

# Recurrent selection to obtain drought-tolerant common bean progenies

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**ABSTRACT.** Common bean yield is directly related to climate conditions, and water deficit is one of the main limiting factors. One way of getting around this problem is increasing the frequency of alleles favorable to drought tolerance by the recurrent selection method. We estimated the morphophysiological and agronomic gains achieved in two recurrent selection cycles for drought tolerance and evaluated the genetic potential of the progenies obtained in each cycle. The first recurrent selection cycle was obtained by intercrossing 10 genotypes. This cycle was followed by physiological, morphophysiological, and agronomic evaluations, resulting in selection of 17 progenies. The second cycle was obtained by intercrossing the 17 selected progenies, followed by the same evaluations, resulting in 20 selected progenies. A randomized block experimental design was used for both selection cycles, with split plots and three replications. The plots consisted of two water treatments (irrigated and water deficit), and the subplots consisted of the progenies under evaluation. To select the progenies and estimate the genetic parameters, only the treatment under water deficit was considered, in randomized blocks with three replications. Irrigation was suspended at the R5 stage. Under these conditions, the following traits were evaluated: stomatal conductance, leaf temperature, relative

chlorophyll index, leaf area, leaf dry matter, and shoot dry matter. After that, irrigation was reestablished and the following determinations were made: plant height, number of pods per plant, number of seeds per plant, number of seeds per pod, 100-seed weight, and grain yield. Recurrent selection was effective for selection of drought-tolerant plants, with gain from selection for grain yield of 231.94 kg ha<sup>-1</sup> in the first cycle and 387.71 kg ha<sup>-1</sup> in the second. Three progenies in the first selection cycle and 19 in the second selection cycle were identified as having better performance under water deficit conditions, which allowed drought-tolerant progenies to be chosen for use in breeding programs.

**Key words:** *Phaseolus vulgaris*; Water deficit; Grain yield; Correlation

## INTRODUCTION

Drought is one of the main abiotic stresses that reduce agricultural yield throughout the world (Assefa et al., 2019) and, according to data from the FAO (2015), this reduction (estimated at 40%) may intensify because of climate change, leading to an increase in the occurrence and duration of drought (Lauer et al., 2012; Lesk et al., 2016). Water restriction affects more than half of world production of dry beans or common beans, and it may occur at any phase of plant development; germination, flowering, and grain filling are most affected (Beebe et al., 2013).

Drought tolerance is a trait of complex inheritance and of low heritability, and it is highly affected by the environment (Blair et al., 2012). Many genes are involved in expression of this trait, and it is manifested in different ways depending on the duration and intensity of the water stress (Blum, 2011). In this respect, breeding programs have directed their attention to tolerant cultivars as a strategy for maintaining crop yield.

The use of recurrent selection, a cyclical process that aims at progressively increasing the frequency of alleles favorable to a determined quantitative trait, may allow selection of drought-tolerant progenies without reducing the genetic variability of the populations studied. It is important to highlight that the selection process is continuous, and progenies of interest can be taken from any selection cycle, making the breeding of autogamous plants more dynamic and efficient (Ramalho et al., 2012).

Amaro et al. (2007) evaluated the yield performance of common bean over five selection cycles and obtained a gain of 8.9% in each cycle. The authors emphasized that there was genetic variability among the progenies throughout the cycles, allowing continuity of the selection method. Silva et al. (2010) estimated gain from selection for bean grain yield of 3.3% per cycle, showing the effectiveness of the method over eight selection cycles. Alves et al. (2015) estimated genetic progress of 8.6% for yield in two selection cycles. Studies were not found in the literature using the recurrent selection method to obtain drought tolerance in common bean. However, existing studies have shown expressive gain in selection from one or more quantitative traits simultaneously.

Based on the hypothesis that the recurrent selection method can progressively increase the genes of interest for drought tolerance, the aims of this study were to estimate

gains from selection from two recurrent selection cycles in regard to drought tolerance and to evaluate the genetic potential of the progenies obtained in each cycle.

## MATERIAL AND METHODS

The recurrent selection method was conducted in 2015, 2016, and 2017 at the Central Experimental Center of the Santa Elisa Farm of the Instituto Agronômico - IAC in Campinas, SP, Brazil (22°54'S, 47°03'W, and 854 AMSL). Initially, the base population (C-0 cycle) was obtained through manual interbreeding of 10 common bean genotypes (Gen TS 3-1, Gen TS 3-2, Gen TS 3-3, Gen TS 4-7, H96A31-P2-1-1-1-1, IAC Sintonia, IAC Imperador, Carioca Precoce, IAC Carioca Eté, and IAPAR 81) previously characterized for drought tolerance (Ribeiro et al.; 2019). In the C-0 cycle, 40 populations were obtained ([Supplementary 1](#)), which were evaluated in regard to drought tolerance in the F<sub>2</sub> generation, with selection of 17 progenies. To obtain the second selection cycle (C-I), these 17 selected progenies were interbred once more, and they gave rise to 103 populations ([Supplementary 4](#)), which were evaluated in the F<sub>3</sub> generation in regard to drought tolerance, with selection of 20 progenies.

SEA 5 (tolerant) and IAC Apuã (susceptible) were used as check cultivars for assessment of drought tolerance. Two water treatments (an irrigated “control” and water deficit) were used in all the experiments to ensure imposition of water deficit; and physiological, morphological, and agronomic traits were evaluated under both water treatments (irrigated and water deficit). However, only the data collected in the treatments under water deficit were considered for selection of the progenies from both selection cycles. The experiments were performed in the soil in a greenhouse, and fertilization consisted of the application of 25 g of the fertilizer formulation 04-14-08 per meter of plant furrow, corresponding to 20 kg ha<sup>-1</sup> of N, 70 kg ha<sup>-1</sup> of P<sub>2</sub>O<sub>5</sub>, and 40 kg ha<sup>-1</sup> of K<sub>2</sub>O. After 25 days, urea was applied in topdressing at the rate of 100 kg ha<sup>-1</sup> of N. The other crop treatments were performed according to crop needs. A randomized block experimental design was used, with split plots and three replications. Two water treatments were applied: irrigated and water deficit, allowing comparison between the treatments and ensuring the imposition of water deficit. The plots were composed of 2.0-m length rows, spaced at 0.50 m, with 24 plants per row. However, only the treatments under water deficit of each selection cycle were considered for selection of tolerant progenies and estimation of genetic parameters, in randomized blocks with three replications.

The treatments were initially maintained under full irrigation, with the matric potential ( $\Psi_m$ ) of the soil monitored by Watermark sensors installed at the depth of 0.40 m. The  $\Psi_m$  between -40 and -30 kPa/centibar was considered satisfactory for crop development in the irrigated plot and the  $\Psi_m$  near -199 kPa/centibar was considered an indication of drought in the plot under water deficit (Gonçalves et al., 2015). Water deficit was applied when more than 50% of all the plants were in the pre-flowering stage (R5 stage, according to the phenological scale of CIAT; Fernández et al., 1983), which is considered the ideal crop development stage for distinguishing drought-tolerant genotypes (Jongrunklang et al., 2013). At that stage, irrigation in the plot under the water deficit treatment was suspended and remained so for 28 days. At that point, the plants showed signs of accentuated wilting, high senescence, and leaf abscission, and the soil sensors exhibited values near -199 KPa/Centibars at the 0.40 m depth, indicating water shortage

(Gonçalves et al., 2015). The following assessments were then made: relative chlorophyll index (RCI, non-dimensional) (SPAD -502 Plus – Konica Minolta), determined in fully expanded leaves from the middle part of the plant; stomatal conductance ( $g_s$ , in  $\text{mmol m}^{-2} \text{s}^{-1}$ ) (Porometer AP4 – Delta T Devices), determined in fully expanded leaves from the middle part of the plant; leaf temperature (LT, in  $^{\circ}\text{C}$ ) (Telatemp AG-42D, Telatemp, Fullerton, CA), determined in the canopy of the plant, with the infrared thermometer kept at 50 cm from the leaf surface at a  $45^{\circ}$  angle; leaf area (LA, in  $\text{dm}^2 \text{pl}^{-1}$ ) (area meter - LI-COR LI-3100C); leaf dry matter (LDM, in g); and shoot dry matter (SDM, in g). After that, irrigation was re-established in the treatment under water deficit and, at physiological maturity of the plants, the following traits were evaluated: plant height (PH, in cm), number of pods per plant (NPP, in units), number of seeds per pod (NSP, in units), number of seeds per plant (NS, in units), 100-seed weight (100SW, in g), and grain yield (GY, in  $\text{kg ha}^{-1}$ ).

The data obtained were evaluated by the R statistical program (Version 3.3.2) by means of analysis of variance, comparison of means by the Scott-Knott test at 5% probability ( $P < 0.05$ ), a scatter plot graphic analysis, and genetic correlation. The following parameters were estimated: genetic correlation ( $r_g = \hat{\sigma}_{gy} / \sqrt{\hat{\sigma}_{gx}^2 \hat{\sigma}_{gy}^2}$ , where  $\hat{\sigma}_{gxy}$  is the estimator of genotypic covariance between the traits  $X$  and  $Y$ , and  $\hat{\sigma}_{gx}^2$  and  $\hat{\sigma}_{gy}^2$  are estimators of the genotypic variances of the traits  $X$  and  $Y$ , respectively); genetic variance ( $\hat{\sigma}_G^2 = \text{MST} - \text{MSR}/r$ , where MST is the mean square of the treatments, MSR is the mean square of the residual, and  $r$  is the number of replications); phenotypic variance ( $\hat{\sigma}_F^2 = \text{MST}/r$ , where MST is the mean square of the treatments and  $r$  is the number of replications); heritability ( $h^2 = (\hat{\sigma}_G^2 / \hat{\sigma}_F^2)$ ); selection differential ( $SD = M_m - M_o$ , where  $M_m$  = mean of the selected progenies and  $M_o$  = mean of the original progenies); and gain from selection ( $GS = SD \times h^2$ ).

## RESULTS AND DISCUSSION

In the assessments of drought tolerance carried out in the C-0 and C-I recurrent selection cycles under water deficit conditions, reductions were observed in the performance of the progenies for all the traits evaluated compared to the irrigated treatment, except for leaf temperature (LT) (data not presented, [Supplementary 7](#) and [Supplementary 8](#)). It was necessary to use two water treatments for assessments of the C-0 and C-I cycles in comparison and validation of the imposition of water deficit (data not presented). However, as the number of progenies and traits evaluated was large and the aim of the study was to select drought-tolerant progenies and estimate the genetic parameters under water deficit, we decided to present only the results that showed significant differences between genotypes under water deficit conditions ( $P \leq 0.01$  and  $P \leq 0.05$ ) and the genetic parameters obtained in that treatment.

Through analysis of variance of the C-0 cycle, significant difference was found for progenies in regard to leaf area (LA), leaf dry matter (LDM), shoot dry matter (SDM), number of seeds per pod (NSP), number of seeds per plant (NS), and grain yield (GY), indicating genetic variability among the progenies studied. This is one of the basic principles for success throughout the recurrent selection cycles (Table 1).

**Table 1.** Summary of the analyses of variance in regard to the traits of relative chlorophyll index (RCI), stomatal conductance ( $g_s$ ), leaf temperature (LT), leaf area (LA), leaf dry matter (LDM), shoot dry matter (SDM), plant height (PH), number of pods per plant (NPP), number of seeds per pod (NSP), number of seeds per plant (NS), 100-seed weight (100SW), and bean grain yield (GY) in reference to 40 progenies of common beans from the first recurrent selection cycle (C-0) and two check cultivars under water deficit. Campinas, SP, Brazil, 2016 Season.

Mean Square							
Source of Variation	DF	RCI (un. SPAD)	$g_s$ (mmol m <sup>-2</sup> s <sup>-1</sup> )	LT (°C)	LA (dm <sup>2</sup> )	LDM (g)	SDM (g)
Blocks	2	0.004	0.060	0.015	0.097	0.039	0.002
Progenies	41	0.004	0.096	0.001	0.088**	0.129**	0.542**
Error	82	0.003	0.119	0.001	0.044	0.045	0.053
Total	125						
CV (%)		3.82	16.77	2.10	7.00	14.41	9.29
Mean Square							
Source of Variation	DF	PH (cm)	NPP (un.)	NSP (un.)	NS (un.)	100SW (g)	GY (kg ha <sup>-1</sup> )
Blocks	2	0.008	0.600	0.064	3.013	3.72	0.023
Progenies	41	0.062	0.123	0.072**	1.167**	6.95	0.257**
Error	82	0.045	0.093	0.031	0.540	7.71	0.024
Total	125						
CV (%)		11.05	14.49	8.66	21.14	13.82	10.56

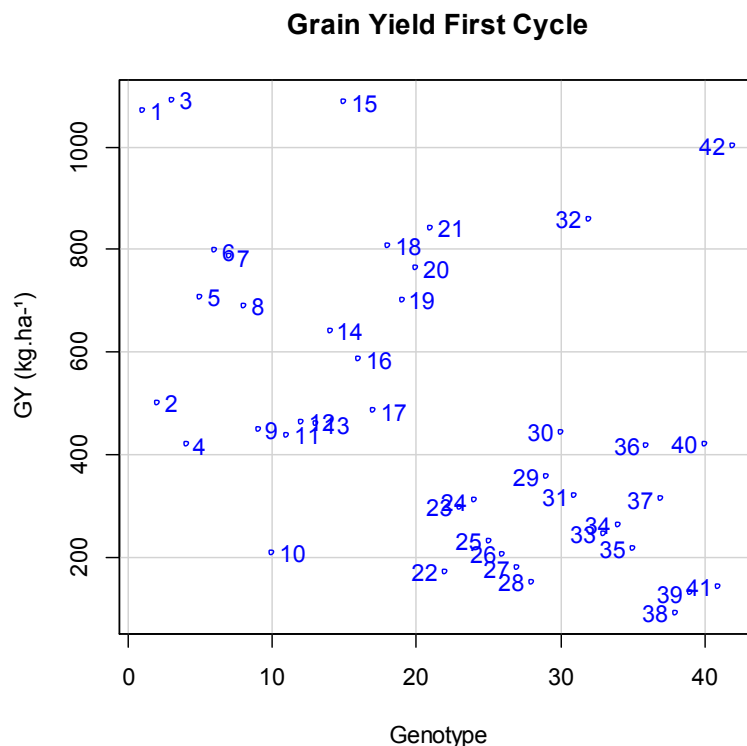
(\*\*, \*) Significant at 1% and at 5% probability by the F test, respectively.

In relation to leaf area (LA), the overall mean was 11.83 dm<sup>2</sup>, and progenies 14 (23.63 dm<sup>2</sup>) and 18 (24.56 dm<sup>2</sup>) stood out ([Supplementary 2](#)). For leaf dry matter (LDM), the mean value was 1.27 g, and the following progenies stood out: 8 (2.08 g), 14 (2.60 g), 15 (2.18 g), 18 (4.11 g), 20 (2.23 g), and 21 (2.01 g) ([Supplementary 2](#)). The shoot dry matter (SDM) trait exhibited a mean value of 5.37 g, and the progenies with greater biomass accumulation under water restriction conditions were 5 (8.15 g), 6 (8.54 g), 12 (8.30 g), 18 (10.13 g), and 42 (8.20 g) ([Supplementary 2](#)). In this study, the traits of LA, LDM, and SDM assisted in selection of the progenies tolerant to water deficit. These traits were also reported by Assefa et al. (2015), who evaluated 34 advanced lines of common bean under water restriction conditions and selected seven lines. These authors emphasized that the genotypes tolerant to water deficit had greater capacity for biomass accumulation and for remobilization of photoassimilates from the shoots for pod production and bean grain yield, favoring crop yield under unfavorable conditions.

For number of seeds per pod (NSP), the overall mean was 3.22, and for number of seeds per plant (NS), it was 11.88, with progenies 14 (4.56) and 1 (22.67) standing out, respectively ([Supplementary 3](#)). According to Polania et al. (2016b), yield components are fundamental for selection of drought-tolerant genotypes since bean seed production is the main goal of breeding programs. Darkwa et al. (2016) evaluated 64 genotypes of common bean and used the traits of number of seeds per pod and pods per plant for selection of drought-tolerant genotypes.

In regard to grain yield (GY), the mean value was 493.50 kg ha<sup>-1</sup>, and the following progenies stood out: 1 (1069.95 kg ha<sup>-1</sup>), 3 (1090.22 kg ha<sup>-1</sup>), 6 (796.71 kg ha<sup>-1</sup>), 15 (1086.48 kg ha<sup>-1</sup>), 18 (806.93 kg ha<sup>-1</sup>), 21 (840.71 kg ha<sup>-1</sup>), and 32 (859.64 kg ha<sup>-1</sup>) (Figure 1, [Supplementary 3](#)). Progenies 1 (1069.95 kg ha<sup>-1</sup>), 3 (1090.22 kg ha<sup>-1</sup>), and 15 (1086.48 kg

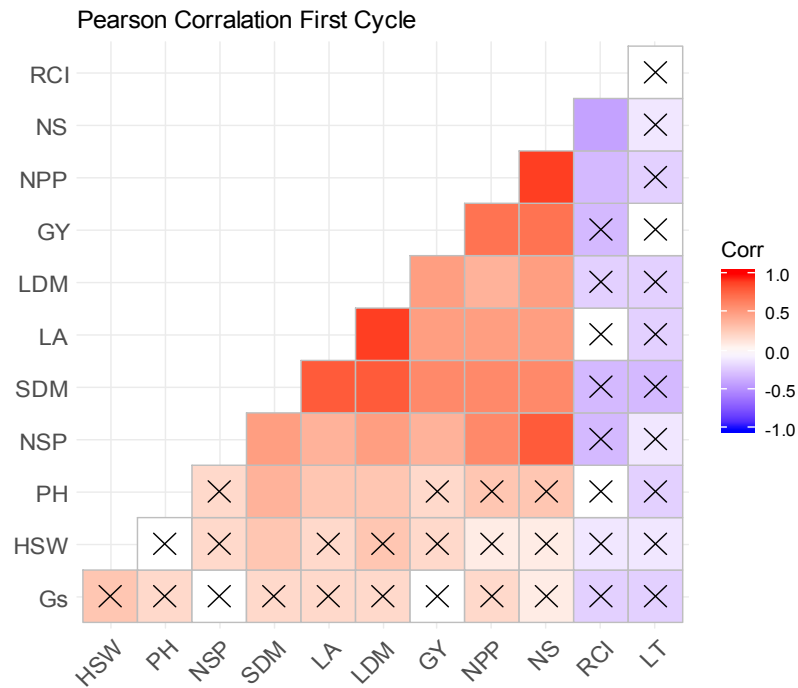
ha<sup>-1</sup>) had higher GY than the test cultivar 42 SEA 5 (1002.40 kg ha<sup>-1</sup>), a reference in regard to drought tolerance, showing the potential of these progenies for achieving drought-tolerant common bean lines (Figure 1, [Supplementary 3](#)).



**Figure 1.** Yield performance (kg.ha<sup>-1</sup>) of the 40 progenies of common beans from the first cycle and the tolerant and susceptible check cultivars of common bean under water deficit. Progenies: 1 - Gen TS 3-1 × Gen TS 3-2, 2 - Gen TS 3-1 × Gen TS 3-3, 3 - Gen TS 3-1 × Gen TS 4-7, 4 - Gen TS 3-1 × FAP F3-2, 5 - Gen TS 3-2 × Gen TS 4-7, 6 - Gen TS 3-2 × Carioca Precoce, 7 - Gen TS 3-2 × Iapar 81, 8 - Gen TS 3-3 × Gen TS 4-7, 9 - Gen TS 3-3 × IAC Sintonia, 10 - IAC Apuã (susceptible check cultivar), 11 - Carioca Precoce × Gen TS 3-1, 12 - Carioca Precoce × Gen TS 3-3, 13 - Carioca Precoce × Gen TS 4-7, 14 - Carioca Precoce × IAC H96A31-P2-1-1-1-1, 15 - IAC Carioca Eté × Gen TS 3-1, 16 - IAC Carioca Eté × Gen TS 3-2, 17 - IAC Carioca Eté × Gen TS 3-3, 18 - IAC Carioca Eté × Gen TS 4-7, 19 - IAC Carioca Eté × Carioca Precoce, 20 - IAC Carioca Eté × IAC H96A31-P2-1-1-1-1, 21 - IAC Carioca Eté × Iapar 81, 22 - IAC Carioca Eté × IAC Imperador, 23 - IAC Sintonia × Gen TS 3-2, 24 - IAC Sintonia × Gen TS 4-7, 25 - IAC Sintonia × Carioca Precoce, 26 - IAC Sintonia × IAC Imperador, 27 - IAC H96A31-P2-1-1-1-1 × Gen TS 3-1, 28 - IAC H96A31-P2-1-1-1-1 × Gen TS 3-2, 29 - IAC H96A31-P2-1-1-1-1 × Gen TS 3-3, 30 - IAC H96A31-P2-1-1-1-1 × Gen TS 4-7, 31 - IAC H96A31-P2-1-1-1-1 × IAC Sintonia, 32 - IAC H96A31-P2-1-1-1-1 × IAC Imperador, 33 - Iapar 81 × Gen TS 3-1, 34 - Iapar 81 × Gen TS 3-3, 35 - Iapar 81 × Carioca Precoce, 36 - Iapar 81 × IAC Sintonia, 37 - Iapar 81 × IAC H96A31-P2-1-1-1-1, 38 - Iapar 81 × IAC Imperador, 39 - IAC Imperador × Gen TS 3-1, 40 - IAC Imperador × Gen TS 4-7, 41 - IAC Imperador × Carioca Precoce, and 42 - Sea 5 (tolerant check cultivar).

In the first cycle, the evaluations for morphoagronomic traits proved to be essential for selecting the 17 drought-tolerant progenies with a 40% selection index, taking into account the higher grain yield under water deficit. In the C-0 cycle, there was negative

genetic correlation (rg) between the traits RCI with NPP and NS. There was positive genetic correlation between LDM with GY, NPP, and NS; SDM with LA, LDM, GY, NPP, and NS; LA with LDM, GY, NPP, and NS; PH with SDM, LA, and LDM; NSP with SDM, LA, LDM, GY, NPP, and NS; 100SW with SDM; GY with NPP and NS; and NPP with NS. The negative correlation coefficient between RCI with the NPP and NS yield components may be related to the early maturity of the progenies evaluated, since these progenies were derived from normal and early cycle parental lines and exhibited high senescence and leaf abscission at the time of assessment, suggesting that the earlier genotypes had higher yield. The variables of LDM, SDM, and LA were positively correlated with NS, NSP, NPP, and GY, implying that the highest yielding progenies had greater SDM and LA, favoring remobilization of photoassimilates toward pod production and bean grain yield (Figure 2).



**Figure 2.** Pearson correlation test ( $P < 0.05$ ) in regard to the traits of relative chlorophyll index (RCI), stomatal conductance (gs), leaf temperature (LT), leaf area (LA), leaf dry matter (LDM), shoot dry matter (SDM), plant height (PH), number of pods per plant (NPP), number of seeds per pod (NSP), number of seeds per plant (NS), 100-seed weight (100SW), and bean grain yield (GY) in the 40 progenies and the SEA 5 (42 - tolerant) and IAC Apuã (10 - susceptible) check cultivars of common beans under water deficit.

The progenies selected in this cycle (C-0) came from the following crosses: 1 (Gen TS 3-1 × Gen TS 3-2), 3 (Gen TS 3-1 × Gen TS 4-7), 4 (Gen TS 3-1 × IAC Sintonia), 5 (Gen TS 3-2 × Gen TS 4-7), 6 (Gen TS 3-2 × Carioca Precoce), 7 (Gen TS 3-2 × Iapar), 8 (Gen TS 3-3 × Gen TS 4-7), 11 (Carioca Precoce × Gen TS 3-1), 13 (Carioca Precoce × Gen TS 4-7), 14 (Carioca Precoce × IAC H96A31-P2-1-1-1-1), 15 (IAC Carioca Eté × Gen

TS 3-1), 16 (IAC Carioca Eté × Gen TS 3-2), 18 (IAC Carioca Eté × Gen TS 4-7), 19 (IAC Carioca Eté × Carioca Precoce), 20 (IAC Carioca Eté × IAC H96A31-P2-1-1-1-1), 21 (IAC Carioca Eté × Iapar 81), and 32 (IAC H96A31-P2-1-1-1-1 × IAC Imperador).

For the second recurrent selection cycle (C-I), there was significance through analysis of variance in regard to the progenies for LA, LDM, SDM, PH, NPP, NSP, 100SW, and GY (Table 2).

**Table 2.** Summary of analyses of variance in regard to the traits of relative chlorophyll index (RCI), stomatal conductance (*gs*), leaf temperature (LT), leaf area (LA), leaf dry matter (LDM), shoot dry matter (SDM), plant height (PH), number of pods per plant (NPP), number of seeds per pod (NSP), number of seeds per plant (NS), 100-seed weight (100SW), and bean grain yield (GY) in reference to 103 progenies of common beans from the second recurrent selection cycle (C-I) and two check cultivars under water deficit. Campinas, SP, Brazil, 2017 season.

Mean Squares							
Source of Variation	DF	RCI (un. SPAD)	<i>gs</i> (mmol m <sup>-2</sup> s <sup>-1</sup> )	LT (°C)	LA (dm <sup>2</sup> )	LDM (g)	SDM (g)
Blocks	2	0.315	0.023	0.027	0.957	4.140	0.134
Progenies	105	0.019	0.063	0.001	0.130*	0.443*	0.033**
Error	208	0.022	0.057	0.001	0.090	0.329	0.019
Total	315						
CV (%)		10.59	11.84	2.89	9.70	24.03	10.40

Mean Squares							
SV	DF	PH (cm)	NPP (un.)	NSP (un.)	NS (un.)	100SW (g)	GY (kg ha <sup>-1</sup> )
Blocks	2	0.007	1.781	0.388	26.57	0.004	0.088
Progenies	105	0.016*	1.269*	0.137*	3.146	0.316**	0.071**
Error	208	0.012	0.922	0.101	2.593	0.068	0.016
Total	315						
CV (%)		6.73	22.64	16.73	24.94	5.57	4.35

(\*\*, \*) Significant at 1% and at 5% probability by the F test, respectively.

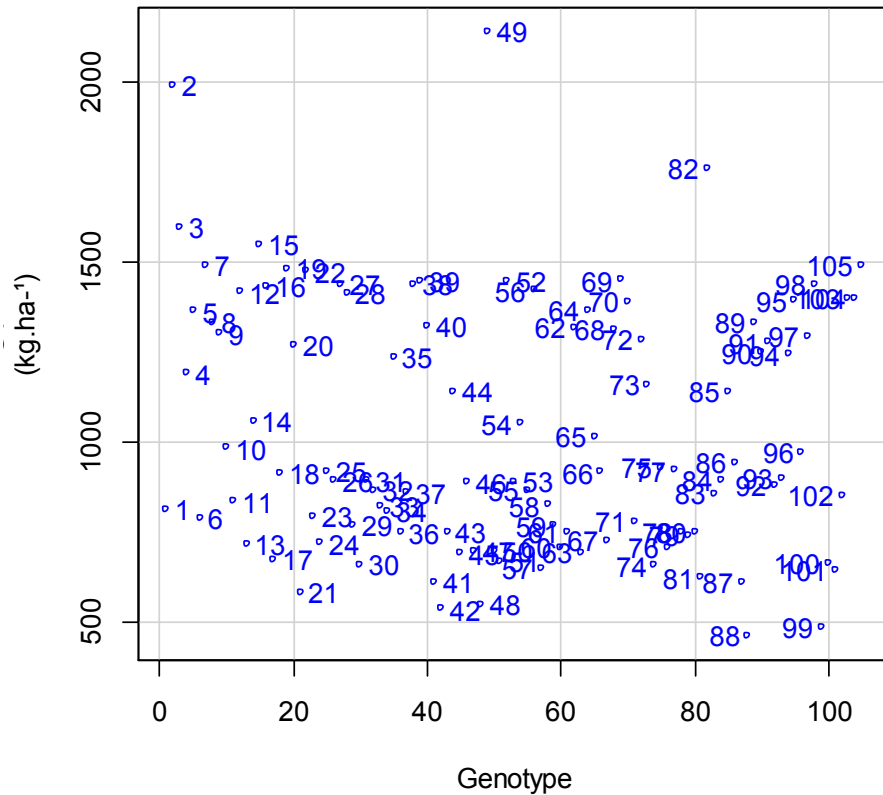
The mean value was 15.68 dm<sup>2</sup> for LA, and the following progenies stood out: 17 (38.29 dm<sup>2</sup>), 19 (24.94 dm<sup>2</sup>), 26 (26.30 dm<sup>2</sup>), 27 (29.71 dm<sup>2</sup>), 31 (25.68 dm<sup>2</sup>), 52 (27.58 dm<sup>2</sup>), and 60 (30.95 dm<sup>2</sup>) ([Supplementary 5](#)). The leaf dry matter (LDM) trait had a mean value of 5.10 g, with the following progenies standing out: 17 (11.43 g), 19 (7.95 g), 27 (10.13 g), 41 (8.43 g), 60 (10.37 g), 64 (12.79 g), and 72 (8.94 g) ([Supplementary 5](#)). For shoot dry matter (SDM), the mean value was 22.49 g, and the progenies with the greatest biomass accumulation under water restriction conditions were 2 (35.77 g), 4 (30.42 g), 9 (32.39 g), 12 (33.68 g), 27 (30.89 g), 31 (33.65 g), 40 (31.01 g), 55 (32.72 g), and 77 (32.59 g) ([Supplementary 5](#)). In regard to the number of pods per plant (NPP), the mean value was 18.04, and the progenies that had the best performance were 2 (27.33), 13 (28.00), 18 (28.00), 27 (32.33), 36 (29.33), 55 (28.00), 78 (29.67), and 104 (28.00) ([Supplementary 6](#)). For the number of seeds per pod (NSP), the mean value was 2.73, and the following progenies stood out: 1 (4.22), 3 (4.46), 63 (4.44), 67 (4.44), and 103 (4.42) ([Supplementary 6](#)).

For grain yield (GY), the mean value was 1028.58 kg ha<sup>-1</sup>, and the highest yielding progenies under conditions of water deficit were 2 (1988.89 kg ha<sup>-1</sup>), 3 (1595.56 kg ha<sup>-1</sup>), 7 (1491.56 kg ha<sup>-1</sup>), 12 (1415.56 kg ha<sup>-1</sup>), 15 (1548.89 kg ha<sup>-1</sup>), 16 (1431.11 kg ha<sup>-1</sup>), 19 (1482.22 kg ha<sup>-1</sup>), 22 (1473.33 kg ha<sup>-1</sup>), 27 (1435.56 kg ha<sup>-1</sup>), 28 (1413.33 kg ha<sup>-1</sup>), 38 (1435.56 kg ha<sup>-1</sup>), 39 (1446.67 kg ha<sup>-1</sup>), 49 (2137.78 kg ha<sup>-1</sup>), 52 (1446.67 kg ha<sup>-1</sup>), 56



(1420.00 kg ha<sup>-1</sup>), 69 (1448.89 kg ha<sup>-1</sup>), 82 (1760.00 kg ha<sup>-1</sup>), 98 (1437.78 kg ha<sup>-1</sup>), 104 (1400.00 kg ha<sup>-1</sup>), and 105 (1491.11 kg ha<sup>-1</sup>) (Figure 3, [Supplementary 6](#)).

### Grain Yield Second Cycle

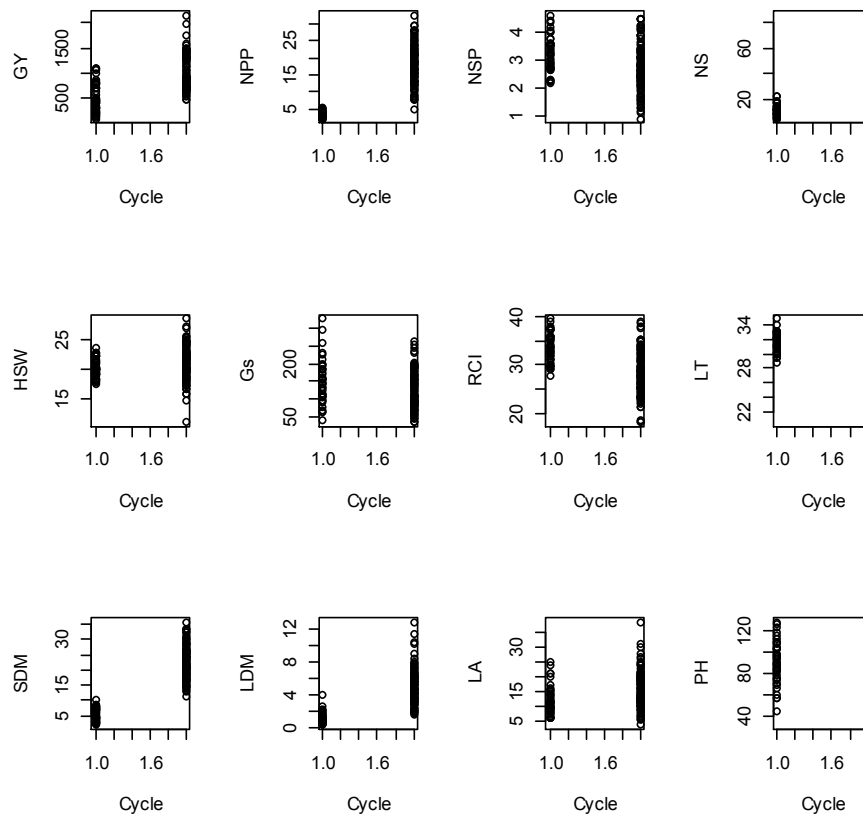


**Figure 3.** Productive performance (kg.ha<sup>-1</sup>) of the 103 progenies and the tolerant and susceptible check cultivars of common bean under water deficit. Progenies: 1 - (Carioca Precoce × Gen TS 3-1) × (IAC Carioca Eté × Gen TS 3-1), 2 - (Carioca Precoce × Gen TS 3-1) × (IAC Carioca Eté × Gen TS 3-2), 3 - (Carioca Precoce × Gen TS 3-1) × (IAC Carioca Eté × Gen TS 4-7), 4 - (Carioca Precoce × Gen TS 3-1) × (IAC Carioca Eté × IAC H96A31-P2-1-1-1-1), 5 - (Carioca Precoce × Gen TS 3-1) × (IAC Carioca Eté × Iapar 81), 6 - (Carioca Precoce × Gen TS 3-1) × (IAC H96A31-P2-1-1-1-1 × IAC Imperador), 7 - (Carioca Precoce × Gen TS 4-7) × (Carioca Precoce × IAC H96A31-P2-1-1-1-1), 8 - (Carioca Precoce × Gen TS 4-7) × (IAC Carioca Eté × Gen TS 3-1), 9 - (Carioca Precoce × Gen TS 4-7) × (IAC Carioca Eté × Gen TS 3-2), 10 - (Carioca Precoce × Gen TS 4-7) × (IAC Carioca Eté × Gen TS 4-7), 11 - (Carioca Precoce × Gen TS 4-7) × (IAC Carioca Eté × Carioca Precoce), 12 - (Carioca Precoce × Gen TS 4-7) × (IAC Carioca Eté × IAC H96A31-P2-1-1-1-1), 13 - (Carioca Precoce × Gen TS 4-7) × (IAC Carioca Eté × Iapar 81), 14 - (Carioca Precoce × Gen TS 4-7) × (IAC H96A31-P2-1-1-1-1 × IAC Imperador), 15 - (Carioca Precoce × IAC H96A31-P2-1-1-1-1) × (IAC Carioca Eté × Gen TS 3-1), 16 - (Carioca Precoce × IAC H96A31-P2-1-1-1-1) × (IAC Carioca Eté × Gen TS 3-2), 17 - (Carioca Precoce × IAC H96A31-P2-1-1-1-1) × (IAC Carioca Eté × Gen TS 4-7), 18 - (Carioca Precoce × IAC H96A31-P2-1-1-1-1) × (IAC Carioca Eté × Carioca Precoce), 19 - (Carioca Precoce × IAC H96A31-P2-1-1-1-1) × (IAC Carioca Eté × IAC H96A31-P2-1-1-1-1), 20 - (Carioca Precoce × IAC H96A31-P2-1-1-1-1) × (IAC Carioca Eté × Iapar 81), 21 - (Carioca Precoce × IAC H96A31-P2-1-1-1-1) × (IAC H96A31-P2-1-1-1-1 × IAC Imperador), 22 - (IAC Carioca Eté × Gen TS 3-1) × (IAC Carioca Eté × Gen TS 4-7), 23 - (IAC Carioca Eté × Gen TS 3-1) × (IAC Carioca Eté × Carioca Precoce), 24 - (IAC Carioca Eté × Gen TS 3-1) × (IAC Carioca Eté × IAC H96A31-P2-1-1-1-1), 25 - (IAC Carioca Eté × Gen TS 3-1) × (IAC Carioca Eté × Iapar 81), 26 - (IAC Carioca Eté × Gen TS 3-1) × (IAC H96A31-P2-1-1-1-1 × IAC Imperador), 27 - (IAC Carioca Eté × Gen TS 3-2) × (IAC Carioca Eté × Carioca Precoce), 28 - (IAC Carioca Eté × Gen TS 3-2) × (IAC Carioca Eté × IAC H96A31-P2-1-1-1-1), 29 - (IAC Carioca Eté × Gen TS 3-2) × (IAC Carioca Eté × Iapar 81), 30 - (IAC Carioca Eté × Gen TS 3-2) × (IAC H96A31-P2-1-1-1-1 × IAC Imperador), 31 - (IAC Carioca Eté ×

Gen TS 4-7) × (IAC Carioca Eté × IAC H96A31-P2-1-1-1-1), 32 - (IAC Carioca Eté × Gen TS 4-7) × (IAC Carioca Eté × Iapar 81), 33 - (IAC Carioca Eté × Gen TS 4-7) × (IAC H96A31-P2-1-1-1-1 × IAC Imperador), 34 - (IAC Carioca Eté × Carioca Precoce) × (IAC Carioca Eté × Iapar 81), 35 - (IAC Carioca Eté × Carioca Precoce) × (IAC H96A31-P2-1-1-1-1 × IAC Imperador), 36 - (Gen TS 3-1 × Gen TS 3-2) × (Carioca Precoce × Gen TS 3-1), 37 - (Gen TS 3-1 × Gen TS 3-2) × (Carioca Precoce × IAC H96A31-P2-1-1-1-1), 38 - (Gen TS 3-1 × Gen TS 3-2) × (IAC Carioca Eté × Gen TS 3-1), 39 - (Gen TS 3-1 × Gen TS 3-2) × (IAC Carioca Eté × Gen TS 3-2), 40 - (Gen TS 3-1 × Gen TS 3-2) × (IAC Carioca Eté × IAC H96A31-P2-1-1-1-1), 41 - (Gen TS 3-1 × Gen TS 3-2) × (IAC Carioca Eté × Iapar 81), 42 - (Gen TS 3-1 × Gen TS 3-2) × (Gen TS 3-1 × Gen TS 4-7), 43 - (Gen TS 3-1 × Gen TS 3-2) × (IAC H96A31-P2-1-1-1-1 × IAC Imperador), 44 - (Gen TS 3-1 × Gen TS 3-2) × (Gen TS 3-2 × Gen TS 4-7), 45 - (Gen TS 3-1 × Gen TS 3-2) × (Gen TS 3-2 × Carioca Precoce), 46 - (Gen TS 3-1 × Gen TS 3-2) × (Gen TS 3-2 × Iapar 81), 47 - (Gen TS 3-1 × Gen TS 3-2) × (Gen TS 3-3 × Gen TS 4-7), 48 - (IAC Carioca Eté × IAC H96A31-P2-1-1-1-1) × (IAC Carioca Eté × Iapar 81), 49 - (IAC Carioca Eté × IAC H96A31-P2-1-1-1-1) × (IAC H96A31-P2-1-1-1-1 × IAC Imperador), 50 - (IAC Carioca Eté × Iapar 81) × (IAC H96A31-P2-1-1-1-1 × IAC Imperador), 51 - (Gen TS 3-1 × Gen TS 4-7) × (Carioca Precoce × Gen TS 3-1), 52 - (Gen TS 3-1 × Gen TS 4-7) × (Carioca Precoce × Gen TS 4-7), 53 - (Gen TS 3-1 × Gen TS 4-7) × (Carioca Precoce × IAC H96A31-P2-1-1-1-1), 54 - (Gen TS 3-1 × Gen TS 4-7) × (IAC Carioca Eté × Gen TS 3-1), 55 - (Gen TS 3-1 × Gen TS 4-7) × (IAC Carioca Eté × Gen TS 3-2), 56 - (Gen TS 3-1 × Gen TS 4-7) × (IAC Carioca Eté × Gen TS 4-7), 57 - (Gen TS 3-1 × Gen TS 4-7) × (IAC Carioca Eté × Carioca Precoce), 58 - (Gen TS 3-1 × Gen TS 4-7) × (IAC Carioca Eté × IAC H96A31-P2-1-1-1-1), 59 - (Gen TS 3-1 × Gen TS 4-7) × (IAC Carioca Eté × Iapar 81), 60 - (Gen TS 3-1 × Gen TS 4-7) × (IAC H96A31-P2-1-1-1-1 × IAC Imperador), 61 - (Gen TS 3-1 × Gen TS 4-7) × (Gen TS 3-2 × Gen TS 4-7), 62 - (Gen TS 3-1 × Gen TS 4-7) × (Gen TS 3-2 × Carioca Precoce), 63 - (Gen TS 3-1 × Gen TS 4-7) × (Gen TS 3-2 × Iapar 81), 64 - (Gen TS 3-1 × Gen TS 4-7) × (Gen TS 3-3 × Gen TS 4-7), 65 - (Gen TS 3-2 × Gen TS 4-7) × (Carioca Precoce × Gen TS 4-7), 66 - (Gen TS 3-2 × Gen TS 4-7) × (Carioca Precoce × IAC H96A31-P2-1-1-1-1), 67 - (Gen TS 3-2 × Gen TS 4-7) × (IAC Carioca Eté × Gen TS 3-1), 68 - (Gen TS 3-2 × Gen TS 4-7) × (IAC Carioca Eté × Gen TS 3-2), 69 - (Gen TS 3-2 × Gen TS 4-7) × (IAC Carioca Eté × Gen TS 4-7), 70 - (Gen TS 3-2 × Gen TS 4-7) × (IAC Carioca Eté × Iapar 81), 71 - (Gen TS 3-2 × Gen TS 4-7) × (IAC H96A31-P2-1-1-1-1 × IAC Imperador), 72 - (Gen TS 3-2 × Gen TS 4-7) × (Gen TS 3-2 × Carioca Precoce), 73 - (Gen TS 3-2 × Gen TS 4-7) × (Gen TS 3-2 × Iapar 81), 74 - (Gen TS 3-2 × Carioca Precoce) × (Carioca Precoce × Gen TS 3-1), 75 - (Gen TS 3-2 × Carioca Precoce) × (Carioca Precoce × Gen TS 4-7), 76 - (Gen TS 3-2 × Carioca Precoce) × (Carioca Precoce × IAC H96A31-P2-1-1-1-1), 77 - (Gen TS 3-2 × Carioca Precoce) × (IAC Carioca Eté × Gen TS 3-1), 78 - (Gen TS 3-2 × Carioca Precoce) × (IAC Carioca Eté × Gen TS 3-2), 79 - (Gen TS 3-2 × Carioca Precoce) × (IAC Carioca Eté × Gen TS 4-7), 80 - (Gen TS 3-2 × Carioca Precoce) × (IAC Carioca Eté × Carioca Precoce), 81 - (Gen TS 3-2 × Carioca Precoce) × (IAC Carioca Eté × IAC H96A31-P2-1-1-1-1), 82 - (Gen TS 3-2 × Carioca Precoce) × (IAC H96A31-P2-1-1-1-1 × IAC Imperador), 83 - (Gen TS 3-2 × Carioca Precoce) × (Gen TS 3-2 × Iapar 81), 84 - (Gen TS 3-2 × Carioca Precoce) × (Gen TS 3-3 × Gen TS 4-7), 85 - (Gen TS 3-2 × Iapar 81) × (Carioca Precoce × Gen TS 3-1), 86 - (Gen TS 3-2 × Iapar 81) × (Carioca Precoce × Gen TS 4-7), 87 - (Gen TS 3-2 × Iapar 81) × (IAC Carioca Eté × Gen TS 3-1), 88 - (Gen TS 3-2 × Iapar 81) × (IAC Carioca Eté × Gen TS 3-2), 89 - (Gen TS 3-2 × Iapar 81) × (IAC Carioca Eté × Gen TS 4-7), 90 - (Gen TS 3-2 × Iapar 81) × (IAC Carioca Eté × Carioca Precoce), 91 - (Gen TS 3-2 × Iapar 81) × (IAC Carioca Eté × Iapar 81), 92 - (Gen TS 3-2 × Iapar 81) × (IAC H96A31-P2-1-1-1-1 × IAC Imperador), 93 - (Gen TS 3-2 × Iapar 81) × (Gen TS 3-3 × Gen TS 4-7), 94 - (Gen TS 3-3 × Gen TS 4-7) × (Carioca Precoce × Gen TS 3-1), 95 - (Gen TS 3-3 × Gen TS 4-7) × (Carioca Precoce × Gen TS 4-7), 96 - (Gen TS 3-3 × Gen TS 4-7) × (Carioca Precoce × IAC H96A31-P2-1-1-1-1), 97 - (Gen TS 3-3 × Gen TS 4-7) × (IAC Carioca Eté × Gen TS 3-1), 98 - (Gen TS 3-3 × Gen TS 4-7) × (IAC Carioca Eté × Gen TS 3-2), 99 - (Gen TS 3-3 × Gen TS 4-7) × (IAC Carioca Eté × Carioca Precoce), 100 - (Gen TS 3-3 × Gen TS 4-7) × (IAC Carioca Eté × Iapar 81), 101 - (Gen TS 3-3 × Gen TS 4-7) × (IAC H96A31-P2-1-1-1-1 × IAC Imperador), 102 - IAC APUA (susceptible check cultivar), 103 - SEA 5 (tolerant check cultivar), 104 - (Gen TS 3-1 × IAC Sintonia) × (IAC H96A31-P2-1-1-1-1 × IAC Imperador), and 105 (Gen TS 3-1 × IAC Sintonia) × (IAC Carioca Eté × Carioca Precoce).

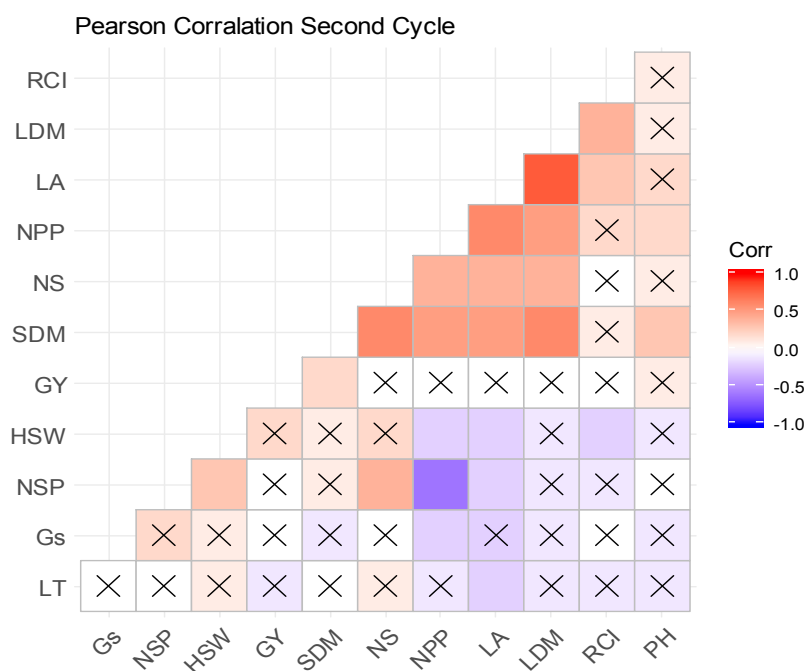
It is noteworthy that all the progenies described above had a higher GY than the cultivar 103 SEA 5 (1400.00 kg ha<sup>-1</sup>), with the exception of 104, which had the same GY ([Supplementary 6](#)). This emphasizes the relationship between climate conditions and crop yield, which, according to Gris et al. (2015), is the characteristic most affected under these conditions.

The progenies for the second cycle (C-I) were selected taking into account the GY under water deficit, with a selection index of 20%. The progenies of the C-I cycle stood out for the traits of grain yield, number of pods per plant, number of seeds per plant, biomass accumulation, and leaf dry matter (Figure 4).



**Figure 4.** Gain from selection in regard to the traits of relative chlorophyll index (RCI), stomatal conductance (*gs*), leaf temperature (LT), leaf area (LA), leaf dry matter (LDM), shoot dry matter (SDM), plant height (PH), number of pods per plant (NPP), number of seeds per pod (NSP), number of seeds per plant (NS), 100-seed weight (100SW), and bean grain yield (GY) in two recurrent selection cycles.

In the C-I cycle, negative correlations were found between LT with LA; *gs* with NPP; NSP with NPP and LA; and 100SW with NPP, LA, and RCI. Positive correlations were found between NSP with 100SW and NS; GY with SDM; SDM with NS, NPP, LA, and LDM; NS with NPP, LA, and LDM; NPP with LA, LDM, and PH; LA with LDM and RCI; and LDM with RCI. According to Hu et al. (2010), water deficit leads to reduction in *gs*, negatively affecting transpiration and absorption of CO<sub>2</sub>, raising leaf temperature and hindering photosynthesis and crop yield. Thus, this suggests that the progenies selected in this study adapted to the stress condition, allowing assimilation of CO<sub>2</sub> and leaf transpiration, favoring crop yield. In the two selection cycles, there was positive correlation between SDM with the yield components, indicating the high relationship between biomass accumulation and the yield components (Figure 5).



**Figure 5.** Pearson correlation test ( $p < 0.05$ ) in regard to the traits of relative chlorophyll index (RCI), stomatal conductance (gs), leaf temperature (LT), leaf area (LA), leaf dry matter (LDM), shoot dry matter (SDM), plant height (PH), number of pods per plant (NPP), number of seeds per pod (NSP), number of seeds per plant (NS), 100-seed weight (100SW), and bean grain yield (GY) of 103 progenies and the SEA 5 (103 - tolerant) and IAC Apuã (102 - susceptible) check cultivars of common bean under water deficit.

Twenty progenies out of 103 were selected in this cycle (C-1), coming from the following crosses: 2 (Carioca Precoce  $\times$  Gen TS 3-1 and IAC Carioca Eté  $\times$  Gen TS 3-2), 3 (Carioca Precoce  $\times$  Gen TS 3-1 and IAC Carioca Eté  $\times$  Gen TS 4-7), 7 (Carioca Precoce  $\times$  Gen TS 4-7 and Carioca Precoce  $\times$  IAC H96A31-P2-1-1-1-1), 12 (Carioca Precoce  $\times$  Gen TS 4-7 and IAC Carioca Eté  $\times$  IAC H96A31-P2-1-1-1-1), 15 (Carioca Precoce  $\times$  IAC H96A31-P2-1-1-1-1 and IAC Carioca Eté  $\times$  Gen TS 3-1), 16 (Carioca Precoce  $\times$  IAC H96A31-P2-1-1-1-1 and IAC Carioca Eté  $\times$  Gen TS 3-2), 19 (Carioca Precoce  $\times$  IAC H96A31-P2-1-1-1-1 and IAC Carioca Eté  $\times$  IAC H96A31-P2-1-1-1-1), 22 (IAC Carioca Eté  $\times$  Gen TS 3-1 and IAC Carioca Eté  $\times$  Gen TS 4-7), 27 (IAC Carioca Eté  $\times$  Gen TS 3-2 and IAC Carioca Eté  $\times$  Carioca Precoce), 28 (IAC Carioca Eté  $\times$  Gen TS 3-2 and IAC Carioca Eté  $\times$  IAC H96A31-P2-1-1-1-1), 38 (Gen TS 3-1  $\times$  Gen TS 3-2 and IAC Carioca Eté  $\times$  Gen TS 3-1), 39 (Gen TS 3-1  $\times$  Gen TS 3-2 and IAC Carioca Eté  $\times$  Gen TS 3-2), 49 (IAC Carioca Eté  $\times$  IAC H96A31-P2-1-1-1-1 and IAC H96A31-P2-1-1-1-1  $\times$  IAC Imperador), 52 (Gen TS 3-1  $\times$  Gen TS 4-7 and Carioca Precoce  $\times$  Gen TS 4-7), 56 (Gen TS 3-1  $\times$  Gen TS 4-7 and IAC Carioca Eté  $\times$  Gen TS 4-7), 69 (Gen TS 3-2  $\times$  Gen TS 4-7 and IAC Carioca Eté  $\times$  Gen TS 4-7), 82 (Gen TS 3-2  $\times$  Carioca Precoce and IAC H96A31-P2-1-1-1-1  $\times$  IAC Imperador), 98 (Gen TS 3-3  $\times$  Gen TS 4-7 and IAC Carioca Eté  $\times$  Gen TS

3-2), 104 (Gen TS 3-1 × IAC Sintonia and IAC H96A31-P2-1-1-1-1 × IAC Imperador) and 105 (Gen TS 3-1 × IAC Sintonia and IAC Carioca Eté × Carioca Precoce).

The estimates of the genetic parameters of the two recurrent selection cycles (C-0 and C-I) are shown in Table 3.

**Table 3.** Estimates of the genetic coefficient of variation ( $\hat{\sigma}_G^2$ ), phenotypic variation ( $\hat{\sigma}_F^2$ ), heritability ( $h^2$ ), selection differential ( $SD$ ), and gain from selection ( $\hat{GS}$ ) for relative chlorophyll index (RCI), stomatal conductance ( $gs$ ), leaf temperature (LT), leaf area (LA), leaf dry matter (LDM), shoot dry matter (SDM), plant height (PH), number of pods per plant (NPP), number of seeds per pod (NSP), number of seeds per plant (NS), 100-seed weight (100SW), and bean grain yield (GY), in reference to two recurrent selection cycles.

Genetic Parameters					
First Cycle					
Variable	$\hat{\sigma}_G^2$	$\hat{\sigma}_F^2$	$\hat{h}^2$	SD	SG
RCI	0.0004	0.0015	0.28	-0.05	-0.01
LT	0.0000	0.0003	0.10	-0.13	-0.01
$gs$	-0.0077	0.0321	-0.24	4.15	-0.99
LA	0.0146	0.0294	0.50	352.14	175.47
LDM	0.0279	0.0431	0.65	0.52	0.34
SDM	0.1632	0.1809	0.90	1.60	1.44
PH	0.0058	0.0208	0.28	6.84	1.90
NPP	0.0099	0.0411	0.24	0.68	0.16
NSP	0.0137	0.0241	0.57	0.31	0.18
NS	0.2088	0.3890	0.54	0.44	0.24
100SW	-0.2737	2.3167	-0.12	0.11	-0.01
GY	0.0778	0.0858	0.91	255.78	231.93
Second Cycle					
Variable	$\hat{\sigma}_G^2$	$\hat{\sigma}_F^2$	$\hat{h}^2$	SD	SG
RCI	-0.0013	0.0063	-0.21	-0.27	0.06
LT	0.0000	0.0005	0.00	-0.65	0.00
$gs$	0.0014	0.0210	0.07	4.59	0.30
LA	0.0132	0.0433	0.30	1.11	0.34
LDM	0.0378	0.1477	0.26	1.00	0.26
SDM	0.0046	0.0109	0.42	1.00	0.42
PH	0.0015	0.0057	0.26	1.16	0.30
NPP	0.1154	0.4230	0.27	1.23	0.34
NSP	0.0122	0.0459	0.26	-0.13	-0.04
NS	0.1843	1.0487	0.18	-0.91	-0.16
100SW	0.0827	0.1053	0.78	0.11	0.09
GY	0.0182	0.0238	0.76	506.44	387.11

In relation to leaf area (LA) and shoot dry matter (SDM), the  $\hat{GS}$  improvements in the first cycle were 175.47 dcm<sup>2</sup> and 1.44 g, and in the second cycle, 0.3 dcm<sup>2</sup> and 0.42 g, respectively (Table 3), indicating that even under water deficit conditions, the selected progenies exhibited greater leaf area and biomass, which may have favored remobilization of photoassimilates for pod production and bean grain yield.

For plant height (PH), there was a positive  $\hat{GS}$  in the two cycles (Table 3), highlighting the selected progenies, since water deficit leads to reduction in moisture

content, in turgor pressure, and in cell expansion, directly affecting plant height (Taiz and Zeiger, 2009).

In the C-0 cycle, low  $\hat{G}S$  was observed for yield components, except for GY, contributing to an increase of 231.92 kg ha<sup>-1</sup> (Table 3). In the C-I cycle, the  $\hat{G}S$  was low and negative for NSP and NS (Table 3). Nevertheless, a positive  $\hat{G}S$  was observed for grain yield (GY), with a  $\hat{G}S$  of 387.11 kg ha<sup>-1</sup> (Table 3), showing the success obtained from recurrent selection, since yield is one of the traits most affected by water deficit conditions (Gris et al., 2015).

The estimates of the  $h^2$  coefficient for LDM (65%), SDM (90%), and GY (91%) were considered to be of high magnitude, and they denote the genetic variability within the C-0 recurrent selection cycle (Table 3). The high estimate of  $h^2$  is favorable for selection of genotypes of interest and, in this study, allowed the selection of progenies tolerant to water deficit. For the C-I cycle,  $h^2$  was of high magnitude for the 100SW (78%) and GY (76%) traits (Table 3).

The estimates of  $h^2$  identified in this study for GY were higher than those reported by Cunha et al. (2005), who reported estimates of 19% to 54% for common bean in recurrent selection. Menezes Júnior et al. (2008) also reported  $h^2$  of lower magnitude for GY, ranging from 19% to 60%. However, these studies were not carried out under water deficit conditions, which limits comparison among the parameters obtained. In addition to assessments of different traits, the method used is a factor that differs among studies using recurrent selection in autogamous plants. For example, Ramalho et al. (2005) indicated genetic progress of 5.7% after four selection cycles in regard to bean grain yield in common bean under full irrigation. These authors evaluated S0:1 and S0:2 families, and each selection cycle spanned around two years. Silva et al. (2007) evaluated early flowering of common bean in S0 families and indicated progress of 4.4% after five selection cycles, and each cycle spanned an average of four and a half months. In the present study, gain from selection of 231.94 kg ha<sup>-1</sup> (47%) was estimated for the first cycle, and of 387.11 kg ha<sup>-1</sup> (38%) for the second, and each cycle spanned an average of one year and four months because assessments regarding drought tolerance were carried out in S2 progenies for the first cycle and in S3 for the second, showing the dynamics of the method used.

The estimates of  $\hat{\sigma}^2 G$  for the first selection cycle were greater for SDM and NS (Table 3), resulting in high coefficients of heritability, 90% and 54%, respectively, and greater  $\hat{\sigma}^2 G$  for NPP and NS for the second cycle. However, this resulted in low coefficients of heritability, 27% and 18%, respectively. It should be emphasized that genetic variability can be raised through inserting new genotypes in the next breeding cycles, just as superior progenies can be chosen in any selection cycle (Ramalho et al., 2005).

In the C-0 cycle, progenies 1 (1069.95 kg ha<sup>-1</sup>), 3 (1090.22 kg ha<sup>-1</sup>), and 15 (1086.48 kg ha<sup>-1</sup>) exhibited higher GY than the check cultivar SEA 5 (1002.40 kg ha<sup>-1</sup>), which is drought tolerant. The genotype SEA 5 has been a reference for drought tolerance in various studies. Polania et al. (2016a) highlighted SEA 5 for bean grain yield and for its ability to maintain a competitive level of water balance, allowing more effective use of water during stress. Gonçalves et al. (2015) recommended this genotype due to its general combining ability, considering bean grain yield under water deficit conditions. In the C-I cycle, the progenies with higher GY than the check cultivar SEA 5 (1400.00 kg ha<sup>-1</sup>) were

2 (1988.89 kg ha<sup>-1</sup>), 3 (1595.56 kg ha<sup>-1</sup>), 7 (1491.56 kg ha<sup>-1</sup>), 12 (1415.56 kg ha<sup>-1</sup>), 15 (1548.89 kg ha<sup>-1</sup>), 16 (1431.11 kg ha<sup>-1</sup>), 19 (1482.22 kg ha<sup>-1</sup>), 22 (1473.33 kg ha<sup>-1</sup>), 27 (1435.56 kg ha<sup>-1</sup>), 28 (1413.33 kg ha<sup>-1</sup>), 38 (1435.56 kg ha<sup>-1</sup>), 39 (1446.67 kg ha<sup>-1</sup>), 49 (2137.78 kg ha<sup>-1</sup>), 52 (1446.67 kg ha<sup>-1</sup>), 56 (1420.00 kg ha<sup>-1</sup>), 69 (1448.89 kg ha<sup>-1</sup>), 82 (1760.00 kg ha<sup>-1</sup>), 98 (1437.78 kg ha<sup>-1</sup>), and 105 (1491.11 kg ha<sup>-1</sup>), showing the effectiveness of selection of drought-tolerant common bean progenies.

## CONCLUSIONS

This is the first study using the recurrent selection method to obtain drought-tolerant common bean progenies. The effects of water deficit applied in two recurrent selection cycles were evaluated for selection of common bean progenies through physiological, morphological, and agronomic traits in 2015, 2016, and 2017. The analysis of variance showed significant differences among the progenies, confirming the genetic variability among them, which allowed for the selection process. The recurrent selection method was effective in selecting drought-tolerant progenies, as gain from selection of 231.94 kg ha<sup>-1</sup> was obtained for bean grain yield in the first cycle (C-0) and 387.71 kg ha<sup>-1</sup> in the second cycle (C1). Three progenies in the first selection cycle and 19 in the second selection cycle were identified with better performance under water deficit conditions, which allowed drought-tolerant progenies to be chosen for use in breeding programs.

## ACKNOWLEDGMENTS

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## CONFLICTS OF INTEREST

The authors declare no conflict of interest.

## REFERENCES

- Alves AF, Menezes Júnior JÂN, Menezes VMPS, Carneiro JES, et al. (2015). Genetic progress and potential of common bean families obtained by recurrent selection. *Crop Breed. Appl. Biotechnol.* 15(4): 218-226.
- Amaro GB, Abreu AFB, Ramalho MAP and Silva FB (2007). Phenotypic recurrent selection in the common bean (*Phaseolus vulgaris* L.) with carioca-type grains for resistance to the fungi *Phaeoisariopsis griseola*. *Genet. Mol. Biol.* 30: 584-588.
- Assefa T, Assibi Mahama A, Brown AV, et al. (2019). A review of breeding objectives, genomic resources, and marker-assisted methods in common bean (*Phaseolus vulgaris* L.). *Mol. Breeding.* 39: 20.
- Assefa T, Wu J, Beebe S, Rao IM, et al. (2015). Improving adaptation to drought stress in small red common bean: phenotypic differences and predicted genotypic effects on grain yield, yield components and harvest index. *Euphytica.* 3: 477-489.
- Beebe SE, Rao IM, Blair MW and Acosta-Gallegos JA (2013). Phenotyping common beans for adaptation to drought. *Front. Physiol.* 4: 35.
- Blair MW, Galeano CH and Tovar E (2012). Development of a Mesoamerican intragenepool genetic map for quantitative trait loci detection in a drought tolerant × susceptible common bean (*Phaseolus vulgaris* L.) cross. *Mol. Breeding.* 29: 71-88.
- Blum A (2011). Drought resistance - is it really a complex trait?. *Funct. Plant Biol.* 38: 753-757.
- Cunha WG, Ramalho MAP and Abreu AFB (2005). Selection aiming at upright growth habit common bean with carioca type grains. *Crop Breed. Appl. Biotechnol.* 5: 379-386.

- Darkwa K, Ambachew D, Mohammed H, Asfaw A, et al. (2016). Evaluation of common bean (*Phaseolus vulgaris* L.) genotypes for drought stress adaptation in Ethiopia. *Crop J.* 14: 367-376.
- FAO (2015). The impact of natural hazards and disasters on agriculture and food security and nutrition. <http://www.fao.org/3/a-i4434e.pdf>. Accessed on 8 June 2021.
- Fernandez F, Gepts P and Lopez M (1983). Etapas de desarrollo de la planta de frijol comun. CIAT, Cali. <https://core.ac.uk/download/pdf/132691059.pdf>. Accessed on 8 June 2021.
- Gris CF, Evaristo CH, Aparecido LEO, Nadaleti DHS, et al. (2015). Dry season bean production at different sowing dates under the South Minas Gerais conditions, Brazil. *Afr. J. Agric. Res.* 10: 2705-2710.
- Gonçalves JGR, Chiorato AF, Silva DA, Esteves JAF, et al. (2015). Combining ability in common bean cultivars under drought stress. *Bragantia.* 2: 149-155.
- Hu L, Wang Z, Du H and Huang B (2010). Differential accumulation of dehydrins in response to water stress for hybrid and common bermudagrass genotypes differing in drought tolerance. *J. Plant Physiol.* 167: 103-109.
- Jongrunklang N, Toomsam B, Vorasoot N, Jogloy S, et al. (2013). Drought tolerance mechanisms for yield responses to pre-flowering drought stress of peanut genotypes with different drought tolerant levels. *Field Crops Res.* 144: 34-42.
- Lauer JG, Bijl CG and Grusak MA (2012). The scientific grand challenges of the 21st century for the Crop Science Society of America. *Crop Sci.* 52: 1003-1010.
- Lesk C, Rowhani P and Ramankutty N (2016). Influence of extreme weather disasters on global crop production. *Nature.* 529: 84-87.
- Menezes Júnior JAN, Ramalho MAP and Abreu AFB (2008). Seleção recorrente para três caracteres do feijoeiro. *Bragantia.* 67: 833- 838.
- Polania J, Rao IM, Cajiao C, Rivera M, et al. (2016a). Physiological traits associated with drought resistance in Andean and Mesoamerican genotypes of common bean (*Phaseolus vulgaris* L.). *Euphytica.* 210: 17-29.
- Polania J, Poschenrieder C, Beebe S and Rao IM (2016b). Estimation of phenotypic variability in symbiotic nitrogen fixation ability of common bean under drought stress using 15 N natural abundance in grain. *Eur. J. Agron.* 79: 66-73.
- Ramalho MAP, Abreu AFB, Santos JB and Nunes JAR (2012). Aplicações da genética quantitativa no melhoramento de plantas autógamas. Universidade Federal de Lavras, Lavras.
- Ramalho MAP, Abreu AFB and Santos JB (2005). Genetic progress after four cycles of recurrent selection for yield and grain traits in common bean. *Euphytica.* 144: 23-29.
- Ribeiro T, Silva DA, Esteves JAF, Azevedo CVG, et al. (2019). Evaluation of common bean genotypes for drought tolerance. *Bragantia.* 78(1): 1-11.
- Silva FB, Ramalho MAP and Abreu AFB (2007). Seleção recorrente fenotípica para florescimento precoce de feijoeiro “carioca”. *Pesq. Agropec. Bras.* 42: 1437-1442.
- Silva GS, Ramalho MAP, Abreu AFB and Nunes JAR (2010). Estimation of genetic progress after eight cycles of recurrent selection for common bean yield. *Crop Breed. Appl. Biotechnol.* 10: 351-356.
- Taiz L and Zeiger E (2009). *Fisiologia Vegetal.* 4.ed. Porto Alegre: ARTMED.