DOI: http://doi.org/10.1590/1678-992X-2021-0160

Scientia Agricola

ISSN 1678-992X

Research Article

Selection strategies for identifying fast cooking, mineral-biofortified bean cultivars with high agronomic performance

Nerinéia Dalfollo Ribeiro[1]*, Sandra Maria Maziero[2], Guilherme Godoy dos Santos[3], Greice Godoy dos Santos[1]

[1]Universidade Federal de Santa Maria/CCR – Depto. de Fitotecnia, Av. Roraima, 1000 – 97105-900 – Santa Maria, RS – Brasil.

[2]Universidade Federal da Fronteira Sul, Rod. ERS 135, 200 – 99700-970 – Erechim, RS – Brasil.

[3]Associação Sulina de Crédito e Assistência Rural/ASCAR-EMATER, Av. Nossa Sra. Medianeira, 278 – 97060-000 – Santa Maria, RS – Brasil.

*Corresponding author <nerineia@hotmail.com>

Edited by: Leonardo Oliveira Medici

Received June 24, 2021
Accepted September 10, 2021

ABSTRACT: Simultaneous selection for various agronomic traits, cooking time and mineral concentration are major challenges for common-bean (*Phaseolus vulgaris* L.) breeding programs. The authors of this study proposed to analyze genetic gain estimates obtained by direct and indirect selection using selection indices and economic weights for 13 traits, and to determine the most efficient selection strategy for the simultaneous selection of fast cooking, mineral-biofortified common bean cultivars with high agronomic performance. For this purpose, three experiments were carried out in different growing seasons to evaluate 49 common bean cultivars of different grain types. Agronomic performance was evaluated based on six traits; cooking time was determined using a Mattson cooker; and the concentration of six minerals was analyzed in samples of raw grains. Significant genotype × environment interaction or genotype effects were observed for all traits, indicating the existence of genetic variability. Direct selection resulted in high genetic gain estimates for individual traits, but caused undesirable changes in one or more of the traits under selection. The classic, base, desired-gains and rank-sum selection indices tested with six economic weights do not provide genetic gain estimates favorable to the selection of all traits. The multiplicative index is the best selection strategy for use in the breeding program when aiming at the simultaneous selection of fast cooking, mineral-biofortified common bean cultivars with high agronomic performance.

Keywords: direct selection, indirect selection, selection indices, genetic gain

Introduction

Common bean (*Phaseolus vulgaris* L.) is grown in several countries and used to feed thousands of people thanks to the ability of this crop to adapt to different growing conditions, a result of the wide genetic diversity observed in its cultivars (Rana et al., 2015). In addition, common bean is an important source of protein, iron and zinc in the human diet (Câmara et al., 2013), which makes it a food essential to combating malnutrition.

The great importance of common bean in the context of food security has encouraged many breeding programs to work with this crop. The development of common bean cultivars with upright plant architecture and high grain yield potential meets the demand of common bean producers. If these cultivars have fast cooking and high mineral concentrations, it may represent a significant contribution to the health of consumers, since fast cooking common bean cultivars retained more potassium, calcium, magnesium, iron, zinc, and copper (Wiesinger et al., 2016).

Simultaneous selection for various agronomic traits, cooking time and mineral concentration is a major challenge for common-bean breeding programs. This is because direct selection allowed for a high genetic gain for traits analyzed individually, but caused undesirable changes in other important traits for selection (Jost et al., 2012; Maziero et al., 2015). Selection indices, in turn, allowed for the identification of superior common bean cultivars for several traits (Arns et al., 2018; Bertoldo et al., 2010; Dias et al., 2020; Gomes et al., 2018; Jost et al., 2012; Maziero et al., 2015; Ribeiro et al., 2019a; Silva et al., 2018; Zanotti et al., 2020), thereby enhancing the efficiency of breeding programs.

Simultaneous selection of common bean cultivars based on various agronomic traits, fast cooking and mineral biofortification, using selection indices and economic weights, is unprecedented in common bean. Identifying the most efficient strategy to achieve this objective represents an important innovation for breeding programs. Therefore, the present study was undertaken to analyze genetic gain estimates obtained by direct and indirect selection using different selection indices and economic weights for 13 traits, as well as to define the most efficient selection strategy for the simultaneous selection of fast cooking, mineral-biofortified common bean cultivars with high agronomic performance.

Materials and Methods

Origin of the seeds and description of the experiments

Seeds of 49 common bean cultivars were multiplied in the spring of 2016 (rainy season crop) in Santa Maria, state of Rio Grande do Sul (RS), Brazil (29°42′ S, 53°43′ W, altitude of 95 m). The climate of the region is the humid subtropical type, with hot summers with no clearly defined dry season. The seeds were provided by family farmers who grow common bean in RS (registration number in SISGEN: A9D54FA) and are assisted by the Southern Association for Rural Credit and Assistance (37 landraces) and the Common-Bean Germplasm Bank of

Federal University of Santa Maria (12 modern cultivars). This first experiment was necessary to an increase in the number of seeds and standardization of the seed production process. The common bean cultivars analyzed vary in grain color, size and shape, representing the diversity of common beans produced in Brazil (Figure 1).

The 49 common bean cultivars were evaluated in three experiments carried out in Santa Maria in a 7 × 7 simple lattice design with two replicates. Sowing was carried out over three growing seasons, namely, summer 2017 (dry season crop), spring 2017 (rainy season crop) and summer 2018 (rainy season crop). The experimental plot consisted of four 3-m rows spaced 0.5 m apart, with only the two central rows considered a usable area (3 m^2).

The soil in the experimental area is a typic alitic Argisol, Hapludalf, and showed the following chemical composition before the experiment's installation: organic matter - 1.8 %; base saturation - 73.9 %; pH (H_20) - 6.1; effective cation exchange capacity - 9.9 cmol$_c$ dm^{-3}; potassium - 80.0 mg dm^{-3}; phosphorus - 12.7 mg dm^{-3}; calcium - 6.7 cmol$_c$ dm^{-3}; iron – 2.026.5 mg dm^{-3}; copper - 1.2 mg dm^{-3}; and zinc - 0.5 mg dm^{-3}.

The soil was prepared in a conventional manner, and fertilized with 275 kg ha^{-1} of the N-P_2O_5-K_2O 5-20-20 formula (urea - 45 % nitrogen; triple superphosphate - 18 % P_2O_5; and potassium chloride - 60 % K_2O) at furrow sowing and 67 kg ha^{-1} of urea (45 % nitrogen) were distributed at the growth stage of the first trifoliate

Figure 1 – Common bean landraces and modern cultivars evaluated. Credit: Greice Godoy dos Santos

leaf. No micronutrients were added to the fertilizers. Seed treatment and control of weed plants and insects were carried out according to the management practices adopted for the common bean crop in RS (CTSBF, 2012). Irrigation was applied only to ensure homogeneity of the initial plant stand, and there was no disease control.

Evaluation of agronomic traits

Lodging was analyzed at the maturity stage (R9), i.e., when the pods began to dry and acquire the color typical of each cultivar, in the usable area of the plots, on a scale of scores ranging from one (all upright plants) to nine (all plants fallen, in contact with the soil). Next, ten plants were randomly harvested from the usable area to measure the insertion of the first pod and the yield components (number of pods per plant, number of grains per pod and mass of 100 grains).

The other plants in the usable area were harvested manually, to avoid mixing the cultivars, and identified with labels. The grains were also threshed manually to reduce the incidence of mechanical damage and oven-dried to 13 % water. Grain yield was determined from the total grain production obtained from the ten plants and the usable area and expressed in kg ha^{-1}.

Evaluation of cooking time and mineral concentration

Cooking time was evaluated using a Mattson cooker with 25 plungers. For this purpose, samples of 25 grains of common bean remained soaked in 50 mL of distilled water for 8 h, at room temperature (20 ± 2 °C), before being distributed over the orifices of the equipment. The cooker was then placed in a 7 L pot with 3 L of hot distilled water and left to cook on a domestic stove. The moment the plunger dropped indicated when the grains were cooked. Cooking time was determined as the average drop time of the first 13 plungers.

To measure the mineral concentration, 30 g of raw grain were collected at random and ground. A 0.5 g aliquot of the flour was used for the acid digestion process, which was carried out as recommended by Miyazawa et al. (2009). The potassium concentration was determined on a flame photometer; phosphorus was analyzed using an optical emission spectrophotometer, and the concentrations of magnesium, iron, zinc, and copper were read with an atomic absorption spectrophotometer.

Statistical analyses

Individual analysis of variance was performed for all the traits evaluated in the different growing seasons and the efficiency of the use of the lattice design was evaluated as described by Ramalho et al. (2005). Homogeneity of residual variances was analyzed by Hartley's maximum F-test (Cruz et al., 2014).

Combined analysis of variance was implemented to consider the effects of genotype (G), environment (E) and G × E interaction as fixed. The significance level was analyzed using the F-test, at 5 % probability. Multicollinearity diagnostics was carried out with the phenotypic correlation matrix obtained from combined analysis of variance according to the criteria established by Montgomery et al. (2012).

Genetic gain was calculated by direct selection and by using the selection indices, based on mean data obtained in three growing seasons. The applied selection intensity was 20 %, which resulted in the selection of ten superior common bean cultivars for agronomic traits, fast cooking and mineral-biofortification. In the direct selection approach one trait was selected at a time. The selection indices were performed to the simultaneous selection of all evaluated traits. The genetic gain (%) expected with direct selection and the selection indices were estimated by the following expression:

$$GG = \{[(Xs - Xo)h^2]100\}/Xo \quad (1)$$

in which GG is the genetic gain (%); Xs the mean of the selected cultivars; Xo the mean of all evaluated cultivars; and h^2 the heritability.

Genetic gain determined by indirect selection, or by the indirect response to selection, was obtained as:

$$GG_{j(i)} = DS_{j(i)}h_j^2 \quad (2)$$

in which $GG_{j(i)}$ is the genetic gain obtained in trait j, by selection on trait i; and $DS_{j(i)}$ the indirect selection differential obtained as a function of the mean of the trait of the cultivars selected based on the other trait i, on which the selection was performed.

The following selection indices were analyzed: classic (Hazel, 1943; Smith, 1936), base (Williams, 1962), desired-gains (Pesek and Baker, 1969), rank-sum (Mulamba and Mock, 1978) and multiplicative (Subandi et al., 1973). The methodology for obtaining these selection indices was described by Cruz et al. (2014). Selection was carried out to obtain the lowest values for lodging and cooking time and the highest values for the other traits evaluated.

For the classic, base, desired-gains and rank-sum indices, the following economic weights were established: (1) equivalent to the coefficient of genetic variation; (2) proportional to the standard deviation; (3) equal to a gain of 10 % in relation to the mean for each trait; (4) weight two for grain yield and weight one for the other traits; (5) weight six for grain yield and weight one for the other traits; and (6) weight six for grain yield, weight three for cooking time and weight one for the other traits. It is not possible to establish economic weights for the multiplicative index.

The means obtained for the different evaluated traits, taking an average over the three growing seasons, were subjected to cluster analysis by Scott-Knott's procedure, at 5 % probability. This analysis was used to allow for the best characterization of the selected common bean cultivars. All statistical analyses were carried out using the Genes software program (Cruz, 2016).

Results and Discussion

Analysis of variance and multicollinearity

Thirty-nine combinations of traits and growing seasons were subjected to individual analysis (13 traits × 3 seasons). The use of the simple lattice design showed < 100 % efficiency for 22 combinations; in other words, in 56.4 % of the analyzed combinations, the application of this experimental design was not efficient. Thus, combined analysis of variance was carried out in a randomized-block design, as recommended by Ramalho et al. (2005).

A significant G × E interaction was observed for all traits, except for the number of pods per plant and potassium concentration, which showed a significant genotype effect (Table 1). A significant G × E interaction had been previously reported for agronomic traits (Dias et al., 2020; Maziero et al., 2015; Ribeiro et al., 2018, 2019a), cooking time (Arns et al., 2018; Dias et al., 2020;

Table 1 – Combined analysis of variance, considering the randomized block design, containing the degrees of freedom, mean squares, mean, coefficient of experimental variation, coefficient of genetic variation, CGV/CEV ratio and selective accuracy for the following traits: lodging, insertion of the first pod, number of pods per plant, number of grains per pod, mass of 100 grains, grain yield, cooking time, concentrations of potassium, phosphorus, magnesium, iron, zinc, and copper of 49 common bean cultivars evaluated in the three growing seasons (dry season of 2017, rainy season of 2017 and dry season of 2018).

	DF	Mean square				
		LDG	IFP	NPP	NGP	M100G
			cm			g
Block/environment	3	35.949	9.865	25.573	0.470	6.489
Genotype (G)	48	4.278*	38.107*	34.028*	1.609*	250.962*
Environment (E)	2	3.309ns	1,394.625*	1,048.233*	0.654ns	406.048*
G × E	96	3.591*	18.533*	5.351ns	0.276*	24.448*
Error	144	1.018	4.775	5.092	0.124	3.502
Mean		6.201	15.192	9.750	3.581	30.002
CEV (%)		16.275	14.383	23.143	9.839	6.238
CGV (%)		11.886	15.515	22.523	13.894	21.405
CGV/CEV ratio		0.730	1.079	0.973	1.412	3.431
SA		0.846	0.862	0.220	0.742	0.926
		YIELD	CT	K	P	Mg
		kg ha^{-1}	min:s	g kg^{-1} of dry mater		
Block/environment	3	667,047.375	44,405.650	1.532	0.503	0.044
Genotype (G)	48	913,927.359*	847,258.534*	1.210*	3.490*	0.212*
Environment (E)	2	27,127,494.264*	2,203,156.296*	8.736ns	12.900*	11.305*
G × E	96	188,400.194*	47,725.376*	0.969ns	5.104*	0.082*
Error	144	95,776.973	19,656.143	0.825	0.609	0.057
Mean		1,440.587	17:26	12.063	4.084	3.050
CEV (%)		21.483	13.405	7.529	19.113	7.809
CGV (%)		25.633	35.511	2.101	16.964	5.278
CGV/CEV ratio		1.193	2.649	0.279	0.887	0.676
SA		0.701	0.766	0.386	0.938	0.555
		Fe	Zn	Cu		
		mg kg^{-1} of dry mater				
Block/environment	3	385.279	105.549	6.976		
Genotype (G)	48	362.052*	61.310*	5.054*		
Environment (E)	2	5,678.167*	1,837.994*	453.435*		
G × E	96	449.138*	26.404*	1.845*		
Error	144	137.892	11.057	1.063		
Mean		67.989	29.812	9.752		
CEV (%)		17.271	10.638	10.572		
CGV (%)		8.990	9.804	8.363		
CGV/CEV ratio		0.520	0.922	0.791		
SA		0.832	0.787	0.651		

*Significant by F test at 0.05 probability; nsNon-significant. CEV = coefficient of experimental variation; CGV = coefficient of genetic variation; SA = selective accuracy; DF = degrees of freedom; LDG = lodging; IFP = insertion of the first pod; NPP = number of pods per plant; NGP = number of grains per pod; M100G = mass of 100 grains; YIELD = grain yield; CT = cooking time; K = potassium; P = phosphorus; Mg = magnesium; Fe = iron; Zn = zinc; Cu = copper.

Steckling et al., 2017) and mineral concentration (Hossain et al., 2013; Steckling et al., 2017) in experiments with common bean genotypes. Thus, there is genetic variability in agronomic traits, cooking time and mineral concentration, which indicates the possibility of selecting superior common bean genotypes.

Multicollinearity diagnostics revealed a condition number equal to 46.1, characterizing weak collinearity, according to Montgomery et al. (2012). Therefore, all the traits evaluated were maintained in the analyses of genetic gain by direct and indirect selection and selection indices.

Genetic gain by direct and indirect selection

When the individual traits were selected, favorable genetic gain estimates were obtained by direct selection to reduce lodging and cooking time and increase all the other traits assessed (Table 2). Negative genetic gain estimates were found for lodging (–14.9 %) and cooking time (–23.3 %), indicating success in the selection of upright plant architecture and fast cooking common bean cultivars. The highest values for positive genetic gain were recorded for mass of 100 grains (34.0 %), grain yield (31.4 %), number of pods per plant (29.2 %), phosphorus concentration (23.0 %) and insertion of the first pod (21.0 %), demonstrating favorable conditions for the selection of superior common bean cultivars for each of these traits. Similarly, genetic gain estimates were observed by direct selection in magnitude and sign favorable to the selection of common bean lines with high agronomic performance and high mineral concentrations (Jost et al., 2012; Maziero et al., 2015). In the present study, direct selection was efficient in obtaining individual genetic gains for different agronomic traits, cooking time and mineral concentration in the selection of common bean cultivars.

As regards selection of grain yield, genetic gain estimates were obtained by indirect selection in magnitude and sign favorable to selection for insertion of the first pod (14.4 %), number of pods per plant (24.2 %), number of grains per pod (14.8 %) and concentrations of magnesium (16.5 %), zinc (1.9 %) and copper (5.3 %), though contrary to the objectives of selection for the other traits (Table 2). A similar response was observed for the other 12 traits, confirming that the direct selection of one trait caused an undesirable response in one or more traits under selection. Therefore, the direct selection of a main trait failed to provide favorable indirect gains for all the secondary traits that are being selected by the breeding program, confirming the results observed in the selection of inbred common bean lines (Jost et al., 2012; Maziero et al., 2015) and progenies in an F_2 generation of soybean (Costa et al., 2004). In this case, the use of selection indices can be an alternative for obtaining more balanced genetic gain estimates for all traits under selection.

Genetic gain obtained by selection indices and economic weights

Total genetic gain estimates ranged from 34.3 to 45.1 % in the 25 combinations of selection indices and economic weights tested (Table 3). The sign and/or magnitude of the obtained individual gains varied, which enabled the analysis and definition of the best combination of selection index and economic weight to be used for the selection of superior common bean cultivars for all the traits evaluated. The use of selection indices allowed the simultaneous selection for several important traits for common bean (Bertoldo et al., 2010; Gomes et al., 2018; Jost et al., 2012; Maziero et al., 2015) and soybean (Costa et al., 2004) breeding programs. The higher total genetic gain estimate and/or the attainment of individual

Table 2 – Genetic gains estimates with direct and indirect selection for the following traits: lodging, insertion of the first pod, number of pods per plant , number of grains per pod, mass of 100 grains, grain yield, cooking time, concentrations of potassium, phosphorus, magnesium, iron, zinc, and copper of 49 common bean cultivars evaluated in three experiments carried out between 2017 and 2018.

	LDG	IFP	NPP	NGP	M100G	YIELD	CT	K	P	Mg	Fe	Zn	Cu
							%						
LDG	–14.96	6.75	1.43	0.81	–4.51	–0.83	6.34	–3.29	1.83	4.50	–0.62	1.63	–1.24
IFP	–6.65	21.07	0.19	11.36	–11.12	5.40	12.58	–3.97	–8.09	7.86	0.94	–0.56	1.07
NPP	4.20	3.47	29.23	6.45	–17.88	17.70	9.41	–2.44	–18.93	12.40	0.05	–7.79	–2.91
NGP	–1.52	8.94	8.67	15.95	–17.96	8.96	8.59	–0.17	–6.42	7.53	0.52	0.75	5.88
M100G	1.94	–14.07	–14.20	–16.14	34.08	–13.06	–13.78	1.47	16.34	–12.32	–1.66	–0.84	–8.18
YIELD	2.24	14.45	24.25	14.84	–25.19	31.44	10.81	–6.61	–15.86	16.54	–2.96	1.95	5.35
CT	23.65	–16.48	–12.20	–14.26	31.33	–11.81	–23.30	19.80	6.30	–11.65	–6.46	–4.58	–9.68
K	0.20	–0.09	–0.13	0.20	0.11	0.16	–0.29	1.72	–0.15	0.93	–0.01	0.20	0.21
P	–6.29	–0.69	–4.29	–1.08	5.30	–5.01	–1.18	3.34	23.06	–3.28	2.86	3.32	–2.82
Mg	–0.42	2.62	2.16	2.36	–4.18	3.23	2.41	1.60	–2.08	5.96	–0.55	–0.14	0.48
Fe	–1.35	0.94	–0.25	2.06	2.46	1.05	–1.31	2.53	3.23	–0.50	9.65	1.15	2.16
Zn	–3.52	0.70	2.28	5.20	–3.04	1.92	–2.72	–0.02	3.69	–0.16	–0.39	12.72	8.37
Cu	–3.06	1.19	1.96	1.41	–2.86	4.43	–2.53	–0.30	0.34	1.46	0.24	7.73	9.61

LDG = lodging; IFP = insertion of the first pod; NPP = number of pods per plant; NGP = number of grains per pod; M100G = mass of 100 grains; YIELD = grain yield; CT = cooking time; K = potassium; P = phosphorus; Mg = magnesium; Fe = iron; Zn = zinc; Cu = copper.

Table 3 – Expected selection gains with the simultaneous selection of the traits lodging, insertion of the first pod, number of pods per plant, number of grains per pod, mass of 100 grains, grain yield, cooking time, concentrations of potassium, phosphorus, magnesium, iron, zinc, and copper obtained from 49 common bean cultivars evaluated in three experiments carried out between 2017 and 2018.

Index	Economic Weight**	Expected selection gain													
		LDG	IFP	NPP	NGP	M100G	YIELD	CT	K	P	Mg	Fe	Zn	Cu	Total gain
		%													
1. Classic	1	0.81	7.00	19.41	9.24	−13.24	28.93	−15.45	−0.19	−0.99	2.58	2.03	−0.25	2.60	42.48
2. Classic	2	−1.24	6.76	18.94	8.30	−12.20	30.80	−13.67	−0.04	−2.22	2.62	0.54	−0.24	3.50	41.85
3. Classic	3	−1.24	6.76	18.94	8.30	−12.20	30.80	−13.67	−0.04	−2.22	2.62	0.54	−0.24	3.50	41.85
4. Classic	4	−1.24	6.76	18.94	8.30	−12.20	30.80	−13.67	−0.04	−2.22	2.62	0.54	−0.24	3.50	41.85
5. Classic	5	−1.24	6.76	18.94	8.30	−12.20	30.80	−13.67	−0.04	−2.22	2.62	0.54	−0.24	3.50	41.85
6. Classic	6	−1.24	6.76	18.94	8.30	−12.20	30.80	−13.67	−0.04	−2.22	2.62	0.54	−0.24	3.50	41.85
7. Base	1	0.40	7.08	16.14	8.73	−12.32	29.20	−15.68	−0.12	−1.25	2.22	−0.78	−0.63	1.32	34.31
8. Base	2	−1.24	6.76	18.94	8.30	−12.20	30.80	−13.67	−0.04	−2.22	2.62	0.54	−0.24	3.50	41.85
9. Base	3	−1.24	6.76	18.94	8.30	−12.20	30.80	−13.67	−0.04	−2.22	2.62	0.54	−0.24	3.50	41.85
10. Base	4	−0.83	5.40	17.70	8.96	−13.06	31.44	−11.81	0.16	−5.01	3.23	1.05	1.92	4.43	43.58
11. Base	5	−0.83	5.40	17.70	8.96	−13.06	31.44	−11.81	0.16	−5.01	3.23	1.05	1.92	4.43	43.58
12. Base	6	−0.83	5.40	17.70	8.96	−13.06	31.44	−11.81	0.16	−5.01	3.23	1.05	1.92	4.43	43.58
13. Desired gains	1	−1.44	5.49	20.22	8.30	−12.52	30.80	−11.59	−0.09	−2.93	2.77	−0.35	1.64	3.46	43.76
14. Desired gains	2	−1.44	5.49	20.22	8.30	−12.52	30.80	−11.59	−0.09	−2.93	2.77	−0.35	1.64	3.46	43.76
15. Desired gains	3	−1.44	5.49	20.22	8.30	−12.52	30.80	−11.59	−0.09	−2.93	2.77	−0.35	1.64	3.46	43.76
16. Desired gains	4	−1.44	5.49	20.22	8.30	−12.52	30.80	−11.59	−0.09	−2.93	2.77	−0.35	1.64	3.46	43.76
17. Desired gains	5	−1.44	5.49	20.22	8.30	−12.52	30.80	−11.59	−0.09	−2.93	2.77	−0.35	1.64	3.46	43.76
18. Desired gains	6	−1.44	5.49	20.22	8.30	−12.52	30.80	−11.59	−0.09	−2.93	2.77	−0.35	1.64	3.46	43.76
19. Rank sum	1	1.83	13.63	9.46	12.20	−15.15	19.84	−19.00	0.08	1.42	2.28	2.67	3.97	4.32	37.55
20. Rank sum	2	4.29	9.71	14.80	9.72	−12.60	25.92	−18.11	−0.09	−1.69	2.96	1.18	−1.18	0.64	35.55
21. Rank sum	3	4.29	9.71	14.80	9.72	−12.60	25.92	−18.11	−0.09	−1.69	2.96	1.18	−1.18	0.64	35.55
22. Rank sum	4	−0.83	7.35	12.40	11.61	−15.03	23.72	−12.34	0.76	−4.50	3.09	3.64	6.93	6.12	42.92
23. Rank sum	5	−1.44	5.43	16.12	10.53	−14.23	28.00	−11.72	0.61	−5.77	3.15	3.44	5.72	5.30	45.14
24. Rank sum	6	−0.62	6.26	17.56	10.25	−13.20	27.72	−14.53	0.36	−4.89	2.53	4.00	2.15	5.22	42.81
25. Multiplicative	–	−2.88	8.24	13.53	11.33	−14.80	23.86	−14.48	0.22	2.38	1.69	2.30	5.14	4.39	40.92

*Economic weight equivalent to: 1: coefficient of genetic variation; 2: standard deviation; 3: 10 % gain in relation to the mean for each trait; 4: two for the grain yield and one for the other traits; 5: six for the grain yield and one for the other traits; 6: six for the grain yield, three for the cooking time and one for the other traits. LDG = lodging; IFP = insertion of the first pod; NPP = number of pods per plant; NGP = number of grains per pod; M100G = mass of 100 grains; YIELD = grain yield; CT = cooking time; K = potassium; P = phosphorus; Mg = magnesium; Fe = iron; Zn = zinc; Cu = copper.

gains favorable to the selection objectives defined the best selection index to be employed in the selection of superior common bean cultivars.

Mass of 100 grains showed negative genetic gain in the 25 combinations of selection indices and economic weights evaluated, which is unfavorable to the selection of common bean cultivars with a larger grain size. This can be explained by the fact that common bean cultivars that stood out as regards grain yield produced grains from small to medium size (≤ 28.3 g, Table 4). The common-bean grain types most consumed in Brazil are carioca (beige seed coat with brown streaks) and black, and their size varies from small to medium. For this reason, obtaining negative genetic gain for mass of 100 grains is not a problem in the selection of superior common bean cultivars, since grains of small to medium size are widely accepted in Brazil.

When the classic index was analyzed with an economic weight equivalent to the coefficient of genetic variation the sixth highest total genetic gain value (42.4 %) and individual genetic gains with signs unfavorable to the selection of common bean cultivars with less lodging and higher concentrations of potassium, phosphorus and zinc (Table 3) were obtained. To the classic index were assigned five more economic weights, being observed equal estimates of individual and total genetic gain in these combinations. In all these cases, the selection direction was not favorable to the objectives of the biofortification program for potassium, phosphorus and zinc. Similary, when the classic index was tested, in combination with different economic weights, one or more agronomic traits (Bertoldo et al., 2010; Gomes et al., 2018) or agronomic traits and mineral concentration (Jost et al., 2012; Maziero et al., 2015) had individual genetic gain estimates unfavorable to the selection of superior common bean cultivars. In the present study, the use of the classic index, considering six economic weights, did not result in estimates of genetic gain favorable to the selection of all the traits evaluated. Therefore, the classic index is not recommended for the selection of fast cooking, mineral-biofortified common bean cultivars with high agronomic performance.

The use of the base index associated with an economic weight equivalent to the coefficient of genetic

Table 4 – Means of the following traits: lodging, insertion of the first pod, number of pods per plant, number of grains per pod, mass of 100 grains, grain yield and cooking time of 49 common bean cultivars evaluated in three experiments carried out between 2017 and 2018.

Cultivar	LDG	IFP	NPP	NGP	M100G	YIELD	CT
		cm			g	kg ha^{-1}	min:s
Selected cultivars by multiplicative index							
Vagem Roxa	3.67 b*	14.82 c	10.78 b	4.46 a	23.83 i	1,669.57 b	15:15 d
Turrialba	6.83 a	16.84 b	12.00 b	4.23 a	23.47 j	1,775.95 a	15:02 d
Mourinho Claro	5.83 b	15.79 b	9.68 b	3.92 a	26.77 h	1,990.38 a	15:13 d
Quero-quero	7.83 a	19.31 a	11.63 b	3.53 b	26.22 h	1,965.70 a	12:20 e
Paraná	6.00 b	16.61 b	12.81 a	3.90 a	27.36 h	1,687.48 b	12:52 e
SCS 205 Riqueza	7.00 a	17.33 b	10.24 b	4.01 a	28.33 h	2,079.32 a	15:08 d
Fepagro Triunfo	5.50 b	14.71 c	13.53 a	4.01 a	25.78 i	1,918.62 a	16:52 d
Carioca Vila Nova do Sul	7.00 a	20.29 a	8.71 c	4.17 a	25.69 i	1,400.77 b	13:36 e
Guapo Brilhante	4.00 b	12.89 d	12.91 a	3.92 a	24.67 i	2,090.54 a	17:04 d
Chumbinho	6.00 b	17.64 b	10.72 b	4.04 a	22.87 j	1,666.62 b	15:07 d
Other cultivars							
Pérola	6.00 b	17.36 b	8.50 c	3.50 b	29.11 g	1,506.79 b	16:35 d
Amendoim Comprido	6.17 b	14.38 c	7.60 c	2.99 c	35.20 e	1,040.35 c	21:50 b
Banana	6.17 b	15.20 c	7.77 c	3.05 c	34.87 e	908.30 d	15:09 d
Inhoque	5.50 b	12.33 d	7.30 c	3.38 c	32.70 f	847.38 d	21:52 b
Verde 208	6.17 b	10.55 d	5.70 c	3.24 c	30.49 g	809.91 d	17:23 d
Rajado 319	7.00 a	15.76 b	10.24 b	3.93 a	22.28 j	1,455.02 b	12:13 e
Guabiju Roxo	6.67 a	16.29 b	5.78 c	2.87 c	32.91 f	853.94 d	14:36 e
Rio Tibagi	6.33 a	14.25 c	11.38 b	4.16 a	24.75 i	1,790.43 a	16:12 d
Preguiçoso	7.00 a	12.87 d	7.63 c	3.06 c	42.86 b	1,029.73 c	22:29 b
Carioca Ibarama	5.17 b	15.49 c	10.87 b	3.72 b	24.31 i	1,503.43 b	15:57 d
Azulão	6.00 b	11.92 d	7.60 c	3.25 c	40.74 c	1,296.77 c	18:55 c
BRS Estilo	6.00 b	13.50 c	10.68 b	3.48 b	27.64 h	1,439.25 b	14:08 e
Argentino	6.83 a	16.96 b	10.92 b	4.00 a	25.32 i	1,501.51 b	15:16 d
Trindade	6.17 b	20.50 a	10.28 b	3.70 b	28.18 h	1,547.02 b	14:03 e
Vermelho Rajado	5.67 b	13.57 c	7.72 c	3.09 c	37.62 d	693.90 d	20:12 b
Carioca Rosa	7.17 a	17.45 b	11.38 b	4.30 a	23.81 i	1,563.46 b	12:44 e
BRS MG Realce	6.17 b	14.68 c	8.90 c	2.93 c	35.76 e	744.82 d	16:33 d
Milico	6.83 a	11.73 d	6.57 c	3.24 c	32.32 f	1,051.27 c	19:12 c
Cavalo Claro Iraí	5.33 b	11.88 d	8.44 c	2.66 d	37.57 d	934.55 d	20:27 b
IPR Uirapurú	5.00 b	16.78 b	10.41 b	4.19 a	25.55 i	1,481.58 b	16:22 d
Folgado	6.17 b	19.52 a	10.40 b	3.97 a	25.58 i	1,799.98 a	13:08 e
Carioca	7.00 a	15.53 c	11.83 b	3.97 a	25.87 i	1,626.82 b	14:26 e
BRS Campeiro	5.50 b	17.04 b	10.84 b	3.94 a	26.95 h	1,865.38 a	15:54 d
Fogo da Serra 322	6.50 a	14.59 c	7.04 c	3.09 c	38.33 d	857.24 d	17:57 c
Manteigão	6.17 b	12.68 d	7.77 c	3.20 c	35.40 e	1,293.73 c	18:05 c
Iraí	5.17 b	11.89 d	8.14 c	2.52 d	38.89 d	1,271.03 c	20:31 b
Vagem Larga	6.83 a	20.96 a	8.95 c	4.24 a	27.18 h	1,706.14 b	16:11 d
Mouro	6.17 b	12.52 d	7.55 c	3.51 b	34.68 e	1,223.14 c	20:37 b
Vermelho Graúdo	5.00 b	12.54 d	9.10 c	2.41 d	45.67 a	1,184.14 c	56:17 a
Pintadinho 114	6.83 a	15.28 c	10.32 b	4.18 a	25.44 i	1,660.46 b	13:16 e
Predominante 140	7.17 a	16.25 b	10.52 b	3.60 b	29.20 g	1,717.14 b	17:45 c
Rosinha	7.33 a	18.16 b	10.65 b	3.82 b	20.22 k	1,494.67 b	16:04 d
IPR Juriti	6.33 a	13.62 c	15.18 a	3.58 b	27.76 h	2,189.25 a	16:22 d
Mouro 128	6.50 a	11.43 d	7.43 c	3.21 c	30.27 g	1,454.95 b	21:53 b
Bege Ibarama	7.33 a	15.53 c	11.16 b	3.56 b	22.47 j	1,396.83 b	16:52 d
Tubiano	5.50 b	13.33 d	6.70 c	2.71 d	42.65 b	836.43 d	18:21 c
Macanudo	7.50 a	14.08 c	15.47 a	3.95 a	24.55 i	1,576.32 b	14:47 d
Mouro Graúdo Cinza	6.00 b	15.34 c	5.72 c	3.11 c	43.62 b	1,503.40 b	18:30 c
Capixaba	5.83 b	14.41 c	14.27 a	3.90 a	26.38 h	1,687.35 b	16:35 d

*Means followed by same letter in a column constitute a homogeneous group according to the Scott-Knott procedure (p = 0.05). LDG = lodging; IFP = insertion of the first pod; NPP = number of pods per plant; NGP = number of grains per pod; M100G = mass of 100 grains; YIELD = grain yield; CT = cooking time.

variation resulted in the lowest total genetic gain (34.3 %). In this situation, genetic gain estimates contrary to the selection of common bean cultivars with less lodging and biofortified with potassium, phosphorus, iron and zinc were observed. Low total genetic gain values were also observed by Maziero et al. (2015) when the base index was analyzed with an economic weight equivalent to the coefficient of genetic variation, with or without restriction, which resulted in a negative genetic gain for the concentrations of potassium, phosphorus and zinc.

When the base index was evaluated with an economic weight proportional to the standard deviation and equal to a gain of 10 % in relation to the mean of each trait, equal individual genetic gain estimates and with an unfavorable sign for selection of the biofortification for potassium, phosphorus and zinc were observed. However, genetic gain estimates favorable to the selection of common bean lines for five agronomic traits and calcium and iron concentrations were obtained by Jost et al. (2012), who used the base index associated with an economic weight proportional to the standard deviation.

When grain yield was considered the main trait, three economic weights were tested: weight two for grain yield and weight one for the other traits; weight six for grain yield and weight one for the other traits; and weight six for grain yield, weight three for cooking time and weight one for the other traits. In these three situations, there was no variation in the genetic gain estimates obtained for the same trait, with the highest genetic gain observed in grain yield (31.4 %). The other individual genetic gain estimates were favorable to selection, except for the phosphorus concentration (–5.0 %). Similarly, Gomes et al. (2018) assigned different weights to the five agronomic traits evaluated in snap bean lines and obtained desirable genetic gain estimates for four traits, applying the base index. In the present study, the base index associated with the economic weights evaluated did not provide individual genetic gain estimates favorable to simultaneous selection. Therefore, the base index is not recommended for the selection of superior common bean cultivars for agronomic performance, cooking time and mineral biofortification.

The desired-gains index did not show variations in terms of individual genetic gain estimates for the six economic weights tested, with the second highest total genetic gain (43.7 %) obtained between the evaluated combinations of selection index and economic weights. In addition, the sign of the genetic gain estimates observed for the concentrations of potassium, phosphorus and iron were unfavorable to the objectives of mineral biofortification. One or more estimates of individual genetic gain were unfavorable to the simultaneous selection of superior genotypes of common bean (Bertoldo et al., 2010; Jost et al., 2012), snap bean (Gomes et al., 2018) and soybean (Costa et al., 2004), when the desired-gains index was combined with different economic weights. Thus, the desired-gains index, similar to the classic and base indices, is not an efficient selection strategy for identifying superior common bean cultivars for agronomic traits, cooking time and mineral concentration.

The rank-sum index provided genetic gain estimates with a sign unfavorable to the objectives of the selection for lodging (economic weight equivalent to the coefficient of genetic variation); lodging and the concentrations of potassium, phosphorus and zinc (economic weight proportional to the standard deviation and equal to a 10 % gain in relation to the mean of each trait); and phosphorus concentration (weight two for grain yield and weight one for the other traits; weight six for grain yield and weight one for the other traits; and weight six for grain yield, weight three for cooking time and weight one for the other traits). Therefore, for none of the economic weights associated with the rank-sum index was it possible to obtain favorable genetic gains in the selection of all evaluated traits, confirming previous results described for the selection of superior common bean cultivars (Ribeiro et al., 2019a, b; Ribeiro and Mezzomo, 2020). The rank-sum index was also used for ranking the common bean genotypes regarding the traits analyzed (Dias et al., 2020; Silva et al., 2018; Zanottti et al., 2020). The genotypes classified in the first positions were not superior for all the determined traits, which constituted a limitation in the use of the rank-sum index for simultaneous selection in common-bean breeding programs. However, Jost et al. (2012) and Maziero et al. (2015) obtained genetic gain estimates favorable to the selection of superior common bean lines for all agronomic and mineral traits using the rank-sum index. The differences observed justify the need for testing different economic weights associated with the rank-sum index and choosing the combination in which individual gains in magnitude and sign favorable to the objectives of selection are obtained.

When the multiplicative index was applied, a total genetic gain estimate of 40.9 % was observed and individual genetic gains in magnitude and sign favorable to the selection of superior cultivars for all agronomic traits, cooking time and mineral concentration were obtained. The use of the multiplicative index also resulted in genetic gain estimates favorable for all agronomic and mineral traits (Jost et al., 2012; Maziero et al., 2015) and technological quality traits (Arns et al., 2018) considered important in the selection of common bean cultivars. Therefore, the multiplicative index is the best selection strategy to apply to the breeding program for the simultaneous selection of common bean cultivars with high agronomic performance, fast cooking and mineral-biofortification. In addition, the multiplicative index does not require economic weights to be established, which makes its use extremely simple in the routine of a breeding program.

The use of the multiplicative index made it possible to select the ten common bean cultivars which simultaneously showed greater agronomic performance, fast cooking and mineral-biofortification: Vagem Roxa, Turrialba, Mourinho Claro, Quero-quero, Paraná, SCS 205 Riqueza, Fepagro Tiunfo, Carioca Vila Nova do Sul, Guapo Brilhante and Chumbinho (Tables 4 and 5). These cultivars have different grain types namely, black, carioca, red and mouro (gray seed coat with black streaks) (Figure 1), and their mass of 100 grains ranges from 22.8 to 28.3 g (Table 4), which meets the preference of

Table 5 – Means of the concentrations of potassium, phosphorus, magnesium, iron, zinc, and copper of 49 common bean cultivars evaluated in three experiments carried out between 2017 and 2018.

Cultivar	K	P	Mg	Fe	Zn	Cu
	g kg^{-1} of dry mater			mg kg^{-1} of dry mater		
Selected cultivars by multiplicative index						
Vagem Roxa	12.68 a*	3.97 c	3.03 a	77.21 a	32.16 b	10.35 b
Turrialba	12.33 a	4.70 b	3.14 a	66.38 b	37.49 a	10.25 b
Mourinho claro	12.30 a	3.96 c	3.18 a	75.56 a	32.39 b	11.65 a
Quero-quero	11.81 a	4.38 b	3.04 a	75.99 a	32.21 b	9.65 b
Paraná	11.95 a	4.35 b	3.01 b	69.16 a	24.81 c	10.14 b
SCS 205 Riqueza	12.16 a	4.44 b	3.24 a	61.58 b	30.43 c	10.40 b
Fepagro Triunfo	12.26 a	3.31 d	3.22 a	84.93 a	29.06 c	9.75 b
Carioca Vila Nova do Sul	12.16 a	5.11 a	3.22 a	68.98 a	31.54 b	10.29 b
Guapo Brilhante	11.60 a	4.55 b	3.00 b	54.39 b	29.04 c	9.62 b
Chumbinho	12.23 a	3.25 d	3.10 a	70.95 a	37.31 a	10.84 a
Other cultivars						
Pérola	13.00 a	4.40 b	3.37 a	61.14 b	33.28 b	9.70 b
Amendoim Comprido	11.49 a	3.81 c	2.76 b	70.61 a	27.73 c	9.94 b
Banana	11.53 a	3.24 d	2.75 b	61.39 b	32.31 b	10.99 a
Inhoque	12.58 a	3.98 c	2.79 b	61.59 b	25.86 c	8.04 d
Verde 208	11.91 a	5.33 a	2.90 b	66.64 b	39.38 a	11.64 a
Rajado 319	12.79 a	3.91 c	3.15 a	62.69 b	30.48 c	9.34 c
Guabiju Roxo	11.60 a	3.41 d	2.88 b	55.81 b	29.76 c	8.70 c
Rio Tibagi	12.72 a	2.97 d	3.27 a	74.74 a	32.51 b	11.29 a
Preguiçoso	12.23 a	5.41 a	3.06 a	65.94 b	28.46 c	9.24 c
Carioca Ibarama	12.33 a	4.32 b	3.13 a	65.61 b	26.78 c	9.10 c
Azulão	12.44 a	5.43 a	2.76 b	69.66 a	24.94 c	10.27 b
BRS Estilo	11.53 a	3.67 c	3.07 a	51.39 b	28.59 c	9.47 c
Argentino	12.75 a	3.92 c	3.23 a	72.98 a	32.18 b	10.99 a
Trindade	11.98 a	4.26 b	3.25 a	62.74 b	27.36 c	9.49 c
Vermelho Rajado	12.44 a	5.64 a	2.97 b	83.26 a	29.99 c	9.45 c
Carioca Rosa	11.70 a	4.33 b	3.31 a	75.93 a	27.06 c	8.79 c
BRS MG Realce	12.09 a	2.68 d	2.83 b	76.72 a	29.68 c	10.14 b
Milico	11.56 a	5.31 a	2.84 b	75.04 a	32.43 b	10.75 a
Cavalo Claro Iraí	11.77 a	2.35 d	2.83 b	72.63 a	28.64 c	9.22 c
IPR Uirapurú	11.49 a	4.17 c	3.21 a	66.63 b	30.29 c	10.17 b
Folgado	11.60 a	3.05 d	3.16 a	67.48 b	26.88 c	10.50 b
Carioca	12.05 a	3.40 d	3.22 a	60.69 b	31.81 b	9.69 b
BRS Campeiro	12.26 a	3.72 c	3.33 a	59.58 b	27.09 c	9.90 b
Fogo da Serra 322	12.16 a	3.88 c	2.84 b	62.71 b	28.39 c	10.32 b
Manteigão	12.16 a	4.05 c	2.91 b	64.23 b	25.89 c	9.22 c
Iraí	12.02 a	3.59 c	2.68 b	52.36 b	27.96 c	8.97 c
Vagem Larga	11.91 a	3.57 c	2.90 b	69.67 a	30.19 c	9.84 b
Mouro	11.32 a	4.54 b	2.90 b	62.89 b	30.13 c	9.90 b
Vermelho Graúdo	12.40 a	3.77 c	3.09 a	70.19 a	28.66 c	8.62 c
Pintadinho 114	11.98 a	3.79 c	3.06 a	70.44 a	27.68 c	7.05 d
Predominante 140	12.30 a	3.60 c	3.05 a	72.64 a	33.24 b	9.97 b
Rosinha	11.74 a	3.71 c	2.99 b	75.76 a	24.38 c	9.50 c
IPR Juriti	12.19 a	3.29 d	3.25 a	70.74 a	27.86 c	9.97 b
Mouro 128	11.49 a	4.61 b	3.05 a	65.97 b	26.49 c	8.29 d
Bege Ibarama	13.35 a	4.49 b	3.50 a	74.23 a	27.99 c	9.12 c
Tubiano	12.02 a	4.98 a	2.86 b	85.49 a	27.38 c	7.79 d
Macanudo	11.46 a	3.78 c	3.16 a	60.69 b	29.93 c	9.50 c
Mouro Graúdo Cinza	11.49 a	5.73 a	2.83 b	67.99 a	33.16 b	9.99 b
Capixaba	11.77 a	4.00 c	3.07 a	59.43 b	31.53 b	10.09 b

*Means followed by same letter in a column constitute a homogeneous group according to the Scott-Knott procedure (p = 0.05). K = potassium; P = phosphorus; Mg = magnesium; Fe = iron; Zn = zinc; Cu = copper.

average bean consumers in Brazil. The cultivars selected stood out for their high grain yield (≥ 1,400.7 kg ha^{-1}) and fast cooking (≤ 17 min 04 s). Of these, seven were landraces, namely, Vagem Roxa, Turrialba, Mourinho Claro, Quero-quero, Paraná, Carioca Vila Nova do Sul and Chumbinho.

As regards the mineral concentration, all common bean cultivars selected by the multiplicative index had a high concentration of magnesium (≥ 2.0 g kg^{-1} of dry matter - DM) and only cultivar Guapo Brilhante showed no high potassium (≥ 12.0 g kg^{-1} DM) and iron (≥ 60.4 mg kg^{-1} DM) concentrations (Table 5), according to the classes established by Ribeiro and Mezzomo (2020), Steckling et al. (2017) and Tryphone and Nchimbi-Msolla (2010), respectively. Cultivars Vagem Roxa, Turrialba, Mourinho Claro, Quero-quero, Carioca Vila Nova do Sul and Chumbinho also stood out for their high zinc concentration (≥ 31.0 mg kg^{-1} DM), according to the classes proposed by Tryphone and Nchimbi-Msolla (2010). These results are particularly important when we consider the fact that seven landraces were selected by the multiplicative index, i.e., the natural selection carried out by farmers in the region preserved common bean cultivars of high nutritional quality. Therefore, the use of these common bean cultivars as part of a diversified and balanced diet represents nutritional gains. In addition, the use of the cultivars selected is recommended for common-bean biofortification programs.

Conclusions

Direct selection provides genetic gain estimates in magnitude and sign favorable to the selection of common bean cultivars based on individual traits, but produces an undesirable response in the indirect selection of one or more traits.

The classic, base, desired-gains and rank-sum selection indices associated with the different economic weights tested do not provide genetic gain estimates favorable to the selection of all evaluated traits.

The multiplicative index is the best selection strategy to be implemented in the breeding program when aiming at the simultaneous selection of fast cooking, mineral-biofortified common bean cultivars with high agronomic performance.

Acknowledgments

To the Brazilian National Council for Scientific and Technological Development (CNPq) for financial support and scholarships (CNPq – process number 302167/2019-6). To the Coordination for the Improvement of Higher Level Personnel (CAPES) for the grants awarded.

Authors' Contributions

Conceptualization: Ribeiro, N.D.; Santos, G.G. **Data acquisition:** Ribeiro, N.D.; Santos, G.G.; Santos, G.G. **Data analysis:** Maziero, S.M. **Design of methodology:** Ribeiro, N.D.; Santos, G.G.; Maziero, S.M. **Writing and editing:** Ribeiro, N.D.

References

Arns, F.D.; Ribeiro, N.D.; Mezzomo, H.C.; Steckling, S.M.; Kläsener, G.R.; Casagrande, C.R. 2018. Combined selection in carioca beans for grain size, slow darkening and fast-cooking after storage times. Euphytica 214: 1-12.

Bertoldo, J.G.; Barili, L.D.; Vale, N.M.; Coimbra, J.L.M.; Stähelin, D.; Guidolin, A.F. 2010. Genetic gain in agronomic traits of common bean in the region of Planalto Catarinense. Euphytica 171: 381-388.

Câmara, C.R.S.; Urrea, C.A.; Schlegel, V. 2013. Pinto beans (*Phaseolus vulgaris* L.) as a functional food: implications on human health. Agriculture 3: 90-111.

Comissão Técnica Sul Brasileira de Feijão [CTSBF]. 2012. Technical information for bean cultivation in Southern Brazil = Informações Técnicas para o Cultivo de Feijão na Região Sul Brasileira. 2ed. Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina, Florianópolis, SC, Brazil (in Portuguese).

Costa, M.M.; Di Mauro, A.O.; Unêda-Trevisoli, S.H.; Arriel, N.H.C.; Bárbaro, I.M.; Muniz, F.R.S. 2004. Genetic gain by different selection criteria in soybean segregant populations. Pesquisa Agropecuária Brasileira 39: 1095-1102 (in Portuguese, with abstract in English).

Cruz, C.D. 2016. Genes Software: extended and integrated with the R, Matlab and Selegen. Acta Scientiarum. Agronomy 38: 547-552.

Cruz, C.D.; Regazzi, A.J.; Carneiro, P.C.S. 2014. Biometric model applied to genetic breeding = Modelos biométricos aplicados ao melhoramento genético. 3ed. UFV, Viçosa, MG, Brazil (in Portuguese).

Dias, P.A.S.; Almeida, D.V.; Melo, P.G.S.; Pereira, H.S.; Melo, L.C. 2020. Effectiveness of breeding selection for grain quality in common bean. Crop Science 61: 1127-1140.

Gomes, A.B.S.; Oliveira, T.R.A.; Cruz, D.P.; Gravina, G.A.; Daher, R.F.; Araújo, L.C.; Araújo, K.C. 2018. Genetic gain via REML/BLUP and selection indices in snap bean. Horticultura Brasileira 36: 195-198.

Hazel, L.N. 1943. The genetic basis for constructing selection indexes. Genetics 28: 476-490.

Hossain, K.G.; Islam, N.; Jacob, D.; Ghavami, F.; Tucker, M.; Kowalski, T.; Leilani, A.; Zacharias, J. 2013. Interdependence of genotype and growing site on seed mineral compositions in common bean. Asian Journal of Plant Sciences 12: 11-20.

Jost, E.; Ribeiro, N.D.; Maziero, S.M.; Possobom, M.T.D.F.; Rosa, D.P.; Domingues, L. S. 2012. Comparison among direct, indirect and index selections on agronomic traits and nutritional quality traits in common bean. Journal of the Science of Food and Agriculture 93: 1097-1104.

Maziero, S.M.; Ribeiro, N.D.; Storck, L. 2015. Simultaneous selection in beans for architecture, grain yield and minerals concentration. Euphytica 205: 369-380.

Miyazawa, M.; Pavan, M.A.; Muraoka, T.; Carmo, C.A.F.S.; Mello, W.J. 2009. Chemical analysis of plant tissue = Análise química de tecido de planta. p. 191-233. In: Silva, F.C., ed. Manual of chemical analyses of soils, plants and fertilizers = Manual de análises químicas de solos, plantas e fertilizantes. 2ed. Embrapa Informação Tecnológica, Brasília, DF, Brazil (in Portuguese).

Montgomery, D.C.; Peck, E.A.; Vining, G.G. 2012. Introduction to Linear Regression Analysis. 5ed. Wiley, New York, NY, USA.

Mulamba, N.N.; Mock, J.J. 1978. Improvement of yield potential of the ETO Blanco maize (*Zea mays* L.) population by breeding for plant traits. Egyptian Journal of Genetics and Cytology 7: 40-51.

Pesek, J.; Baker, R.J. 1969. Desired improvement in relation to selection indices. Canadian Journal of Plant Science 49: 803-804.

Ramalho, M.A.P.; Ferreira, D.F.; Oliveira, A.C. 2005. Experimentation in genetic and plant breeding = Experimentação em genética e melhoramento de plantas. 3ed. UFLA, Lavras, MG, Brazil (in Portuguese).

Rana, J.C.; Sharma, T.R.; Tyagi, R.K.; Chahota, R.K.; Gautam, N.K.; Singh, M.; Sharma, P.N.; Ojha, S.N. 2015. Characterisation of 4274 accessions of common bean (*Phaseolus vulgaris* L.) germplasm conserved in the Indian gene bank for phenological, morphological and agricultural traits. Euphytica 205: 441-457.

Ribeiro, N.D.; Mezzomo, H.C. 2020. Phenotypic parameters of macromineral and phenolic compound concentrations and selection of Andean bean lines with nutritional and functional properties. Ciência e Agrotecnologia 44: 1-12.

Ribeiro, N.D.; Kläsener, G.R.; Mezzomo, H.C.; Possobom, M.T.D.F.; Steckling, S.M.; Casagrande, C.R. 2018. Combined selection in beans for cycle, plant architecture and grain yield. Bioscience Journal 34: 108-119.

Ribeiro, N.D.; Kläsener, G.R.; Somavilla, I.P.; Santos, G.G. 2019a. Upright plant architecture traits and their relationship with grain yield in the selection of Mesoamerican common bean lines cultivated at low altitude. Genetics and Molecular Research 18: 1-13.

Ribeiro, N.D.; Steckling, S.M.; Mezzomo, H.C.; Somavilla, I.P. 2019b. Genetic parameters and combined selection for phosphorus, phytate, iron, and zinc in Mesoamerican common bean lines. Ciência e Agrotecnologia 43: 1-13.

Silva, F.C.; Pereira, H.S.; Melo, P.G.S.; Melo, L.C. 2018. Selection of parents and segregating populations of common bean with high agronomic potential and slow seed-coat darkening. Pesquisa Agropecuária Tropical 48: 75-82.

Smith, H.F. 1936. A discriminant function for plant selection. Annals of Eugenics 7: 240-250.

Steckling, S.M.; Ribeiro, N.D.; Arns, F.D.; Mezzomo, H.C.; Possobom, M.T.D.F. 2017. Genetic diversity and selection of common bean lines based on technological quality and biofortification. Genetics and Molecular Research 16: 1-13.

Subandi, W.; Compton, A.; Empig, L.T. 1973. Comparison of the efficiencies of selection indices for three traits in two variety crosses of corn. Crop Science 13: 184-186.

Tryphone, G.M.; Nchimbi-Msolla, S. 2010. Diversity of common bean (*Phaseolus vulgaris* L.) genotypes in iron and zinc contents under screenhouse conditions. African Journal of Agricultural Research 5:738-747.

Wiesinger, J.A.; Cichy, K.A.; Glahn, R.P.; Grusak, M.A.; Brick, M.A.; Thompson, H.J.; Tako, E. 2016. Demonstrating a nutritional advantage to the fast-cooking dry bean (*Phaseolus vulgaris* L.). Journal of Agricultural and Food Chemistry 64: 8592-8603.

Williams, J.S. 1962. The evaluation of a selection index. Biometrics 18: 375-393.

Zanotti, R.F.; Lopes, J.C.; Motta, L.B.; Mengarda, L.H.G.; Marçal, T.S.; Guilhen, J.H.S. 2020. Genetic variability and heritability of biofortified grain beans genotypes. Brazilian Journal of Development 6: 29381-29395.