Genetic progress resulting from forty-three years of breeding of the carioca common bean in Brazil

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ABSTRACT. We aimed to evaluate 40 common bean cultivars recommended by various Brazilian research institutions between 1970 and 2013 and estimate the genetic progress obtained for grain yield and other agronomic traits. Additionally, we proposed a bi-segmented nonlinear regression model to infer the year in which breeding began to show significant gains in Brazil. The experiment was carried out in Viçosa/MG and Coimbra/MG, in the dry and winter seasons of 2013. For this, a randomized complete block design with three replications was employed. The following traits were evaluated: number of pods per plant (NPP); number of seeds per pod (NSP); 1000-seed weight

(W1000); grain yield (Yield); plant architecture (Arch); and grain aspect (GA). Genotypic means were estimated over years using linear mixed models, and genetic gains were estimated using bi-segmented nonlinear regression models. In summary, the methodology proposed in the present study indicated that bean breeding programs in Brazil began to influence Yield beginning in 1990, resulting in a gain of 6.74% per year (68.15 kg/ha per year). The years from which estimated genetic progress for NPP (5.62% per year), NSP (4.59% per year), W1000 (2.08% per year), and GA (1.36% per year) began to increase were 1994, 1990, 1989, and 1986, respectively.

Key words: *Phaseolus vulgaris* L.; Cultivars; Genetic gain; Agronomic traits; Bi-segmented regression

INTRODUCTION

Common bean (*Phaseolus vulgaris* L.) is one of the most important food legumes globally in terms of socioeconomic and nutritional importance (Benchimol et al., 2007). The carioca bean type was developed in Brazil in 1970. Currently, it is the type preferred by consumers, producers and breeders, and accounts for approximately 79% of the beans consumed in Brazil (Carneiro et al., 2012).

The majority of bean breeding programs in Brazil have concentrated their efforts on the improvement of carioca-type cultivars. The main institutions generating bean cultivars are those from the governmental (public) sector and have contributed to an increase in productivity of bean grain from 500 kg/ha (late 1970s) to 1000 kg/ha (2012-2013) (Conab, 2014). According to Lotze-Campen et al. (2015), the global demand for agricultural products is increasing, and the most viable solution to meet this demand is an increase in agricultural productivity that is provided by genetic improvement. Over the past 50 years, the largest contribution to the increase in global agricultural production was due to the increase in grain yields, which accounts for approximately 80% of increased production (FAO, 2010).

Costs reductions, increased bean nutritional quality and the extensive area planted to beans in Brazil are strongly attributed to improvements gained through breeding (Ramalho et al., 2012; Veloso et al., 2015). Some studies have been conducted to estimate the genetic progress of bean crops in Brazil (Elias et al., 1999; de Matos et al., 2007; Chiorato et al., 2010; de Faria et al., 2013 and de Faria et al., 2014) and other countries (Singh et al., 2007); however, the genetic materials which have been evaluated are only lines and/or cultivars belonging to a particular breeding program. Moreover, most of these studies included data from trials termed "value for cultivation and use", where every 2 to 3 years lines are added or removed and the experimental structures are modified, thus affecting the estimation of efficiency. Furthermore, according to de Faria et al. (2014), these studies are restricted to grain yield and do not address other traits that are considered important in the bean production industry.

Thus, it is appropriate to evaluate the efficiency of bean breeding programs in Brazil as a whole, comparing recommended historical and modern cultivars from a substantial breeding time period side-by-side in the same experiment. It is also important to consider other relevant traits, including primary yield components, cycle vegetative, plant architecture, and the technological quality of grains (Moda-Cirino et al., 2012).

The aim of this study was to evaluate 40 common bean cultivars recommended by various Brazilian research institutions between 1970 and 2013 and estimate the genetic progress obtained for grain yield and other agronomic traits. Additionally, we also propose a bi-segmented nonlinear regression model to infer about the year in which breeding began to show significant gains in Brazil.

MATERIAL AND METHODS

Experiments were conducted at Universidade Federal de Viçosa experimental stations in Viçosa, MG, Brazil (20°45'14"S, 42°52'55"W, 648 m asl) and Coimbra, MG, Brazil (20°51'24" S, 42°48'10" W, 720 m asl), during the 2013 dry and winter seasons.

Forty carioca cultivars recommended between 1970 and 2013 by various research institutions in Brazil were evaluated. Cultivars were generally chosen based on scientific and breeder reports. Initial seed samples were obtained from the relevant institutions and multiplied in order to standardize germination rates during the experiments. Experiments were performed in a randomized complete block design with three replicates per cultivar. The plots consisted of four 3 m rows with a spacing of 50 cm between rows and 15 seeds sown per meter. Fertilization was applied according to the results of soil analyses to ensure ideal conditions for development and production. Insect pests, invasive plants, and weeds were controlled as needed according to official recommendations for common bean.

The following traits were evaluated: number of pods per plant (NPP), obtained by counting a sample of six plants per plot; number of seeds per pod (NSP), calculated as the total number of seeds divided by the total number of pods; 1000-seed weight (W1000) (g), obtained by harvesting and weighing 1000 seeds taken at random from the plot; grain yield (Yield) (kg/ha), obtained by weighing the grain of the two inside rows of the plot, adjusted to 13% moisture and calculated as kg/ha; plant architecture (Arch), evaluated on a 1-5 rating scale (Ramalho et al., 1998), with 1 for erect plants with high insertion of the first pod and branch angle <45°, and 5 for very prostrate plants; and grain aspect (GA), evaluated on a 1-5 rating scale, where 1 indicates cream-colored grains with light brown streaks, light background, without hilum, not flattened and with mean grain 100-weight of 25-27 g, and 5 for grains with cream to brown color, with dark brown streaks, dark seed coat, with hilum, flattened and with mean grain 100-weight <22 g (Ramalho et al., 1998).

Statistical analysis

Data were analyzed using the following model:

$$Y_{ijk} = m + G_i + B_k + A_j + GA_{ij} + E_{ijk} \quad \text{(Equation 1)}$$

where Y_{ijk} is the observed value of the i^{th} genotype in the k^{th} block and in the j^{th} environment; m is the general mean; G_i is the random effect of the i^{th} genotype (i = 1, 2, 3, ..., 40); A_j is the random effect of the j^{th} environment (j = 1, 2, 3, 4); $GA_{(ij)}$ is the random effect of the interaction between the i^{th} and j^{th} environments; B_k is the random effect of block k (k = 1, 2, 3); and E_{ijk} is the experimental error. It was assumed that $G \sim N(0, \sigma^2_G)$; $A_j \sim N(0, \sigma^2_A)$; $GA_{ij} \sim N(0, \sigma^2_{GA})$; $B_k \sim N(0, \sigma^2_k)$ and $E_{ijk} \sim N(0, \sigma^2_e)$.

This model was fitted using the PROC MIXED command in the SAS® software (SAS 2014, version 9.4), and genotype means were compared using the test of Scott and Knott (1974) in the Genes software (Cruz, 2013).

Aiming to infer the true year (x_0) in which common bean improvement began realizing significant gains, we proposed to fit segmented regression models to the trajectory of trait means over the year in which the cultivars were recommended. Given the behavior of these trajectories, we opted for the following nonlinear-plateau (LP) model:

$$y_i = \begin{cases} p + e_i, & \text{if } x_i < x_0 \\ b_0 + b_1 x_i + e_i, & \text{if } x_i \geq x_0 \end{cases} \quad \text{(Equation 2)}$$

where y_i is the trait mean observed in each year (x_i = 1, 2, …, 43); b_0 is the intercept; b_1 is the slope; p is the plateau before the effective genetic progress; x_0 is the parameter to be estimated and e_i is the residual term, assumed as $e_i \sim N(0,\sigma_e^2)$. The LP model is nonlinear when x_0 is treated as unknown, thus the PROC NLIN tool of the SAS software was used to fit this model using an iterative least squares procedure based on the Gauss-Newton algorithm.

The point (x_0) corresponds to the year in which genetic progress was estimated to have begun. In the model in question, the linear regression coefficient (b_1) estimates the genetic progress per year from the initial breakpoint. The average annual genetic progress (GP_a) was calculated as a percentage for each characteristic by dividing the regression slope (b_1) by the regression intercept (b_0) according de Matos et al. (2007):

Years were coded in ascending order whereby year 1 represents 1970 and year 43 represents 2013, corresponding to 43 years of carioca bean breeding.

RESULTS AND DISCUSSION

Analysis of variance

A significant genotype x environment (G x E) interaction effect was observed for all evaluated traits except NSP (Table 1). A significant G x E interaction is common in experiments of this nature given that each genotype has a unique genetic constitution, thus leading to different behaviors in different environments. Significant G x E interactions in NPP, W1000, Yield, Arch and GA were also observed by Zilio et al. (2011), do Vale et al. (2012), de Faria et al. (2013), and Moura et al. (2013). Moura et al. (2013) also found no significant G x E interaction for NSP, indicating that this trait is less influenced by the environment.

Genetic progress of grain yield

Beginning in 1990, Brazilian breeding programs started to make available a larger number of carioca bean cultivars (Table 2). Similarly, 1990 was observed to have been the effective beginning of increased GP_a for yield grain (Figure 1A). From 1990 to 2013, GP_a for bean grain yield in Brazil was 6.74% per year, which corresponds to 68.15 $kg \cdot ha^{-1} \cdot year^{-1}$. Table 2 shows mean grain yields of cultivars and the years in which each was recommended for grower use. For example, cultivars recommended in the last five years (2009-2013) presented grain yields of over 3700 kg/ha, including IAC Formoso (4106 kg/ha), BRSMG Madrepérola

Table 1. Summary of analysis of variance regarding the grain yield (Yield), grain aspect (GA), plant architecture (Arch), number of pods per plant (NPP), number of grains per pod (NSP), and 1000 seed weight (W1000) of carioca bean cultivars recommended in Brazil between 1970 and 2013. Viçosa and Coimbra, 2013 dry and winter seasons.

Source of variation	d.f.	QM					
		Yield	GA	Arch	NPP	NSP	W1000
Blocks	2	511,065.7*	0.03^{ns}	0.29^{ns}	1.71^{ns}	0.35^{ns}	970.31**
Cultivars	39	4,469,875.8**	10.24**	3.08**	61.82**	6.11**	8,626.16**
Environment	3	25,911,051.8**	5.40**	7.21**	143.55**	1.86**	47,732.09**
Culti. x Envir.	117	181,346.1**	0.51**	0.41**	3.54**	0.25^{ns}	332.05**
Residue	318	118,526.8	0,18	0.15	2.45	0.31	154.15
Mean	-	3,100	3.07	3.91	14.42	4.61	233.57
CV (%)	-	11.10	13.59	9.82	10.85	11.99	5.31

**,*Significant at 1 and 5% probability, respectively, by the F-test. ns = non-significant; d.f. = degrees of freedom; CV = coefficient of variance

Table 2. Means of grain yield (Yield), grain aspect (GA), plant architecture (Arch), number of pods per plant (NPP), number of grains per pod (NSP) and 1000 seed weight (W1000) of carioca bean cultivars recommended in Brazil between 1970 and 2013. Viçosa and Coimbra, 2013 dry and winter seasons.

Cultivars	Institution	Year	Code	Yield (kg/ha)	GA	Arch	NPP	NSP	W1000 (g)
Carioquinha	IAC	1970	1	2316^c	4.1^e	4.5^d	12.2^c	3.7^c	198.9^c
Carioca 80	IAC	1980	10	2457^c	4.0^e	4.6^d	12.1^c	3.8^c	196.6^c
IAPAR 16	IAPAR	1986	16	2155^d	5.0^f	4.8^d	11.2^c	3.7^c	198.0^c
Rio doce	EMCAPA	1987	17	2381^c	4.2^e	4.7^d	12.3^c	3.6^c	194.9^c
IAC Carioca	IAC	1987	17	2295^c	3.4^d	4.4^c	12.3^c	3.6^c	200.8^c
Carioca 1070	IAC	1989	19	1967^d	4.1^e	4.6^d	12.0^c	3.6^c	182.6^c
IAPAR 31	IAPAR	1991	21	2495^c	5.0^f	4.3^c	12.5^c	3.8^c	205.9^c
Aporé	Embrapa	1992	22	2457^c	4.3^e	4.8^d	12.3^c	3.6^c	209.8^c
FT bonito	FT-sementes	1992	22	2428^c	3.0^c	4.3^c	11.9^c	3.8^c	214.9^c
IAPAR 57	IAPAR	1992	22	2306^c	4.0^e	2.7^a	12.8^c	3.6^c	209.8^c
Pérola	Embrapa	1996	26	2986^b	2.1^b	4.1^c	11.6^c	4.3^b	256.5^a
Rudá	Embrapa	1994	24	2109^d	4.1^e	4.4^c	12.6^c	3.8^c	191.3^c
BR-IPA 11-Brígida	IPA/PE	1994	24	2465^c	4.0^e	4.8^d	11.2^c	3.7^c	194.2^c
IAC - Carioca Pyatã	IAC	1994	24	2838^b	3.0^c	3.9^c	14.6^b	4.6^b	211.3^c
IAC - Carioca Akytá	IAC	1996	26	3017^b	3.6^d	4.3^c	15.5^b	4.8^b	206.8^b
IAPAR 81	IAPAR	1997	27	2975^b	2.8^c	3.9^c	11.9^c	4.1^b	233.0^b
BRSMG Talismã	Embrapa	2002	32	3135^b	2.9^c	4.5^d	15.0^b	4.8^b	236.7^b
BRS Requinte	Embrapa	2003	33	3133^b	2.9^c	4.1^c	15.3^b	5.2^a	231.3^b
BRS Pontal	Embrapa	2003	33	3373^b	3.0^c	4.8^d	14.3^b	5.3^a	244.8^b
SCS Guará	EPAGRI	2004	34	3091^b	2.0^b	4.3^c	13.8^b	4.6^b	239.9^b
IPR Saracura	IAPAR	2004	34	3210^b	2.1^b	4.1^c	14.3^b	4.8^b	244.5^b
IPR Colibri	IAPAR	2004	34	3015^b	3.6^d	4.0^c	14.3^b	4.6^b	239.0^b
BRS Majestoso	Embrapa	2005	35	3385^b	3.0^c	4.1^c	16.6^a	4.8^b	245.9^b
BRSMG Pioneiro	Embrapa	2005	35	3335^b	3.3^d	4.3^c	15.2^b	4.9^b	235.0^b
IAC Votuporanga	IAC	2005	35	3361^b	3.6^d	4.1^c	15.0^b	4.9^b	243.6^b
IAC-Ybaté	IAC	2005	35	3335^b	3.6^d	4.3^c	14.3^b	4.7^b	234.6^b
IAC-Apuã	IAC	2005	35	3544^a	3.3^d	4.2^c	14.7^b	4.7^b	241.4^b
BRS Cometa	Embrapa	2006	36	3172^b	3.0^c	2.5^a	14.7^b	4.9^b	250.9^b
IPR Eldourado	IAPAR	2006	36	3195^b	2.3^b	4.3^c	14.4^b	4.7^b	246.3^b
IAC Alvorada	IAC	2007	37	3476^a	1.7^a	4.0^c	14.0^b	4.7^b	264.5^a
IPR 139	IAPAR	2007	37	3657^a	2.1^b	3.4^b	14.7^b	4.8^b	254.8^a
IPR Tangará	IAPAR	2008	38	3611^a	2.1^b	3.5^b	15.0^b	5.2^a	263.7^a
BRS Estilo	Embrapa	2009	39	3924^a	2.4^b	3.6^b	17.8^a	5.8^a	264.6^a
IAC Formoso	IAC	2011	41	4106^a	1.7^a	4.6^d	18.0^a	5.6^a	273.4^a
IPR Campos Gerais	IAPAR	2011	41	3884^a	2.2^b	3.8^b	17.5^a	5.6^a	255.8^a
BRSMG Madrepérola	Embrapa	2012	42	3954^a	1.1^a	4.3^c	18.1^a	5.8^a	273.9^a
BRS Notável	Embrapa	2013	43	3929^a	3.3^d	3.4^b	19.4^a	5.7^a	261.8^a
VC15	UFV	2013	43	4111^a	1.9^a	4.7^d	18.4^a	5.8^a	264.0^a
IPR Andorinha	IAPAR	2013	43	3708^a	2.6^c	4.3^c	17.3^a	5.6^a	263.7^a
IAC Imperador	IAC	2013	43	3742^a	2.7^c	4.3^c	18.5^a	5.5^a	265.3^a

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

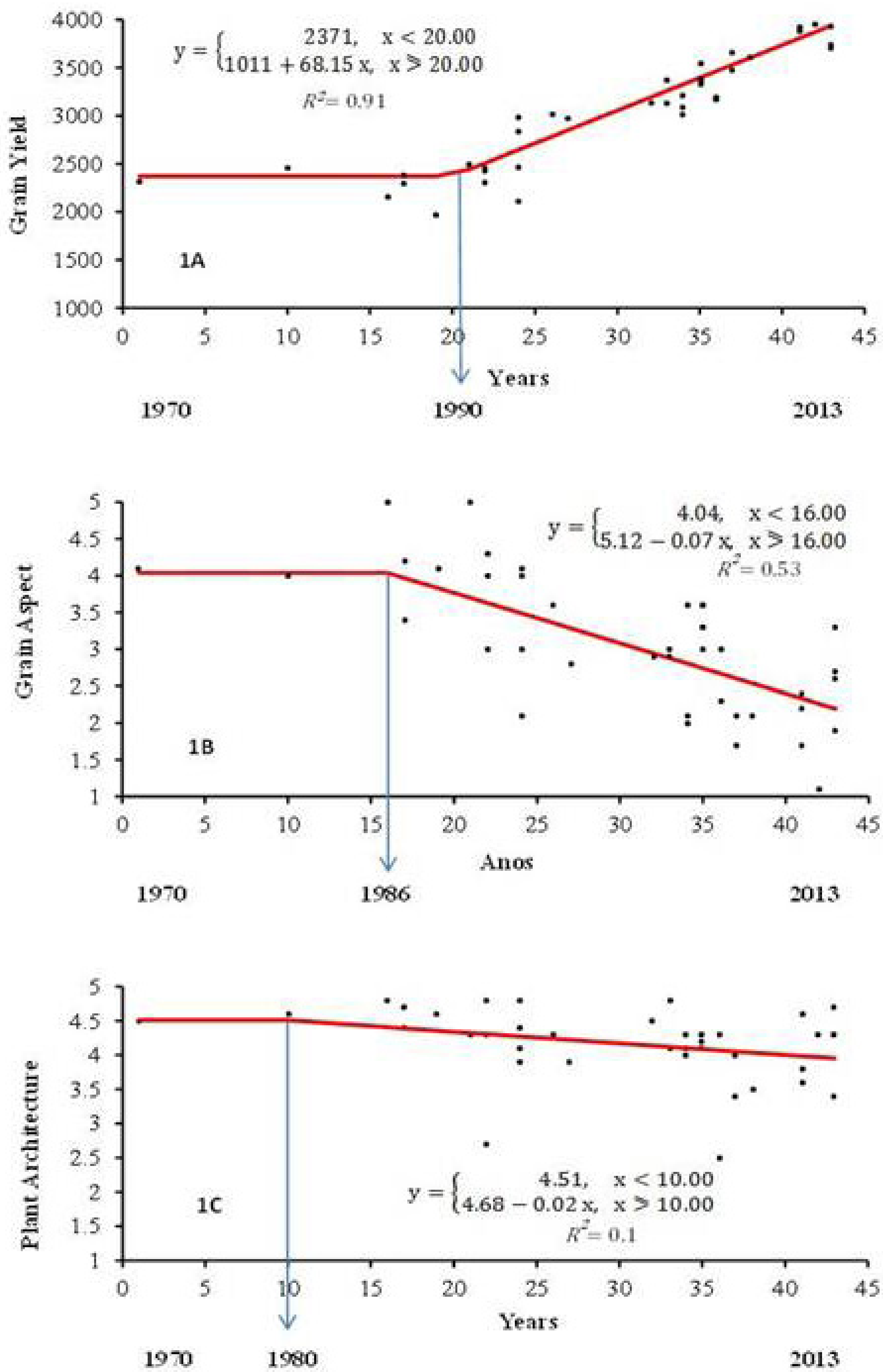

Figure 1. Annual genetic progress for yield grain (**A**), grain aspect (**B**) and plant architecture (**C**) of carioca cultivars recommended between 1970 and 2013 through bi-segmented linear regression.

(3954 kg/ha), BRS Notável (3929 kg/ha), BRS Estilo (3924 kg/ha), IPR Campos Gerais (3884 kg/ha), IAC Imperador (3742 kg/ha), IPR Andorinha (3708 kg/ha), and VC 15 (in pre-release) (4111 kg/ha). These findings demonstrate the commitment of bean breeders to developing improved cultivars that have increased grain yield.

Genetic gain estimates for grain yield in Brazil are often presented in the literature (Abreu et al., 1994; Elias et al., 1999; de Matos et al., 2007; Chiorato et al., 2010; de Faria et al., 2013; and de Faria et al., 2014). The annual genetic progress obtained in these studies ranged from 0.72% (de Faria et al., 2013) to 4.36% per year (de Matos et al., 2007). In general, differences in the statistical methodologies and the aims of breeding programs can be understood as main reasons why the estimates obtained in these studies were less than those reported in the present study.

Genetic progress of grain aspect and plant architecture

The genetic progress for grain aspect (where a lower score indicates higher grain quality), although slight, was significant, reducing the score by -0.07 (or -1.36%) per year from 1986 through 2013 (Figure 1B). Similarly, de Faria et al. (2013) reported a 2.3% improvement per year for grain aspect over a period of 22 years of breeding for Embrapa Rice and Bean. The Pérola cultivar stands out in the market due to its excellent grain quality, and is considered a standard for this trait (Carbonell et al., 2010). On a rating scale of 1 to 5, the Pérola cultivar scored 2.1. As such, cultivars with equal or lower scores may be considered to have excellent grain aspect (Table 2). In general, cultivars recommended in the first decades presented completely non-standard grains. Conversely, several cultivars from the most recent two decades had grain aspect scores that were equivalent or even superior to Pérola, including SCS Guará (2.0), IAC Alvorada (1.7), IAC Formoso (1.7), BRSMG Madrepérola (1.1) and VC 15 (1.9). Cultivars with high yield potential were restricted in the past due to unfavorable grain characteristics (Ramalho and Abreu, 2015), highlighting again the need of breeding programs which focus on developing cultivars that show an acceptable grain pattern.

Genetic progress for plant architecture was not significant ($P < 0.01\%$ and 0.05) during the studied period. However, Arch data from the cultivars recommended between 1970 and 2013 were plotted in order to demonstrate phenotypic trends (Figure 1C).

Based on calculated means (Table 2), only IAPAR 57 (1992) and BRS 9435 Cometa (2005) cultivar had plant architecture scores less than 3.0. Similarly, Del Peloso et al. (2006) found that BRS 9435 Cometa was the only erect cultivar of all cultivars in their study. Erect plants allow mechanical harvesting with reduced losses, reduced incidence of disease and improved grain quality (de Souza et al., 2013; Ramalho and Abreu 2015). For this reason, and by the results obtained, the need for greater efforts from breeding programs towards the development of cultivars with better plant architecture is evident. However, selection of erect plants is challenging, as many component traits influence plant architecture and thus may influence character expression (Silva et al., 2013). In this way, plant breeders must develop more accurate evaluation techniques that better discriminate between superior and undesirable genotypes in order to maximize gains in a reduced time period (Oliveira et al., 2015).

Genetic progress in yield components: number of pods per plant, number of seeds per pod, 1000-seed weight

NPP, the primary component of grain yield, remained approximately 12.17 until 1994, after which there were progressive and significant yearly increases (Table 2 and Figure 2A). In 19 years (1994-2013) the increase was 5.62% per year, or 0.29 pods·plant^{-1}·year^{-1}. Cultivars recommended from 2000 to 2010 and from 2010 to 2013 showed an average increase of 3 to 5 pods per plant, respectively, when compared to cultivars recommended prior to 1994. According to Barili et al. (2011), NPP is the trait with the greatest potential for selection when the objective is to increase grain yield. As such, the selection of lines with higher NPP certainly contributed to the genetic progress observed in grain yield.

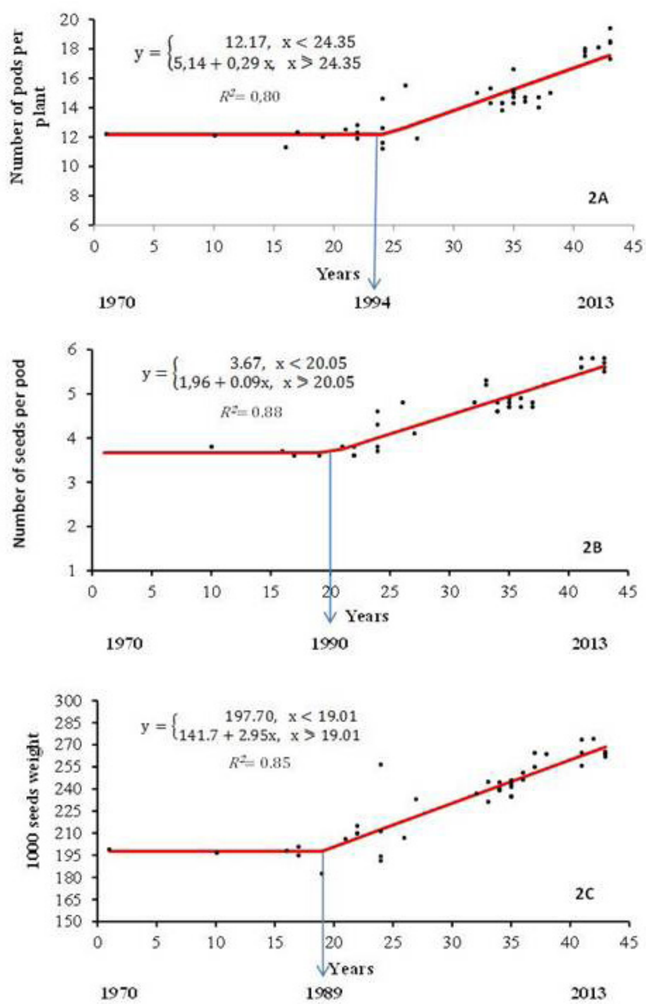

Figure 2. Annual genetic progress for number of pods per plant (**A**), number of seeds per pod (**B**) and thousand seed weight (**C**) of carioca cultivars recommended between 1970 and 2013 through bi-segmented linear regression.

Increases in NSP was also generally observed in cultivars recommended for use after 1990 (Figure 2B). Before 1990, few bean cultivars had been recommended by breeding programs, which helps explain the absence of genetic progress at that time. Whereas carioca bean emergence was met with increased preference among consumers, producers and breeders, breeding programs have focused on introgression of resistance to various pathogens in novel cultivars, neglecting other traits, such as NSP. Between 1990 and 2013, GP_a obtained for NSP was 4.59% per year, or 0.09 seeds·pod^{-1}·year^{-1}, resulting in a mean of 5.6 seeds per pod (Table 2) for the most recent cultivars (2010-2013).

Figure 2C shows that W1000 remained constant until 1989, and only after that time point was a significant increase in this trait observed. The genetic progress for W1000 in the period 1989-2013 was 2.08% per year, or a yearly increase of 2.95 g per thousand seeds. A preference for larger grains in the Brazilian market is also worth noting (de Faria et al., 2013). The carioca cultivar recommended in 1970 had been considered the standard for grain size (22 g per 100 seeds) until 1996, when the cultivar Pérola (27 g per 100 seeds) was recommended (Carbonell et al., 2010). de Faria et al. (2013) evaluated the genetic progress of the carioca common bean in Embrapa rice and common bean breeding programs between 1985 and 2006 and observed an annual gain of 0.31% for 100 seed weight. Ribeiro et al. (2003) evaluated bean cultivars in southern Brazil and reported a 0.58% annual gain. In these studies, genetic gain was estimated by the direct method using simple linear regression equations. As such, the results obtained in this study using bi-segmented regression were more expressive, given that these models allowed estimation of GP_a exactly when it occurred (after the cut-off year), instead of dissolving genetic gains into the period in which breeding gains were not efficient, such as between 1970 and 1990 for W1000 (Figure 2C).

Improved cultivars represent one of the most important contributions of agricultural research to Brazilian society, as they increase yield and production stability with no additional costs to farmers (Polizel et al., 2013). This has been reported in many bean breeding studies, as mentioned above. The present study made a global assessment and portrays the great contributions to genetic improvement of bean in Brazil, with significant gains in commercial grain quality, yield, and yield components. This is due to the substantial effort of research institutions in Brazil in activities related to breeding the plant.

CONCLUSIONS

In summary, the methodology proposed in the present study allowed conclusion that bean breeding programs in Brazil became effective from 1990 for grain yield, resulting in a gain of 6.74% per year (68.15 kg·ha^{-1}·year^{-1}). The years in which the estimated genetic progress for NPP (5.62% per year), NSP (4.59% per year), W1000 (2.08% per year), and GA (1.36% per year) became effective were 1994,1990, 1989 and 1986, respectively.

Conflicts of interest

The authors declare no conflict of interest.

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