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Genetic progress during 22 years of improvement of carioca-type common bean in Brazil

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ABSTRACT

Between 1984 and 2010, the program for the improvement of common bean coordinated by Embrapa Rice & Beans released 50 new cultivars at an average rate of 1.9 cultivars per year. Any breeding program must be periodically subjected to critical analysis with respect to its performance, seeking methodologies that can improve its effectiveness. In this context, the estimation of genetic progress is one of the options used in this analysis. The aim of the present study was to estimate the genetic progress in terms of grain yield and other agronomic traits achieved by the Embrapa program. These estimates represent the progress achieved during a 22-year period between 1985 and 2006 and totaling 11 biannual cycles of final assessments of the lines. Two types of field experiments were performed to assess the genetic progress: field experiments of lines and of cultivars. To perform the line experiments, the top three inbred lines from each of the 11 cycles evaluated comprised the 33 evaluated treatments. These evaluations were established in 20 environments and served to estimate the progress in yield, quality, and size of grains because these were the criteria applied to select the elite lines. The cultivar evaluations included the 10 cultivars recommended by the Brazilian Agricultural Research Corporation (Empresa Brasileira de Pesquisa Agropecuária – Embrapa) during the investigated period and were established in 21 environments. These evaluations served to estimate the improvements in the reaction to angular leaf spot, plant architecture, and resistance to lodging because cultivars usually exhibit superior phenotypes for such characteristics. The experimental design in all evaluations included completely randomized blocks with four replicates. The evaluations were performed during three sowing seasons (rainy, dry, and fall-winter) between 2008 and 2010. The results show the efficiency of the Embrapa program in improving the genetic makeup of common bean in Brazil between 1985 and 2006. The estimated improvement in grain yield was 17.3 kg ha^{-1} or 0.72% per year. Improvements were also found in plant architecture (2.0%), tolerance to lodging (2.0%), and grain quality (2.4%). There was no significant progress for the character weight of the 100 grains or for resistance to bacterial blight.

1. Introduction

Brazil is one of the main producers and consumers of common bean (*Phaseolus vulgaris* L.) worldwide, and for seven out of the last ten years, it ranked first in this regard (Food and Agriculture Organization, 2011). Common bean is one of the major components of the diet of the Brazilian population because it is an excellent source of protein (Vieira et al., 2005). It is cultivated in Brazil year round by small, medium, and large producers in subtropical and tropical ecosystems, including savannah (Cerrado biome), the Atlantic rainforest, and semi-arid areas, under different cropping systems, as either a monoculture or combined with other crops. In 2010, 2.7 million tons of common bean were produced in Brazil in an area of 2.1 million hectares, with productivity reaching 1285 kg ha^{-1} (Feijão, 2011).

Embrapa Rice & Beans coordinates a nationwide program for the genetic improvement of common bean that encompasses all of the producing areas in the country. The assessment of the

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common bean lines developed by this program is systematized in an organized national network that includes bean-producing states that together contribute more than 90% of the national output. This network evaluates the best lines in terms of yield, stability, and other desirable agronomic traits to produce cultivars that meet the requirements of the bean production chain.

The performance of any genetic improvement program must be subjected periodically to critical analysis to develop better methods to increase its efficacy. Estimates of genetic progress are one of the variables used for this purpose, and thus, several authors have estimated the genetic gain achieved by state-based genetic improvement programs for common bean in Brazil, e.g., in Minas Gerais (Abreu et al., 1994; Matos et al., 2007), in São Paulo (Chiorato et al., 2010), in Santa Catarina (Elias et al., 1999), in Paraná (Fonseca Júnior, 1997), and in Rio Grande do Sul (Antunes, 2000; Ribeiro et al., 2002). Estimates of the genetic progress in common bean have also been performed in other countries (Singh et al., 2007), as well as for other crops, such as rice, wheat, and soybean (De Vita et al., 2007; Jin et al., 2010; Peng et al., 2000; Tabien et al., 2008).

As a rule, there are two basic methods to estimate genetic progress: direct and indirect methods. The direct method uses field experiments with replicates to compare the estimates of grain yield and agronomic traits among genotypes developed in a given period of study. In most such studies, the estimates of progress are restricted to one or a few environmental conditions (Matos et al., 2007) and a few phenotypic characteristics. This approach limits the reach and representativeness of the results. Therefore, when using the direct method, wide-scope experimental assessments are needed to obtain consistent and representative estimates, i.e., those that represent the conditions of genotype × environmental interaction to which inbred lines and cultivars are subjected. When this requirement is met, the estimates produced by the direct method are most consistent, i.e., more reliable.

The field experiments of the common bean breeding program at Embrapa include a vast geographic region, covering a broad variety of soil types, climate and cultivation variations, including dry and wet seasons and transitions between them. This variability is necessary because the low utilization rate of commercial seeds of the common bean in Brazil means that the seed companies usually favor broadly adapted cultivars, which are more likely to be traded. This concept is supported by the fact that the most planted cultivars in terms of area are precisely those with the greatest range of adaptation.

The breeding program of Embrapa Rice and Beans until then had not been evaluated under the aspect of genetic progress, and considering that the carioca bean is the most planted type of bean in Brazil, accounting for approximately 70% of the total beans consumed by the Brazilian population (Del Peloso and Melo, 2005). Therefore, the aim of the present study was to obtain average estimates of genetic progress in terms of grain yield and other agronomic traits of carioca-type common bean within the context of the Brazilian nationwide genetic improvement program using the direct method.

2. Materials and methods

The 22-year period between 1985 and 2006 was chosen to estimate the genetic progress of *P. vulgaris* L. The genotypes to be used in the evaluations were divided into 11 biannual cycles of final assessments of the lines.

Two types of comparison field experiments were performed: evaluation of lines and of recommended cultivars. To perform the former, the three best lines of each cycle of assessment were selected according to the information on yield, quality, and size of grains available in the database. These particular traits were chosen because they were the criteria used in the improvement program during the period under investigation. The cultivar experiments comprised one initial reference control (Carioca – 1985), which was the cultivar most widely planted in Brazil at that time, and the cultivars recommended by Embrapa during the investigated period (Aporé – 1992, Rudá – 1994, Pérola – 1996, BRSMG Talismã – 2002, BRS Pontal – 2003, BRS Requinte – 2003, BRS Horizonte – 2004, BRS 9435 Cometa – 2005 and BRS Estilo – 2006). In the cultivar evaluation, genetic progress estimates were obtained for the reaction to angular leaf spot, plant architecture, and lodging of the plants because cultivars must exhibit superior phenotypes for these characteristics to be released to the market.

The seeds of lines and cultivars were obtained from the Embrapa Rice & Beans Germplasm Active Bank and were multiplied during the winter harvest (planted in May) of 2008 in Santo Antônio de Goiás, state of Goiás, to standardize the germination vigor of seeds. Both types of field experiments were performed in the four main common bean–producing areas in Brazil (South, Southeast, Center-West, and Northeast) on samples sown during the rainy, dry, and fall-winter harvest seasons, for a total of 20 environments in the line evaluations and 21 in the cultivar evaluation. Table 1 lists the municipalities and sites where the 41 evaluations were performed, as well as the harvest seasons/years and the corresponding sowing dates.

The experiments were performed in randomized blocks, with four replicates, in parcels with two 4 m rows, a spacing of 50 cm between rows, and 15 seeds sown per linear meter. Fertilizers were added according to the results of soil analyses to ensure ideal conditions for development and production. Insect pests, invasive plants, and irrigation were controlled as needed according to the official recommendations for the cultivation of common bean (Posse et al., 2010). Diseases were not controlled in these experiments.

Agronomic traits such as the lodging and architecture of the plants, reaction to angular leaf spot, and the commercial quality of the grains were assessed by assigning them scores, whereas the mass of 100 seeds and the grain yield were estimated by weighing samples with 13% water content.

The scale used for evaluating architecture and plant lodging was developed by Melo (2009). For plant architecture considers the length of the guides, the height from the end of the pod to the ground and the angle of insertion of the primary branches. For plant lodging considers the steepness of the plant and the percentage of lodged plants in the plot. Therefore, grade 1 refers to genotypes suitable for mechanized harvesting (short guides, high pods, closer branches and without bedding) and grade 9 to genotypes that are unable to be mechanically harvested (long guides, low pods, open branches and lodged plants).

The variable "severity of disease" was used in the assessment of disease and was defined as the ratio between the area of plant tissue affected by disease and the total area. A descriptive scale was used for this purpose, where scores varied between 1 (absence of symptoms) and 9 (most of the plant was defoliated or dead) (Sartorato and Thung, 2002). Architecture, lodging, and the reaction to disease were assessed in two replicates per experiment.

The harvest was performed after physiological maturity, when the leaves began to dry up. When the moisture content of grains reached 13%, the parcels were weighed; then, 100 seeds from parcel in two replicates were counted and weighed. The grain in the parcels was scored for its commercial quality, with one repetition, using a scale ranging between 1 and 5, based on visual observation and on the mass of 100 seeds (Ramalho et al., 1998):

1. Standard typical carioca grain: cream-colored with light-brown stripes, light background color, no colored halo around the hilum,

Table 1
Environments in the main Brazilian common bean-producing areas where the evaluations were conducted (in 2008–2010) to estimate the genetic progress of the Embrapa improvement plan after its first 22 years.

Municipality	Site	Area	Harvest Season/Year	Sowing Date
Anápolis, GO	ES[a] of Rural Agency	CW	Rainy/2008	Nov/23/2008
			Winter/2009	May/13/2009
Santo Antônio de Goiás, GO	Embrapa Rice & Beans	CW	Winter/2008	Jun/02/2008
			Rainy/2008	Nov/05/2008
			Winter/2009	May/23/2009
			Rainy/2009	Dec/01/2009
			Dry/2010	Feb/17/2010
			Winter/2010	May/30/2010
Rio Verde, GO	ESUCARV[b]	CW	Rainy/2008	Nov/19/2008
			Rainy/2009	Nov/10/2009
Urutaí, GO	IFG[c]	CW	Winter/2009	Apr/28/02009
Sete Lagoas, MG	Embrapa Maize & Sorghum	SE	Winter/2008	Jun/30/2008
			Winter/2009	Apr/14/2009
			Dry/2010	Mar/11/2010
Frei Paulo, SE	ES[a] of Embrapa Coastal Tablelands	NE	Rainy/2009[d]	May/15/2009
Petrolina, PE	Embrapa Semi-arid	NE	Winter/2009[e]	Mar/30/2009
			Winter/2010[f]	May/28/2010
Ponta Grossa, PR	Embrapa SNT[g]	S	Rainy/2008	Nov/17/2008
			Dry/2009	Feb/03/2009
			Rainy/2009	Oct/24/2009
			Dry/2010	Feb/13/2010

CW – midwest; SE – southeast; NE – northeast; S – south.
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[c] Goiás Federal Institute – Urutaí Campus - GO (Instituto Federal Goiano Campus Urutaí – GO.
[d] In the semi-arid Northeast the only sowing season is the rainy period between May and September.
[e] With supplemental irrigation.
[f] With total irrigation.
[g] Office for Technological Business of Ponta Grossa, PR (Escritório de Negócios Tecnológicos de Ponta Grossa-PR).

average mass of 100 seeds from 25 to 27 g, and no flattened beans;

2. Carioca grain exhibiting flaws in one of the characteristics of the standard type;
3. Carioca grain exhibiting flaws in two of the characteristics of the standard type;
4. Carioca grain exhibiting flaws in three of the characteristics of the standard type;
5. Cream-colored grain with dark-brown stripes, dark tegument, with halos, average mass of 100 seeds less than 25 g, and flattened grains.

2.1. Statistical analysis

Individual analysis of variance (ANOVA) of grain yield in kg ha^{-1} was performed with the PROC ANOVA statement in SAS (SAS Institute, 1990). Joint variance analysis within each type of evaluation was performed by PROC MIXED in SAS considering all factors as random, except cycle and block within environment, according to the following model:

$$Y_{ijk} = m + C_n + G_{i(n)} + A_k + B_{j(k)} + CA_{nk} + GA_{i(n)k} + \in_{ijk}$$

where Y_{ijk} is the observation of genotype i in block j within environment k; m is the general average; C_n is the effect of cycle n; $G_{i(n)}$ is the effect of genotype i in cycle n; A_k is the effect of environment k, while the effects of years, harvests, and sites were included in the environment; $B_{j(k)}$ is the effect of block j within environment k; CA_{nk} is the effect of the interaction between cycle n and environment k; $GA_{i(n)k}$ is the effect of the interaction of genotype i with cycle n and environment k; and $\in_{ijk}$ is the average experimental error N(0, s^2).

In the experiments where the residual variances were not homogeneous according to Hartley's test (the ratio between the largest and smallest variance), the degrees of freedom of the average error and of the genotype × environment ($G \times E$) interaction were adjusted by Cochran's method (1954). The phenotypic averages were subjected to a Scott–Knott means test (1974) at 5% probability.

To investigate the contribution of each source of variation to the total variation, the coefficient of determination (R^2) was calculated according to equation $R^2 = SQ_i/SQ_t$, where SQ_i is sum of the squares of variation from source i and SQ_t is the total sum of squares.

The estimates of genetic progress were obtained from the regression analyses of the grain yield, plant architecture, resistance to lodging, reaction to angular leaf spot, mass of 100 seeds, and quality of the grain. The investigated characteristics were considered dependent variables, and the cycles of improvement were considered independent variables. The average annual genetic progress (GP_a) was calculated for each characteristic by dividing the regression slope (b_1) by the intercept (b_0) of the regression according to the following equation:

$$GP_a = \frac{(b_1/b_0) \times 100}{2}$$

3. Results and discussion

In most studies that use the direct method, the estimation of genetic progress is usually restricted to one or a few environmental conditions (Alves et al., 2001; Pompeu, 2002), which limits the scope of the results obtained. Therefore, the present study sought to investigate a number of environments representing the main conditions under which common bean is cultivated in Brazil. A total of 21 assessment environments were used in the 41 field experiments, which were performed in all three sowing seasons over three years (Table 1). The harvest seasons fall-winter (43%) and rainy (38%) prevailed.

Interactions between genotypes and environments are routine in genetic improvement programs for common bean and have been described by several authors in Brazil (Carbonell et al., 2004; Pereira et al., 2009, 2010, 2011) and worldwide (Adjei et al., 2010; Atuahene-Amankwa et al., 2004; Dar et al., 2009; Mekbib, 2002;

Table 2
Structure of the matrix Z and estimates of variance components of grain yield to the random factors in the mixed model, in 20 evaluations with 33 lines of carioca-type common bean obtained during 22 years of improvement by Embrapa. Assessed in 2008–2010.

Random factor	Number of columns in Z[a]	Estimates of variance components
Line (cycle)	33	30,755
Environment	20	495,187
Environment vs. cycle	220	4880
Line (cycle) vs. environment	660	61,473
Error	933	155,744

[a] Z is the design matrix of random factors.

Raffi et al., 2004). In the present study, the $G \times E$ interaction was highly significant in both types of evaluations (Table 2). This is an important fact because the differences in stability among the lines investigated affect their performance in different environments, interfering with their productive potential and, consequently, with the estimates of genetic progress. Because the conditions of cultivation were representative of the common bean producing areas of Brazil, the presence of a significant $G \times E$ interaction indicates that the estimation of genetic progress was obtained in accordance with the expected.

3.1. Genetic progress in terms of yield, quality, and the size of the grains

The joint variance analysis of grain yield in the experiments comparing lines (Table 2) showed that the variable "environment" made the largest contribution to the total variation (66.2%) due to the marked differences among environments, reflecting the wide variation of environmental conditions in Brazil, which include several types of soils, climates, and biotic and abiotic stressors. The variation sources "environment vs. cycle", "line (cycle)" and "line (cycle) vs. environment" contributed less to the total variation: 0.65%, 4.11% and 8.22%, respectively.

Genetic gains (b_1) for grain yield (YIELD) and score grain quality (SGQ) were statistically significant (Table 3), indicating that there was annual genetic progress in grain yield (0.72%**) and quality (−2.37%**) in the carioca-type lines during the investigated 22-year period. The program of common bean improvement in the State of Rio Grande do Sul found a similar result of 0.9% genetic progress in grain yield (Ribeiro et al., 2002). However, these lines did not exhibit significant increases in the mass of 100 grains. In Brazil it is very important to increase the grain weight because the market demands larger carioca grain to increase the market value.

Table 4 summarizes the assessment of the agronomic traits from the line evaluations. In the top group, comprising the seven most productive lines, three came from the 2001/02 cycle: CNFC 8075, CNFC 8063, and CNFC 8058. This result indicates the superiority of that cycle, which was the antepenultimate one. The top group also included lines CNF 4108 from the 1987/88 cycle, which was the second in the investigated period; CNCF 10429 and CNCF 10431 from the 2005/06 cycle, which was the last; and CNCF 7827 from the 1999/00 cycle, which was the eighth.

Table 3
Estimates of the regression coefficients and genetic progress in terms of grain yield (kg ha^{-1}), mass of 100 grains, and grain quality after 22 years of the Embrapa carioca-type common bean improvement plan. Assessed in 2008–2010.

Parameters	Yield	P100	SGQ
Intercept b_0	2379	22.4	3.8
Slope b_1	34.44	0.14	−0.18
P-value (Ho:b_1 = 0)	0.011	0.188	0.0003
Coefficient of determination (%)	52.6	18.2	78.4
Annual genetic progress (%)	0.72	0.31	−2.37

Yield = productivity in kg ha^{-1}; P100 = mass of 100 grains, in grams; SGQ = score of grain quality.

The average overall performance of the three lines from the 2005/06 cycle was excellent (Table 4). In addition to their high productivity, these lines (CNFC 10429, CNFC 10431, and CNFC 10432) exhibited the best scores of grain quality. Therefore, the 2005/06 lines meet the current market requirements regarding the carioca-type, with a pattern characterized by cream-colored grains with light-brown stripes, light background, no halos, and no flattening. These lines also exhibited the best scores of plant architecture and lodging, thus confirming that the lines from the last cycle of the investigated period exhibited the best overall performance. In regard to SGQ, only one among the nine lines of the last three cycles (2001/02, 2003/04, and 2005/06) was not included within the two best groups. This result confirms the improvement of SGQ in the Embrapa program.

The second group formed by the Scott–Knott test comprised two of the three lines from the penultimate cycle (2003/04), namely CNCF 9158 and CNCF 9461; one line from the last cycle (2005/06), CNCF 1043; and two lines from the eighth cycle (1999/00), CNFC 7813 and CNFC 7818. Therefore, all lines that represented the last four cycles were included in the two groups with the best yield performance.

The lines that were chosen to represent each cycle were selected mainly based on the grain yield and quality data included in the program database. The combination of productivity with upright architecture and tolerance to lodging is a recent trait in carioca-type lines. However, the selection based on grain yield induced unfavorable results for plant architecture and lodging, and consequently, the most productive lines did not necessarily represent improvements in those two variables. Only two among the seven lines in the group that scored best in plant architecture and lodging were also included in the group of the most productive lines (Table 4).

The estimation of genetic progress (b_1) in grain yield was 34.44 kg, which corresponded to a period of two years, because every VCU cycle is biennial. Upon dividing the grain yield value by 2, the annual genetic progress was 17.2 kg or 0.72% per year. Taking into account the entire period (22 years), there was 380 kg ha^{-1} of productivity as a result of the improvement program, which is equivalent to one-third of the average national production of 1285 kg ha^{-1} (Feijão, 2011). As this estimate was obtained from the samples representing the best lines of each cycle and was based on studies performed under the same environmental conditions, this direct method supplies the most precise and consistent estimate of the actual genetic gain achieved by the Embrapa improvement program for common bean.

The estimates of genetic progress obtained in the present study represent the average annual genetic progress in productivity achieved in the main production areas of common bean in Brazil. No study could be found in the literature that estimated the genetic progress in the primary Brazilian common bean producing areas. However, similar results have been reported estimates of progress regarding the cultivation of common bean at the regional level: 1.9% per year (Abreu et al., 1994) and 4.4% annual progress in Minas Gerais (Matos et al., 2007), 1.4% and 1.6% per year in Paraná (Fonseca Júnior, 1997), 1.2% per year in Santa Catarina, (Elias et al., 1999), 0.9% per year in Rio Grande do Sul (Ribeiro et al., 2002), and 1.8% per year in São Paulo (Pompeu, 2002). It is worth noting that these estimates are similar in magnitude to the ones reported for other crops in Brazil, e.g., 1.2% of progress per year with maize (Arias and Ramalho, 1998), 0.9% per year with soybean (Alliprandini et al., 1993), and 0.8% per year (Soares et al., 1999) and 1.4% per year with rice (Breseghello et al., 2011). Estimate of the genetic progress in common bean was obtained with 0.65% annual progress (Singh et al., 2007), as well as for other crops shows similar results

Table 4
Means of grain yield (kg ha^{-1}) and other agronomic traits of Embrapa carioca-type common bean lines after 22 years of improvement, assessed in 20 environments from 2008 to 2010.

No.	Line	Cycle	Yield	P100	SGQ	Arch	Lodg	ALS
1	CNFC 8075	2001/02	2914 a	24.6 c	2.0 b	5.1 e	4.9 c	6.1 c
2	CNFC 8063	2001/02	2883 a	24.9 c	2.0 b	5.0 d	4.8 c	6.1 c
3	CNF 4108	1987/88	2853 a	21.1 h	3.1 d	5.0 d	5.2 d	5.0 b
4	CNFC 8058	2001/02	2845 a	23.4 e	2.1 b	4.4 b	4.7 c	4.9 b
5	CNFC 10429	2005/06	2844 a	24.5 c	1.3 a	4.0 a	3.7 a	2.4 a
6	CNFC 7827	1999/00	2809 a	23.9 d	2.3 b	5.6 f	5.9 e	5.6 c
7	CNFC 10431	2005/06	2793 a	23.0 e	1.7 a	3.8 a	3.8 a	3.0 a
8	CNFC 7813	1999/00	2779 b	24.8 c	2.5 c	5.6 f	6.1 e	4.9 b
9	CNF 5824	1989/90	2778 b	24.5 c	3.8 e	5.5 f	5.9 e	5.1 b
10	CNFC 9518	2003/04	2769 b	23.9 d	2.9 d	5.2 e	5.2 d	5.4 b
11	CNFC 7818	1999/00	2761 b	23.7 d	2.7 c	5.7 g	6.1 e	4.9 b
12	CNF 7569	1997/98	2757 b	23.0 e	2.5 c	5.1 e	4.9 c	5.9 c
13	CNFC 9461	2003/04	2729 b	25.2 c	1.5 a	4.1 a	4.0 a	6.0 c
14	CNF 5550	1985/86	2706 b	24.8 c	4.2 e	5.5 f	6.0 e	6.6 c
15	CNF 7461	1997/98	2705 b	21.0 h	2.9 d	4.9 d	5.3 d	4.7 b
16	CNF 7091	1989/90	2686 b	23.8 d	2.3 b	5.8 g	6.0 e	6.4 c
17	CNFC 10432	2005/06	2668 b	23.8 d	1.7 a	3.8 a	3.7 a	2.7 a
18	CNF 5547	1987/88	2656 b	24.5 c	4.5 f	3.8 a	4.0 a	6.1 c
19	CNFC 9458	2003/04	2556 c	24.1 d	1.9 b	3.9 a	3.7 a	5.9 c
20	CNF 6548	1991/92	2534 c	20.7 h	2.7 c	5.8 g	6.4 f	6.1 c
21	CNF 7079	1995/96	2526 c	23.6 d	4.2 e	4.7 c	4.4 b	3.3 a
22	CNF 7093	1995/96	2497 c	19.9 i	3.3 d	4.3 b	4.6 b	5.4 b
23	CNF 5545	1985/86	2490 c	20.3 i	5.0 g	4.2 b	3.7 a	5.7 c
24	CNF 6778	1993/94	2472 c	27.2 a	2.6 c	5.6 f	5.7 e	5.8 c
25	CNF 7098	1995/96	2455 c	21.5 g	2.3 b	4.0 a	4.1 a	4.6 b
26	CNF 6783	1993/94	2452 c	20.2 i	3.1 d	5.6 f	6.3 f	5.4 b
27	CNF 6773	1991/92	2413 c	22.2 f	2.8 c	4.8 d	4.9 c	6.0 c
28	CNF 6777	1993/94	2327 d	25.9 b	2.7 c	5.9 g	6.5 f	5.9 c
29	CNF 6772	1991/92	2264 d	23.0 e	3.0 d	5.4 f	6.0 e	5.6 c
30	CNF 7464	1997/98	2232 d	21.3 g	3.9 e	4.8 d	4.6 b	6.0 c
31	CNF 5555	1985/86	2226 d	22.1 f	2.6 c	5.3 e	5.8 e	5.7 c
32	CNF 5558	1989/90	2218 d	22.2 f	2.6 c	5.5 f	5.8 e	5.9 c
33	CNF 5552	1987/88	2189 d	24.3 d	2.7 c	4.4 b	4.3 b	5.1 b
No. evaluations[a]	–	–	20	13	15	18	18	9

* Means followed by the same letter were not significantly different according to Scott–Knott test at 5% probability.
[a] Number of evaluations supplying the data to calculate the mean values of each trait. Yield = productivity in kg ha^{-1}; P100 = mass of 100 grains, in grams; SGQ = score of grain quality; Arch = score of plant architecture; Lodg = score of lodging; ALS = score of angular leaf spot.

worldwide, e.g., 1% progress per year in irrigated rice (Peng et al., 2000), 0.7% per year in wheat (Zhou et al., 2007), and 0.6% per year in soybean (Jin et al., 2010).

3.2. Genetic progress in the resistance to angular leaf spot and in plant architecture and lodging

Significant genetic progress in terms of plant architecture and tolerance to lodging was found in the field experiments that evaluated released varieties (Table 5). The coefficient of determination showed that the adjustment of the means to the regression lines was adequate. The scores for these two traits decreased during the period studied, which indicates that there was significant improvement in the architecture and tolerance to lodging of carioca-type cultivars during the period investigated. The results obtained with the more modern cultivars BRS 9435 Cometa, BRS Horizonte, and BRS Estilo confirm the occurrence of genetic progress in the carioca-type for those traits (Table 6).

Table 5
Estimates of regression coefficients and genetic progress in terms of plant architecture, lodging, and reaction to angular leaf spot after 22 years of the Embrapa carioca-type common bean improvement plan. Assessed in 2008–2010.

Parameters	Arch	Lodg	ALS
Intercept b_0	6.4	6.4	5.7
Slope b_1	−0.25	−0.25	0.03
P-value (Ho:$b_1 = 0$)	0.03	0.06	0.736
Coefficient of determination (%)	68.9	63.1	1.5
Annual genetic progress (%)	−1.95	−1.95	0.26

Arch = score of plant architecture; Lodg = score of lodging; ALS = score of angular leaf spot.

Cultivars BRS 9435 Cometa and BRS Horizonte, whose plant architecture is characterized by few lateral branches and few pods per plant, exhibit limited production per plant. Therefore, to compensate for their low production, the population per area needs to be increased, for example by reducing the spacing between the planting rows. In the present study, the spacing between rows was 50 cm, but these cultivars are not able to achieve their full productive potential under this sowing density because the population of plants is too low. Silva et al. (2008) found that 40 cm spacing increased the productivity of BRS Horizonte by 1 ton/ha. Melo et al. (2007) found that BRS Horizonte stood out among carioca-type cultivars due to its upright plant architecture and tolerance to lodging that were similar to the black-seeded cultivars, which traditionally exhibit better plant architecture.

Cultivar BRS Estilo, which was the newest in the investigated period (Melo et al., 2010), exhibits upright growth, as shown by its best architectural score (3.8) and good tolerance to lodging (4.1), in addition to its high productive potential, in contrast to BRS 9435 Cometa and BRS Horizonte (Table 6). This shows that the Embrapa improvement program only recently produced cultivars that combine upright architecture and tolerance to lodging with good yield potential.

Among the several diseases that affect common bean, angular leaf spot, caused by the fungus *Pseudocercospora griseola*, is one of the most widespread; it occurs in virtually all Brazilian common bean-producing areas. Several genes control the reaction to this disease (Mahuku et al., 2003), and the pathogen exhibits

Table 6
Means of grain yield (kg ha^{-1}) and other agronomic traits of carioca-type common bean cultivars after 22 years of the Embrapa improvement plan, assessed in 21 environments from 2008 to 2010.

No.	Cultivar	Year[b]	Yield[c]	P100	SGQ	Arch	Lodg	ALS
1	RUDÁ	1994	2789 a	22.3 e	3.1 d	5.1 c	5.1 c	4.6 a
2	BRS ESTILO	2006	2760 a	26.6 b	1.2 a	3.8 b	4.1 b	5.9 b
3	PÉROLA	1996	2723 a	27.6 a	1.2 a	5.3 c	5.2 c	6.1 b
5	BRS PONTAL	2003	2676 b	25.4 c	2.5 c	5.8 d	5.9 d	5.6 b
4	BRS REQUINTE	2003	2663 b	22.9 e	1.9 b	5.2 c	5.3 c	6.3 c
6	CARIOCA	1985	2640 b	24.0 d	2.4 c	6.1 e	6.1 d	6.8 d
7	APORÉ	1992	2577 b	26.7 b	3.7 e	5.6 d	5.8 d	5.4 b
8	BRS 9435 COMETA	2005	2484 c	25.1 c	2.3 c	3.6 a	3.4 a	5.5 b
9	BRSMG TALISMÃ	2002	2396 c	23.4 d	2.1 b	5.6 d	5.5 c	6.9 d
10	BRS HORIZONTE	2004	2253 d	26.5 b	2.0 b	3.9 b	3.7 a	7.3 d
No. evaluations[a]	–	–	21	13	15	18	18	9

[a] Number of evaluations supplying the data to calculate the mean values of each trait. YIELD = productivity in kg ha^{-1}; P100 = mass of 100 grains, in grams; SGQ = score of grain quality; Arch = plant architecture; Lodg = lodging; ALS = angular leaf spot.
[b] Year when the cultivar was released.
[c] Means followed by the same letter do not differ according to Scott–Knott test at 5% probability.

different pathotypes in different producing areas (Sartorato and Alzate-Marin, 2004). Therefore, it is difficult to obtain cultivars with broad-scope and long-lasting resistance (Amaro et al., 2007); hence, genetic progress in controlling this disease is slow. In addition, the Embrapa improvement program for the reaction to angular leaf spot is relatively recent, and it has succeeded in developing elite lines with broad-scope resistance to different pathotypes of *P. griseola* only recently. Therefore, the progress in angular leaf spot resistance breeding was expected to be less marked than plant architecture and lodging, whose corresponding improvement programs were launched much earlier and had a greater degree of genetic variability to act upon.

In addition to productivity, the Embrapa program for the improvement of common bean also takes into account other priority traits, such as plant architecture, resistance to lodging, commercial value of the grain, and resistance to pathogens. Selection according to several traits at the same time usually leads to less gain for each individual trait. Thus, the estimates of the productivity improvements in the line evaluations were not entirely reflected in the actual performance of the new cultivars because the gains in other traits (architecture and resistance to lodging) restricted the improvement of productivity. Nevertheless, a positive evolution in the overall performance of the new cultivars was found.

4. Conclusions

The Embrapa program for the genetic improvement of carioca-type common bean exhibited significant genetic progress in terms of grain yield (0.72% per year), plant architecture (2% per year), resistance to lodging (2% per year), and quality of grains (2.4% per year) between 1985 and 2006 in the main Brazilian common bean-producing areas.

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