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Higher-precision experimental statistics for the selection of early and upright common bean lines

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ABSTRACT. The development of early and upright common bean cultivars is necessary to meet the demand of producers. The objectives of this work were to evaluate more precise experimental statistics for the selection of early and upright common bean lines and identify the traits that provide better genetic differentiation between lines. For this purpose, 156 common bean lines of different grain colours were evaluated in 23 experiments carried out in the southern region of Brazil between 1998 and 2015. The traits related to earliness (flowering and cycle) and upright plant architecture (lodging, insertion of the first pod and insertion of the last pod) were evaluated with high experimental precision by determining F-test values for genotype (Fc), heritability (h^2), and selective accuracy (SA). In the experiments with Fc ⩾ 2.00, h^2 ⩾ 49.00%, and SA ⩾ 0.70, the best genetic differentiation of early common bean lines was performed by the cycle; and the best genetic differentiation of common bean lines with upright plant architecture was carried out by the insertion of the first and the last pod.

Keywords: *Phaseolus vulgaris*; genetic variability; statistical parameters; selection efficiency.

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Introduction

Regular consumption of common beans is healthy due to their nutritional and functional properties (Câmara, Urrea, & Schlegel, 2013). Brazil is among the countries with the highest per capita consumption of common beans in the world, at approximately 17 kg inhabitant^{-1} year^{-1}. Therefore, an increase of common bean production would have both social and economic benefits.

Breeding programmes have focused on the development of common bean cultivars with high grain yield. The most consumed bean types in Brazil, black beans and Carioca beans (beige tegument with brown stripes), have recorded annual genetic gain from 0.72 to 1.10% for grain yield (Ribeiro, Cargnelutti Filho, Poersch, Jost, & Rosa, 2008; Faria et al., 2013; 2014). This is the result of genetic modifications in the traits related to earliness, with the development of earlier cultivars for flowering and cycle (Ribeiro et al., 2008). In addition, the release of common bean cultivars with upright plant architecture has stood out due to their higher tolerance for lodging (Faria et al., 2013; 2014) and to the lower insertion of the last pod (Ribeiro et al., 2008).

However, more precise experimental statistics are required for bean breeding programmes to obtain increasing genetic gains in the selection process of superior lines. The coefficient of experimental variation (CEV) has been widely used in common bean experiments to evaluate the experimental precision of the traits related to earliness and upright plant architecture (Cargnelutti Filho, Storck, & Ribeiro, 2009; Cargnelutti Filho, Ribeiro, & Burin, 2010; Jost, Ribeiro, Rosa, Possobom, & Maziero, 2014; Bertoldo, Coutinho, Pelisser, Favreto, & Silva, 2015; Maziero, Ribeiro, & Facco, 2016; Ribeiro et al., 2016). Nevertheless, the CEV and the least significant difference between the genotype means using Tukey's test (LSD) are not the most adequate statistics to evaluate the genetic superiority of lines in value of cultivation and use (VCU) experiments (Resende & Duarte, 2007; Cargnelutti Filho et al., 2009; Benin, Storck, Marchioro, Franco, & Schuster, 2013).

The results of F-test values for genotype (Fc), heritability (h^2), and selective accuracy (SA) statistics have been used to identify more precise experiments for the selection of common bean genotypes (Cargnelutti

Filho et al., 2009; 2010; Cargnelutti Filho & Ribeiro, 2010; Ribeiro et al., 2016). However, for the traits related to earliness and upright plant architecture, no experimental precision classes have been reported in the literature for CEV, LSD, Fc, h^2, and SA. Nevertheless, Resende and Duarte (2007), based on theoretical studies, recommended that if Fc ⩾ 2.00 and SA ⩾ 0.70, the experiment can be used for selection for presenting acceptable experimental precision. According to the authors, these values can be employed for any trait and crop.

The statistics that confer higher experimental precision for the selection of earlier and upright common bean plants have not yet been reported in the literature. In addition, different traits can be used to characterize earliness (flowering and cycle) and upright plant architecture (lodging, insertion of the first pod and insertion of the last pod) in common beans. However, no prior definition on which of these traits allows a better genetic differentiation between the common bean lines in the experiments has been made available. This information is fundamental for greater efficiency in the identification of the genetic superiority of common bean lines for the traits of interest. Thus, the objectives of this work were to evaluate more precise experimental statistics for the selection of early and upright common bean lines and identify which traits provide better genetic differentiation between lines.

Material and methods

The experiments were carried out in a field area of the Bean Breeding Programme of the Plant Science Department of the Federal University of Santa Maria, Santa Maria, State of Rio Grande do Sul, Brazil (29° 42' S, 53° 43' W, and 95 m in altitude). Sowing was carried out in October from 1998 to 2015 (rainy season), and in February in the years of 2009, 2011, 2013, 2014, and 2015 (dry season), totaling 23 experiments.

The climate of the region is humid subtropical, with a warm summer and no definite dry season, according to the Köppen classification. The soil of the experimental area is classified as typical alitic Argisol (Hapludalf), belonging to the Santa Maria mapping unit and was prepared in a conventional manner. Fertilizers were applied according to the needs determined by soil chemical analysis, with the aim of providing adequate amounts of nutrients for the development of the crop.

The experiment consisted of a randomized block design with three or four replications, depending on the number of seeds available for each experiment. The plot consisted of four 4-m rows spaced 0.5 m apart. The two central rows were analysed to avoid varietal mixture, and thus the useful area was 4 m^2. The number of common bean lines evaluated in each experiment ranged from 13 to 26, totaling 156 lines of the Mesoamerican and Andean gene pools. The following types of common beans were used: black, Carioca (beige tegument with brown stripes), cranberry (cream-coloured tegument with red stripes), mouro (gray tegument with black stripes), red, yellow and pink. These lines characterize the diversity of common beans produced in Brazil; they were developed by different breeders, and they represent the technological advances of common bean breeding programmes in southern Brazil between 1998 and 2015.

The experiments were carried out according to the minimum requirements for the determination of VCU for the register of common bean cultivars in the National Register of Cultivars of the Ministry of Agriculture, Livestock and Supply (NRC-MALS) in Brazil. Management practices were similar in all experiments. Seeds were treated at sowing with Maxim XL fungicide (Fludioxonil and Metalaxyl-M) and Cruiser insecticide (Thiamethoxam), both at a dose of 200 mL 100 kg^{-1} of seeds. During the development of the crop, the Engeo Pleno insecticide (Thiamethoxam and lambdacyhalothrin) was applied at a dose of 125 mL ha^{-1}. Weeding was carried out whenever necessary. Fungicides were not applied to control disease.

Earliness was evaluated by flowering, which corresponds to the number of days between emergence (V1) and the opening of the first flower (R6), and cycle, which corresponds to the interval between the number of days between emergence (V1) and maturation (R9). Data were recorded when 51% of the plants of the useful area reached the stages V1, R6, and R9.

Upright plant architecture was characterized by lodging, insertion of the first pod and insertion of the last pod. Lodging was determined using a score scale ranging from 1 to 9, with score 1 corresponding to 100% upright plants and score 9 corresponding to 100% lodged plants. Insertion of the first pod and insertion of the last pod were measured in 10 plants randomly collected from the useful area by calculating the distance between the ground and the insertion of the first pod and the last pod in the main branch, respectively.

Data were subjected to analysis of variance. For each trait evaluated in each of the 23 experiments, the following statistics were obtained: minimum value; maximum value; overall mean of the experiment ($\hat{m}$); genotype mean square (GMS); and F-test value for genotype (Fc), estimated by the expression Fc = GMS/EMS, where EMS is the value of the error mean square. The coefficient of experimental variation (CEV) was expressed by CEV= $100\sqrt{EMS}/\hat{m}$. The least significant difference (LSD) between the means of the genotypes using the Tukey test, at 5% probability, was calculated using the formula: LSD= $100\Delta/\hat{m}$, where: $\Delta = q_{\alpha(n;DFE)}\sqrt{EMS/J}$ and $q_{\alpha(n;DFE)}$ are the critical values for use of the Tukey test; n is the number of genotypes; and DFE is the number of degrees of freedom of the error.

Subsequently, the mean heritability statistic was estimated by (h^2 = GMS - EMS/GMS), and the selective accuracy (SA) was obtained by the expressions SA= $\sqrt{1 - \frac{1}{Fc}}$, for Fc ⩾ 1; and SA = 0, for Fc < 1 (Resende & Duarte, 2007). Statistical analyses were performed using Microsoft Office Excel and Genes Software (Cruz, 2013).

Results and discussion

Experimental precision of traits related to earliness in common beans

A significant effect of genotype was observed for flowering ($p \leqslant 0.05$) in 18 experiments (Table 1). Therefore, common bean lines presented genetic variability for flowering in most of the experiments, which allows selecting earlier lines. However, efficient selection of early common bean lines in VCU experiments requires the use of statistics that allow the differentiation of lines with high experimental precision.

CEV values ranged from 1.30 (experiment 11) to 12.26% (experiment 20) for flowering. Similar CEV values were observed when evaluating flowering in common bean cultivar competition experiments (Balcha, 2010; Cargnelutti Filho et al., 2010; Bertoldo et al., 2015; Ribeiro et al., 2016). LSD had similar variation to that of CEV, ranging from 1.16 (experiment 11) to 13.15% (experiment 20). The lowest scores of CEV and LSD statistics were obtained in experiment 11 (2006 rainy season), indicating higher experimental precision in the evaluation of flowering. No other studies have defined the experimental precision classes for the CEV and LSD statistics for the evaluation of flowering in common bean experiments.

Table 1. Analysis of variance containing the number of lines evaluated by experiment (N), commercial group (G), minimum value (minimum), maximum value (maximum), mean ($\hat{m}$), genotype mean square (GMS), F-test values for genotype (Fc), coefficient of experimental variation (CEV, %), least significant difference between the means of the genotypes using the Tukey test at 5% probability (LSD, %), heritability (hr^2, %) and selective accuracy (SA) for flowering obtained in 23 common bean experiments carried out between 1998 and 2015.

Exp	Year/season	N	G[1]	Flowering (days)								
				Minimum	Maximum	$\hat{m}$	GMS	Fc	CEV	LSD	h^2	SA
1	1998/rainy	20	Co	35.00	45.00	39.97	4.59*	3.43	2.89	3.59	70.87	0.84
2	1999/rainy	20	Co	55.00	62.00	58.90	2.00*	2.16	1.63	2.99	53.72	0.73
3	2000/rainy	24	B	35.00	46.00	39.53	14.98*	5.82	4.06	5.06	82.83	0.91
4	2001/rainy	14	C	42.00	49.00	47.43	3.76ns	1.83	3.02	4.31	45.52	0.67
5	2001/rainy	18	B	33.00	43.00	39.26	11.59*	3.02	4.99	6.02	66.91	0.82
6	2002/rainy	18	Co	27.00	42.00	36.11	34.67*	25.81	3.21	3.56	96.12	0.98
7	2003/rainy	16	C	35.00	46.00	41.14	15.69*	5.82	3.99	4.99	82.81	0.91
8	2003/rainy	26	B	29.00	46.00	39.83	29.50*	24.03	2.78	3.52	95.84	0.98
9	2004/rainy	16	Co	30.00	44.00	36.20	18.41*	5.28	5.16	4.79	81.05	0.90
10	2005/rainy	16	Co	29.00	38.00	34.39	10.06*	10.96	2.79	2.46	90.87	0.95
11	2006/rainy	13	Co	34.00	37.00	35.44	0.76*	3.54	1.30	1.16	71.75	0.85
12	2007/rainy	15	Co	35.00	44.00	38.68	15.02*	4.86	4.54	4.48	79.42	0.89
13	2009/dry	17	Co	35.00	39.00	35.90	1.19ns	1.23	2.74	2.54	18.75	0.43
14	2010/rainy	14	Co	29.00	41.00	39.00	65.54*	184.45	1.53	1.50	99.46	1.00
15	2011/dry	16	Co	29.00	38.00	33.56	13.65*	13.92	2.95	2.54	92.82	0.96
16	2011/rainy	16	Co	30.00	40.00	34.12	7.77*	2.30	5.38	4.71	56.58	0.75
17	2012/rainy	14	Co	27.00	35.00	32.55	9.88*	5.23	4.22	4.13	80.88	0.90
18	2013/dry	14	Co	39.00	52.00	45.14	21.93*	6.05	4.22	5.73	83.47	0.91
19	2013/rainy	15	Co	34.00	40.00	36.89	1.75ns	1.21	3.25	3.63	17.45	0.42
20	2014/dry	16	Co	28.00	45.00	35.25	10.07ns	0.54	12.26	13.15	0.00	0.00
21	2014/rainy	16	Co	37.00	46.00	42.22	2.89*	1.90	2.92	3.16	47.48	0,69
22	2015/dry	14	Co	36.00	42.00	38.84	3.95*	3.08	2.91	2.85	67.57	0.82
23	2015/rainy	14	Co	36.00	42.00	37.93	1.09ns	1.85	2.03	1.94	45.90	0.68

nsNot significant. *Significant by the F-test at 0.05 probability. [1]Group (G): B = black; C = Carioca; Co = colours (black, Carioca and other colours).

When Fc, h^2 and SA statistics were used to evaluate the experimental precision, the lowest scores were observed in the experiments where the genotype mean square was not significant for flowering (4, 13, 19, 20, and 23). In these experiments, low experimental precision was observed for flowering, according to the classifications of Resende and Duarte (2007) (Fc < 2.00 and SA < 0.70) and Cargnelutti Filho and Storck (2007) (h^2 < 49.00%). Similarly, when there was no differentiation of common bean genotypes for flowering by the F-test, low experimental precision was verified by the Fc, hr^2 and SA statistics (Cargnelutti Filho et al., 2010; Ribeiro et al., 2016).

In experiment 21, despite the differentiation for flowering among common bean genotypes, the experimental precision evaluated by the Fc, h^2 and SA statistics was low. Therefore, the significant effect for genotype does not qualify an experiment as precise, which is in agreement with previous results observed by Benin et al. (2013) in wheat cultivar competition experiments. In the present study, experiment 21 presented Fc < 2.00 and SA < 0.70 for flowering. In this case, Resende and Duarte (2007) recommend discarding the experiment for the selection.

Flowering was evaluated with high experimental precision by the CEV and LSD statistics (CEV ⩽ 12.26 and/or LSD ⩽ 13.15%) in all experiments. CEV and LSD depend on the residual variance and the mean and thus are adequate to evaluate the precision of experiments with similar means (Cargnelutti Filho & Storck, 2007). Therefore, the evaluation of experimental precision using the CEV and LSD statistics does not always correctly identify and select superior common bean lines. In the present study, if the CEV and LSD statistics had been used alone, selection in experiments with no genetic variability for flowering would have occurred, which is a mistake.

The Fc, h^2 and SA statistics, in turn, are obtained according to the genetic variance information (Resende & Duarte, 2007; Cargnelutti Filho et al., 2009). Therefore, they are more suitable for the selection of lines with genetic superiority (Cargnelutti Filho et al., 2009; Benin et al., 2013). In this study, the selection of early common bean lines for flowering was performed with high experimental precision, with h^2 ⩾ 49.00% (Cargnelutti Filho & Storck, 2007), Fc ⩾ 2.00, and SA ⩾ 0.70 (Resende & Duarte, 2007) in 73.91% of the experiments. In these experiments, a significant effect for genotype was observed for flowering.

For the cycle, significant differences for genotype were observed in all experiments, except for experiments 20 and 22 (Table 2). Experiments 20 and 22 presented the highest CEV and LSD values, the lowest values for Fc (Fc ⩽ 0.81), and null values for h^2 and SA. For the cycle, all the statistics were similar in the identification of experiments with low experimental precision (20 and 22). In this case, the use of CEV and LSD statistics was adequate to evaluate the quality of experiments with similar means. Experiments 20 and 22 presented greater experimental error from the CEV, LSD, Fc, h^2 and SA statistics, which did not allow differentiation among common bean lines for the cycle.

The cycle was evaluated with high experimental precision, with CEV ⩽ 4.85%, LSD ⩽ 12.30%, Fc ⩾ 2.00, h^2 ⩾ 49.00%, and SA ⩾ 0.70 in 91.30% of the experiments. Previous studies have also shown that the cycle of common bean cultivars was evaluated with high experimental precision in 95% of the experiments when using CEV, Fc and h^2 statistics (Ribeiro et al., 2016), and in 100% of the experiments when using CEV, Fc and SA statistics (Cargnelutti Filho et al., 2010). In the present study, in the 21 experiments in which the genotype mean square for the cycle was significant, selection can be performed based on the genetic superiority with high experimental precision.

Earliness of the common bean genotypes has been evaluated by flowering and cycle, which are correlated traits (Balcha, 2010; Cabral, Soares, Lima, Soares, & Silva, 2011; Checa & Blair, 2012; Bertoldo et al., 2015). In the present study, the selection of early common bean lines can be performed with high experimental precision in 21 experiments, given the highest scores of Fc, h^2, and SA statistics (Table 2). The same pattern of experimental precision was obtained in 17 experiments when the selection of common bean lines was based on early flowering (Table 1). The evaluation of the cycle in the VCU experiments that presented Fc ⩾ 2.00, h^2 ⩾ 49.00%, and SA ⩾ 0.70 allowed the best genetic differentiation of the earliest common bean lines.

Experimental precision of traits related to upright plant architecture

Significant differences for lodging were observed in 16 experiments (Table 3). Therefore, in seven VCU experiments, based on the lodging evaluation, the selection of common bean lines with upright plant architecture was not possible. However, Cargnelutti Filho and Ribeiro (2010) observed that common bean cultivars differed for lodging in the nine experiments evaluated, allowing the selection of less lodged plants. In this case, the greater genetic variability among the genotypes evaluated in each experiment and the lower experimental error may justify the differences observed in these results.

Table 2. Analysis of variance containing the number of lines evaluated by experiment (N), commercial group (G), minimum value (minimum), maximum value (maximum), mean ($\hat{m}$), genotype mean square (GMS), F-test values for genotype (Fc), coefficient of experimental variation (CEV, %), least significant difference between the means of the genotypes using the Tukey test at 5% probability (LSD, %), heritability (h^2, %) and selective accuracy (SA) for cycle obtained in 23 common bean experiments carried out between 1998 and 2015.

Exp	Year/season	N	G[1]	Cycle (days)								
				Minimum	Maximum	$\hat{m}$	GMS	Fc	CEV	LSD	h^2	SA
1	1998/rainy	20	Co	77.00	85.00	82.93	7.70*	11.81	0.97	2.51	91.53	0.96
2	1999/rainy	20	Co	77.00	87.00	80.57	9.58*	2.10	2.65	6.63	52.48	0.72
3	2000/rainy	24	B	72.00	87.00	78.28	25.79*	3.39	3.52	8.69	70.55	0.84
4	2001/rainy	14	C	80.00	83.00	80.78	3.77*	4.67	1.11	2.70	78.60	0.89
5	2001/rainy	18	B	69.00	79.00	72.57	15.56*	4.87	2.46	5.49	79.49	0.89
6	2002/rainy	18	Co	76.00	90.00	82.09	69.56*	11.20	3.03	7.66	91.07	0.95
7	2003/rainy	16	C	76.00	93.00	82.27	19.03*	4.29	2.56	6.41	76.67	0.88
8	2003/rainy	26	B	66.00	82.00	77.93	25.44*	21.78	1.39	3.43	95.41	0.98
9	2004/rainy	16	Co	62.00	75.00	69.55	16.54*	4.21	2.85	5.08	76.24	0.87
10	2005/rainy	16	Co	71.00	79.00	75.20	6.51*	7.19	1.26	2.44	86.10	0.93
11	2006/rainy	13	Co	81.00	87.00	81.87	6.07*	2.76	1.81	3.71	63.81	0.80
12	2007/rainy	15	Co	79.00	87.00	81.68	15.12*	4.87	2.16	4.49	79.47	0.89
13	2009/dry	17	Co	77.00	85.00	81.79	15.94*	5.67	2.05	4.33	82.36	0.91
14	2010/rainy	14	Co	74.00	85.00	77.95	22.51*	7.85	2.17	4.27	87.27	0.93
15	2011/dry	16	Co	76.00	95.00	86.62	93.47*	22.01	2.38	5.28	95.45	0.98
16	2011/rainy	16	Co	65.00	77.00	71.31	8.15*	2.61	2.48	4.53	61.72	0.79
17	2012/rainy	14	Co	73.20	93.00	83.29	45.07*	3.67	4.20	10.54	72.77	0.85
18	2013/dry	14	Co	93.00	118.00	108.43	129.56*	7.75	3.77	12.30	87.10	0.93
19	2013/rainy	15	Co	72.00	87.00	79.15	50.56*	4.49	4.24	10.15	77.75	0.88
20	2014/dry	16	Co	80.00	117.00	103.12	63.64^{ns}	0.55	10.40	32.63	0.00	0.00
21	2014/rainy	16	Co	74.00	95.00	84.06	56.65*	3,40	4.85	10.45	70.63	0.84
22	2015/dry	14	Co	89.00	120.00	112.00	65.54^{ns}	0.81	8.05	22.75	0.00	0.00
23	2015/rainy	14	Co	64.00	86.00	73.05	62.58*	6.05	4.40	8.12	83.46	0.91

^{ns}Not significant. *Significant by the F-test at 0.05 probability. [1]Group (G): B = black; C = Carioca; Co = colours (black, Carioca and other colours).

Table 3. Analysis of variance containing the number of lines evaluated by experiment (N), commercial group (G), minimum value (minimum), maximum value (maximum), mean ($\hat{m}$), genotype mean square (GMS), F-test values for genotype (Fc), coefficient of experimental variation (CEV, %), least significant difference between the means of the genotypes using the Tukey test at 5% probability (LSD, %), heritability (h^2, %) and selective accuracy (SA) for lodging obtained in 23 common bean experiments carried out between 1998 and 2015.

Exp	Year/season	N	G[1]	Lodging								
				Minimum	Maximum	$\hat{m}$	GMS	Fc	CEV	LSD	h^2	SA
1	1998/rainy	20	Co	2.00	9.00	5.60	7.04*	4.21	23.08	4.01	76.27	0.87
2	1999/rainy	20	Co	1.00	9.00	5.45	12.29*	4.38	30.74	5.20	77.17	0.88
3	2000/rainy	24	B	2.00	9.00	6.32	4.62*	2.06	23.67	4.72	51.57	0.72
4	2001/rainy	14	C	2.00	9.00	8.00	2.56*	3.04	11.48	2.76	67.07	0.82
5	2001/rainy	18	B	1.00	9.00	6.37	11.52*	4.25	25.85	5.06	76.47	0.87
6	2002/rainy	18	Co	8.00	9.00	8.96	0.03^{ns}	0.91	2.18	0.60	0.00	0.00
7	2003/rainy	16	C	2.00	9.00	7.10	2.96^{ns}	1.29	21.32	4.61	22.62	0.47
8	2003/rainy	26	B	2.00	8.00	3.68	6.09*	3.89	34.02	3.98	74.29	0.86
9	2004/rainy	16	Co	1.00	8.00	3.12	6.60*	6.37	32.57	2.61	84.30	0.92
10	2005/rainy	16	Co	2.00	8.00	4.69	8.25*	8.73	20.73	2.49	88.55	0.94
11	2006/rainy	13	Co	3.00	8.00	6.54	1.08^{ns}	1.97	11.31	1.85	49.21	0.70
12	2007/rainy	15	Co	3.00	9.00	6.20	7.68*	6.02	18.22	2.88	83.39	0.91
13	2009/dry	17	Co	1.00	8.00	5.15	15.00*	21.42	16.26	2.16	95.33	0.98
14	2010/rainy	14	Co	2.00	9.00	5.32	14.09*	7.42	25.90	3.48	86.52	0.93
15	2011/dry	16	Co	2.00	9.00	6.31	7.22*	3.65	22.26	3.60	72.63	0.85
16	2011/rainy	16	Co	2.00	9.00	4.87	6.63^{ns}	1.66	41.01	5.12	39.74	0.63
17	2012/rainy	14	Co	1.00	9.00	5.07	14.67*	12.84	21.08	3.22	92.21	0.96
18	2013/dry	14	Co	5.00	9.00	7.67	2.20*	6.65	7.51	1.73	84.97	0.92
19	2013/rainy	15	Co	2.00	9.00	5.80	5.42*	4.63	18.66	3.27	78.38	0.88
20	2014/dry	16	Co	2.00	9.00	5.23	2.88^{ns}	1.02	32.13	5.11	1.88	0.14
21	2014/rainy	16	Co	3.00	8.00	5.42	2.16^{ns}	1.73	20.59	2.86	42.23	0.65
22	2015/dry	14	Co	3.00	9.00	5.89	3.33*	2.48	19.66	2.92	59.75	0.77
23	2015/rainy	14	Co	2.00	5.00	3.25	1.42^{ns}	1.86	26.89	2.20	46.33	0.68

^{ns}Not significant. *Significant by the F-test at 0.05 probability. [1]Group (G): B = black; C = Carioca; Co = colours (black, Carioca and other colours).

For lodging, great variation was observed for CEV, ranging from 2.18 to 41.01%. High scores for the CEV statistic (20.93 to 21.69%) were previously verified by Jost et al. (2014) in an experiment of selection of less lodged common bean lines. However, for LSD, low scores (LSD ≤ 5.20%) were obtained for lodging in the experiments evaluated in this study. No previous studies on the experimental precision classes for lodging have been reported using the CEV and LSD statistics for common bean experiments.

The scores of Fc, h^2 and SA statistics were high for lodging in 16 experiments, i.e., Fc ⩾ 2.00 (Resende & Duarte, 2007), h^2 ⩾ 49.00% (Cargnelutti Filho & Storck, 2007), and SA ⩾ 0.70 (Resende & Duarte, 2007). In these experiments, the effect of genotype was significant. Similarly, Cargnelutti Filho and Ribeiro (2010) observed that in the common bean cultivar competition experiments in which the F test was significant for genotype, lodging was evaluated with high experimental precision by the Fc and SA statistics.

Selection of common bean lines with lower lodging scores can be performed with high experimental precision in 69.56% of the experiments, given the highest scores of Fc, h^2 and SA statistics. This was the lowest percentage of experimental precision obtained among the traits evaluated in the present study. Since this evaluation is carried out using a score scale, and given the degree of inclination of the plants of the useful area, greater experimental error was expected for this trait. This is because during the 17 years of experiments, lodging was not always evaluated by the same person. Visual evaluations are usually subjective and do not have high repeatability when performed by different people.

For the insertion of the first and the last pod, the percentage of experiments with significant effect for genotype was 82.61% (Tables 4 and 5). The existence of genetic variability for insertion of the first pod and insertion of the last pod makes it possible to select upright common bean lines in most of the VCU experiments. Common bean cultivars with insertion of the first pod equal to or greater than 12 cm are easier to harvest (Melo, 2009). In addition, upright plants with lower insertion of the last pod are usually more resistant to lodging (Mambrin, Ribeiro, Storck, Domingues, & Barkert, 2015).

The experiments that presented the lowest scores for CEV and LSD statistics were not the same as those with the highest Fc, h^2 and SA for the insertion of the first pod and the last pod, indicating no correlation between these statistics. CEV and LSD statistics do not consider the level of genotype variation and thus are not the most adequate statistics to evaluate experiment quality, according to Resende and Duarte (2007).

The lowest scores for Fc, h^2 and SA statistics were observed in experiments 10, 12, 17 and 22 for insertion of the first pod (Table 4) and in experiments 5, 10, 11, and 17 for insertion of the last pod (Table 5). In these experiments, no significant effect for genotype was observed by the F-test for either of the traits. In the other experiments, the mean square of genotype was significant, Fc ⩾ 2.00, h^2 ⩾ 49.00%, and SA ⩾ 0.70, allowing the selection of common bean lines with higher insertion of the first pod and lower insertion of the last pod with greater experimental precision. Preliminary results indicated the possibility of selecting common bean lines with moderate to high experimental precision for insertion of the first and last pod using the Fc and SA statistics (Cargnelutti Filho et al., 2010).

Table 4. Analysis of variance containing the number of lines evaluated by experiment (N), commercial group (G), minimum value (minimum), maximum value (maximum), mean ($\hat{m}$), genotype mean square (GMS), F-test values for genotype (Fc), coefficient of experimental variation (CEV, %), least significant difference between the means of the genotypes using the Tukey test at 5% probability (LSD, %), heritability (h^2, %) and selective accuracy (SA) for insertion of the first pod obtained in 23 common bean experiments carried out between 1998 and 2015.

Exp	Year/season	N	G[1]	Insertion of the first pod (cm)								
				Minimum	Maximum	$\hat{m}$	GMS	Fc	CEV	LSD	h^2	SA
1	1998/rainy	20	Co	6.80	19.00	12.72	12.33*	2.78	16.56	6.54	63.99	0.80
2	1999/rainy	20	Co	5.10	20.20	8.99	9.76*	2.70	21.13	5.90	63.02	0.79
3	2000/rainy	24	B	6.40	30.20	14.56	40.81*	2.19	29.67	13.62	54.27	0.74
4	2001/rainy	14	C	17.70	50.90	27.94	123.89*	3.75	20.55	17.28	73.37	0.86
5	2001/rainy	18	B	13.30	47.30	25.49	81.65*	2.04	24.79	19.44	51.08	0.71
6	2002/rainy	18	Co	12.64	67.78	33.54	285.44*	4.02	25.12	25.92	75.13	0.87
7	2003/rainy	16	C	11.80	28.60	19.84	31.78*	2.71	17.26	10.42	63.12	0.79
8	2003/rainy	26	B	10.70	27.50	16.62	20.17*	3.38	14.70	7.76	70.40	0.84
9	2004/rainy	16	Co	12.40	28.10	19.39	17.56*	2.86	12.78	6.35	65.00	0.81
10	2005/rainy	16	Co	15.30	32.00	21.97	13.13^{ns}	0.83	18.06	10.17	0.00	0.00
11	2006/rainy	13	Co	20.90	43.41	29.39	38.58*	2.06	14.73	10.85	51.40	0.72
12	2007/rainy	15	Co	13.78	25.84	19.70	10.96^{ns}	1.06	16.32	8.19	5.66	0.24
13	2009/dry	17	Co	9.75	22.46	15.78	13.07*	2.93	13.38	5.45	65.90	0.81
14	2010/rainy	14	Co	9.13	24.71	17.04	22.27*	4.66	12.82	5.52	78.55	0.89
15	2011/dry	16	Co	11.89	24.10	16.96	18.81*	3.04	14.67	6.38	67.10	0.82
16	2011/rainy	16	Co	14.25	27.52	19.78	17.32*	2.24	14.05	7.13	55.39	0.74
17	2012/rainy	14	Co	20.00	43.70	29.50	39.40^{ns}	1.59	16.89	14.99	36.99	0.61
18	2013/dry	14	Co	10.67	18.60	14.71	9.91*	5.18	9.41	4.16	80.69	0.90
19	2013/rainy	15	Co	8.50	27.88	17.57	35.64*	6.02	13.84	7.36	83.40	0.91
20	2014/dry	16	Co	9.74	22.00	15.09	13.84*	2.16	16.77	7.70	53.75	0.73
21	2014/rainy	16	Co	9.11	26.00	18.31	35.21*	3.08	18.45	8.66	67.55	0.82
22	2015/dry	14	Co	9.00	16.50	11.37	3.78^{ns}	1.59	13.57	3.89	37.13	0.61
23	2015/rainy	14	Co	8.30	22.60	15.50	23.89*	4.36	15.11	5.91	77.05	0.88

^{ns}Not significant. *Significant by the F-test at 0.05 probability. [1]Group (G): B = black; C = Carioca; Co = colours (black, Carioca and other colours).

Table 5. Analysis of variance containing the number of lines evaluated by experiment (N), commercial group (G), minimum value (minimum), maximum value (maximum), mean ($\hat{m}$), genotype mean square (GMS), F-test values for genotype (Fc), coefficient of experimental variation (CEV, %), least significant difference between the means of the genotypes using the Tukey test at 5% probability (LSD, %), heritability (h^2, %) and selective accuracy (SA) for insertion of the last pod obtained in 23 common bean experiments carried out between 1998 and 2015.

Exp	Year/season	N	G[1]	Insertion of the last pod (cm)								
				Minimum	Maximum	$\hat{m}$	GMS	Fc	CEV	LSD	h^2	SA
1	1998/rainy	20	Co	28.60	68.80	50.80	126.55*	5.04	9.86	15.55	80.17	0.89
2	1999/rainy	20	Co	19.90	56.60	37.50	94.24*	3.14	14.61	17.02	68.14	0.82
3	2000/rainy	24	B	10.00	59.20	32.01	219.09*	3.01	26.63	26.89	66.82	0.82
4	2001/rainy	14	C	42.20	75.40	59.92	106.48*	2.05	12.03	21.70	51.16	0.71
5	2001/rainy	18	B	32.08	74.88	55.47	126.95ns	1.48	16.68	28.46	32.56	0.57
6	2002/rainy	18	Co	28.16	114.10	74.45	716.22*	2.89	21.14	48.41	65.42	0.81
7	2003/rainy	16	C	38.10	81.60	55.44	227.59*	4.51	12.81	21.61	77.83	0.88
8	2003/rainy	26	B	24.40	61.50	39.94	104.96*	3.63	13.46	17.07	72.48	0.85
9	2004/rainy	16	Co	27.40	59.00	43.27	86.86*	3.89	10.92	12.11	74.28	0.86
10	2005/rainy	16	Co	36.20	66.40	51.20	53.45ns	1.16	13.25	17.39	13.87	0.37
11	2006/rainy	13	Co	58.75	85.25	70.06	61.64ns	1.55	9.01	15.82	35.40	0.59
12	2007/rainy	15	Co	47.46	76.97	59.53	114.51*	4.47	8.50	12.89	77.62	0.88
13	2009/dry	17	Co	33.90	68.15	46.54	97.04*	5.11	9.36	11.25	80.45	0.90
14	2010/rainy	14	Co	31.18	67.27	45.54	111.93*	3.55	12.32	14.16	71.87	0.85
15	2011/dry	16	Co	27.40	73.57	43.73	218.18*	8.05	11.91	13.35	87.57	0.93
16	2011/rainy	16	Co	33.15	61.30	45.44	72.72*	2.51	11.83	13.78	60.25	0.78
17	2012/rainy	14	Co	30.50	82.20	56.78	151.40ns	1.85	15.91	27.18	46.09	0.68
18	2013/dry	14	Co	18.44	39.10	29.00	44.94*	4.77	10.58	9.23	79.03	0.89
19	2013/rainy	15	Co	12.11	47.83	34.15	151.53*	5.83	14.93	15.42	82.86	0.91
20	2014/dry	16	Co	21.22	62.70	45.38	221.00*	4.49	15.47	21.35	77.71	0.88
21	2014/rainy	16	Co	22.00	70.70	42.46	339.89*	7.16	16.22	17.66	86.03	0.93
22	2015/dry	14	Co	21.00	47.00	29.96	55.32*	5.52	10.57	7.99	81.87	0.90
23	2015/rainy	14	Co	16.60	69.80	36.34	133.85*	2.35	20.78	19.06	57.39	0.76

nsNot significant. *Significant by the F-test at 0.05 probability. [1]Group (G): B = black; C = Carioca; Co = colours (black, Carioca and other colours).

Upright common bean lines have been characterized by lodging, insertion of first pod and insertion of the last pod (Ribeiro et al., 2008; Faria et al., 2013; 2014; Jost et al., 2014; Maziero et al., 2016; Ribeiro et al., 2016). In this study, considering the highest scores for Fc, h^2 and SA statistics, it was possible to select common bean lines with high experimental precision in 19 experiments by the evaluation of the insertion of the first and the last pod (Tables 4 and 5), and in 16 experiments by evaluation of lodging (Table 3). Therefore, a better genetic differentiation between common bean lines for upright plant architecture was achieved by evaluating the insertion of the first and the last pod in the VCU experiments that presented Fc $\geqslant$ 2.00, $h^2 \geqslant$ 49.00%, and SA $\geqslant$ 0.70.

Conclusion

F-test values for genotype, heritability and selective accuracy allow a better evaluation of the genetic superiority of lines in relation to earliness and upright plant architecture and should be used in common bean breeding programmes. In the experiments of value of cultivation and use, with F-test values for genotype $\geqslant$ 2.00, heritability $\geqslant$ 49.00%, and selective accuracy $\geqslant$ 0.70, the best genetic differentiation of early common bean lines is performed by the cycle; the best genetic differentiation of upright plant architecture is carried out by the insertion of the first pod and the last pod.

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