_{τ} (.) is given by:

$$\rho_{\tau}[Y_k - \beta_0(\tau) - \beta_1(\tau)I_k] = \begin{cases} \tau[Y_k - \beta_0(\tau) - \beta_1(\tau)I_k], & if\ Y_k - \beta_0(\tau) - \beta_1(\tau)I_k \geq 0 \\ -(1-\tau)[Y_k - \beta_0(\tau) - \beta_1(\tau)I_k], & otherwise. \end{cases}$$

In order to verify that the coefficients of the quantile regression model ($\beta_0(\tau)$ and $\beta_1(\tau)$) differ between the equations adjusted for the three quantiles (τ = 0.2, 0.5, 0.8) the confidence intervals for the 3 models were obtained. The 95% confidence intervals were constructed based on the ranks inversion test since it is mildly affected by problems of heterogeneity (KOENKER, 1994).

Finally, after adjustment and construction of the confidence intervals of the different models, each cultivar was classified into one of the groups formed, defined by different regression coefficients (adaptability parameter).The criterion used to insert the cultivar in one of the groups previously defined by means of the confidence interval was the lowest value of the Euclidian distance between the grain yield value of the same and the value estimated by the adjusted QR models. This procedure aimed the formation of groups that present different adaptability patterns throughout the distribution of phenotypic values. As a result, we are able to assess if newer genotypes are associated with the adjusted equation for high values of grain yield.

All analyses were performed using the software R (R CORE TEAM, 2018).The adjustment of the QR model was performed using the *rq* function of the quantreg package (KOENKER et al., 2017), and the Euclidean distance calculation was performed by means of the function *dist* from the R software base.

RESULTS AND DISCUSSION

The analysis of combined variance revealed a significant effect of all factors, showing a differentiated response of bean cultivars to

Table 1 - Identification of 40 black bean cultivars (*Phaseolus vulgaris L.*) grown by research institutes in Brazil.

Cultivar	Year	Institute*	QR	Cultivar	Year	Institute*	QR
Rico 23	1959	UFV	0.2	Ouro Negro	1992	EMBRAPA	0.2
Rio Tibagi	1971	IAPAR	0.2	Onix	1992	EMGOPA	0.2
Capixaba Precoce	1980	EMCAPA	0.2	BR- IPA 10	1992	IPA	0.2
Moruna	1980	IAC	0.2	IAPAR 65	1993	IAPAR	0.2
IRAÍ	1981	IPAGRO	0.2	Xamego	1993	EMGOPA	0.2
Milionário 1732	1983	EPAMIG	0.2	IAC-Una	1994	IAC	0.8
Rico 1735	1983	EPAMIG	0.2	IPR Uirapurú	2000	IAPAR	0.8
IAPAR 8-Rio Negro	1983	IAPAR	0.2	BRS Valente	2001	EMBRAPA	0.8
BR-2 Grande Rio	1985	PESAGRO	0.2	IPR Graúna	2002	IAPAR	0.8
BR-3 Ipanema	1985	PESAGRO	0.2	BRS Campeiro	2003	EMBRAPA	0.8
BR 1- Xodó	1985	PESAGRO	0.2	BRS Grafite	2003	EMBRAPA	0.8
FT 120	1986	FT-Sementes	0.2	BRS Supremo	2004	EMBRAPA	0.8
IAPAR 20	1987	IAPAR	0.2	IAC-Tunã	2005	IAC	0.8
BR-IPAGRO 2-Pampa	1989	EMCAPA	0.2	BRS Esplendor	2006	EMBRAPA	0.8
BR-IPAGRO 1-Macanudo	1989	IPAGRO	0.2	IPR Gralha	2006	IAPAR	0.8
BR 6-Barriga verde	1990	EMPASC	0.2	IPR Tiziu	2006	IAPAR	0.8
IAPAR 44	1990	IAPAR	0.2	BRS Expedito	2007	EMBRAPA	0.8
Preto Uberabinha	1990	IPEACO/MG	0.2	IPR Tuiuiu	2010	IAPAR	0.8
Varre-Sai	1991	PSAGRO/RJ	0.2	VP 22	2013	UFV	0.8
Diamante Negro	1991	EMBRAPA	0.8	VP 33	2013	UFV	0,8

*UFV: Federal University of Viçosa; IAPAR: Agronomic Instituto of Paraná; EMCAPA: Capixaba Company of Agricultural Research; IAC: Agronomic Institute; IPAGRO: Institute of Agronomic Research; EPAMIG: COMPANY OF AGRICULTURAL RESEARCH OF MINAS GERAIS; PESAGRO: Agricultural Research Company of RJ; EMPASC: Catarinense Company of Agricultural Research; IPEACO/MG: Agricultural Research and Experimentation Institute of Central-West Brazil; EMBRAPA: Brazilian Agricultural Research Corporation.

environmental changes as presented in table 2 from BARILI et al. (2015). Differentiated yield response of bean genotypes in different environments was also observed by RIBEIRO et al. (2008) and MOURA et al. (2013).

The estimated values for $\hat{\beta}_0(\tau)$ and $\hat{\beta}_1(\tau)$ and their respective confidence intervals (α=0.05) for the 3 models adjusted by QR are shown in Figures 1A and 1B. According to figures 1A and 1B, it is possible to observe that the intercept and the adaptability parameter presented an increasing trend along the distribution (quantiles) of the phenotypic values of productivity.

In general, the 95% confidence intervals, presented in Figure 1, indicated that both the average productivity, $\hat{\beta}_0(\tau)$, and the adaptability parameter differ along the distribution of phenotypic productivity values. Specifically, average productivity increases as assessed quantiles increase accordingly. Moreover, it can be seen that for the 3 quantiles evaluated (τ = 0.2, 0.5, 0.8), the average productivity, $\hat{\beta}_0(\tau)$ differs from the average productivity of the experiment (2797.7 kg.ha^{-1}, dashed line) (Figure 1A). In terms of the adaptability parameter, it is observed that it presents different values of the unit (general adaptability according to EBERHART & RUSSEL, 1966) for the extreme quantile (τ = 0.2 and τ = 0.8) of the distribution of phenotypic values of productivity (Figure 1B). These results indicated that less productive cultivars have a lower response to environmental improvement when compared to more productive cultivars (Figure 1B). The estimated equations for the quantiles 0.2 and 0.8 were, respectively, y_k = 2359.18+0.85 I_k and y_k = 3286.10+1.24I_k and are shown in figure 2.

After observing differences in terms of the adaptability parameter for the extreme quantiles (τ = 0.2 and 0.8), each cultivar was then classified into one of the two groups using as criterion the lowest value of the Euclidean distance between the productivity value of grains of the same and the value estimated by the adjusted QR models. After the grouping, a total of 24 and 16 cultivars were classified in groups $QR_{0.2}$ and $QR_{0.8}$, respectively (Table 1).In addition, it was noted that the cultivars more recently are those that present higher productivity, and therefore, are more responsive to environment improvement (Table 1).

Specifically, the cultivars recommended until 1993 were classified as belonging to the group represented by the model $QR_{0.2}$ whereas those most recently recommended (after 1993), were classified in the group represented by model $QR_{0.8}$. In view of these results, we noted that the most recent cultivars (those that were introduced over the last 15 years) present higher productivity and are more responsive to environmental improvement. BARILI et al. (2015) noted that genetic improvement programs have contributed to the increase of grain yield with the recommendation of new cultivars.

According to RAMALHO et al. (2012), the increase in grain yield in the bean crop in the country observed in the last decades reflect a continuous action of the Brazilian research institutes in activities

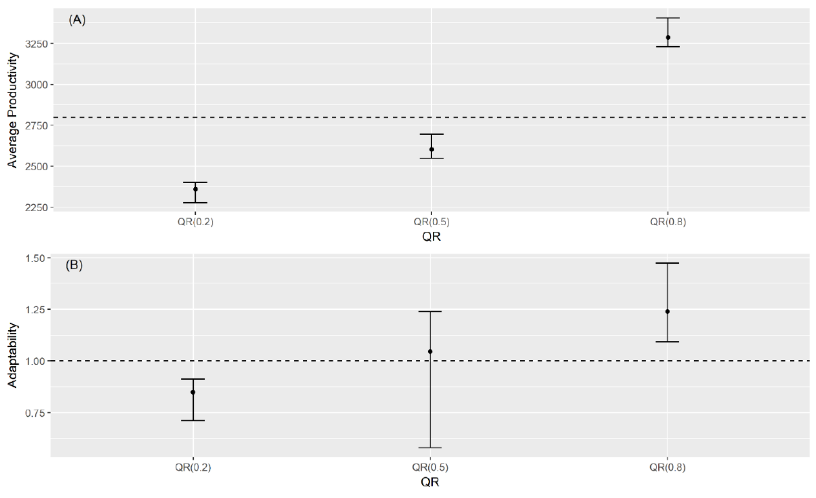

Figure 1 - Confidence intervals (α = 0.05) and estimates of average grain yield (Kg.ha-1) (A) and adaptability (B) of 40 bean cultivars released over the last 50 years.

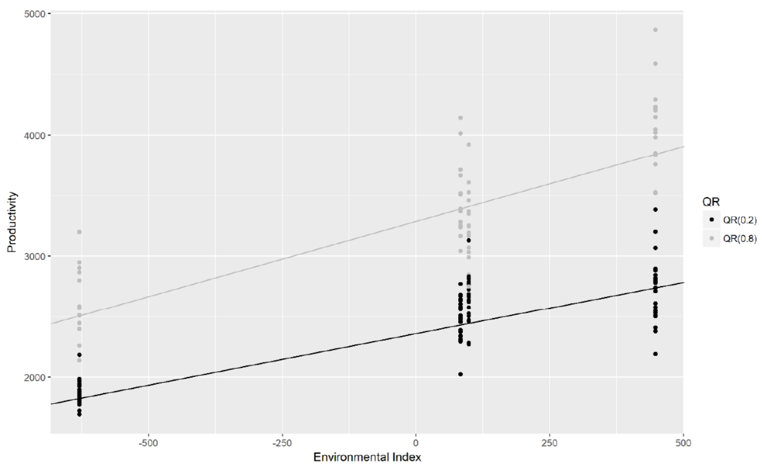

Figure 2 - Linear models adjusted for the quantiles τ = 0.2 (black line) and τ = 0.8 (gray line) of the average grain yield (kg.ha-1) of 40 bean cultivars launched over the last 50 years.

linked to the genetic improvement of beans. Studies on genetic progress conducted by MATOS et al. (2007), CHIORATO et al. (2010), FARIA et al. (2014), and BARILI et al. (2016) show genetic gains ranging between 1.07% and 3.26% per year.

It should be emphasized that, unlike the studies carried out by MATOS et al. (2007), CHIORATO et al. (2010), FARIA et al. (2014) and BARILI et al. (2016), the use of QR made it possible to obtain information about the effect of the adaptability parameter throughout the grain yield distribution; and therefore, how it changed over the last 50 years of genetic improvement.

CONCLUSION

The average productivity values and adaptability estimates of the recommended black bean cultivars over the last 50 years have an increasing behavior throughout this time span. The recently recommended cultivars were classified as belonging to the group $QR_{0.8}$ indicating that these cultivars have higher grain yield and are more responsive to environmental improvement than those recommended until 1993.

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DECLARATION OF CONFLICTING INTERESTS

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

AUTHORS' CONTRIBUTIONS

The authors contributed equally to the manuscript.

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