Efficiency in the use of phosphorus by common bean genotypes

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ABSTRACT: Common bean (*Phaseolus vulgaris* L.) is frequently grown in weathered soils with low phosphorus (P) availability, and this is one of the main limitations on its production. This study aimed to assess 20 common bean genotypes in a hydroponic system to select the best P concentration for inducing nutritional deficiency and to classify the genotypes in terms of nutrient utilization efficiency. The concentrations of P applied were 8.00, 4.00, 2.00 and 0.05 mg L^{-1}. At 21 days, in the plot subjected to an application of the most severe stress, the 0.05 mg L^{-1} dose of P, had smaller plant size and early leaf abscission was observed. The 4.00 mg L^{-1} dose of P was the most efficient in inducing stress for discrimination of cultivars in terms of efficiency of use of P. The following genotypes: IAPAR 81, Carioca Comum, IAC Carioca Tybatã, IAC Imperador and G 2333 stood out as being efficient and responsive to P, while the two cultivars DOR 364 and Jalo Precoce were the most inefficient and unresponsive.

Keywords: *Phaseolus vulgaris* L., phosphorus nutrition, classification of genotypes for P, hydroponics, P deficiency

Introduction

Common bean (*Phaseolus vulgaris* L.) is a nutrient-demanding crop due to its sensitivity to environmental stresses. One of the most significant factors for explaining its low yield performance in Brazil is the low fertility of tropical soils, which limits plant nutrition. Among the most important factors responsible for this limitation is phosphorus (P) availability in these soils (Silva and Vahl, 2002). Low performance, morphophysiological adjustments, lower dry matter production and reduced leaf area are associated with an inadequate supply of P to plants (Ericsson and Ingestad, 1988). Various strategies of adaptation to P deficiency in the soil have been developed by plants, involving diverse uptake mechanisms, use and remobilization of phosphate (Vance et al., 2003; Hammond et al., 2004; Lambers et al., 2006).

The fact that uptake, transport and redistribution of nutrients are controlled genetically gives rise to the possibility of breeding or selecting cultivars which are more efficient with regard to use of nutrients (Gabelman and Gerloff, 1983; Fageria, 1998). Beebe et al. (1995); Singh et al. (2003); Liao et al. (2004) and Henry et al. (2010) carried out assessments on soils with low P content and observed germplasm tolerant to this deficiency and variability with regard to plant architecture and root production, and they attained lines with divergence with regard to P uptake efficiency, creating opportunities for development and selection of new varieties.

Although it is possible to observe positive correlation between greater root dry matter production and stress conditions attributable to P, as well as greater uptake of the nutrient by some genotypes, Henry et al. (2010) observed low correlation between root production and increased yield. Thus, Parentoni et al. (2011) report the importance of conducting experiments up to the production phase for classification and selection of superior materials because indirect and early selection performed in the vegetative phase has proven to be rather ineffective, conferring low correlation with the performance of plants assessed under field conditions.

This study aimed to assess the morphophysiological responses of 20 common bean genotypes with regard to P uptake at different concentrations of the element, to select the best dose for inducing nutritional deficiency and to classify the genotypes with regard to their efficiency in utilization of the nutrient with a view toward selecting superior genotypes.

Materials and Methods

The experiment was conducted in a greenhouse in Campinas, in the state of São Paulo, Brazil, in June 2012. Twenty common bean genotypes were assessed (Table 1). Among them, G 4000 and G 2333 were used as a standard for efficiency, and the Dor 364 genotype was used as a standard of inefficiency, as it is characterized as having roots with little vigor (Vieira et al., 2007 and Vieira et al., 2008).

The experimental design used was split-plots consisting of four plots (P concentration), 20 subplots (genotypes) and six replications. Nutrient solutions were applied to the plots, differing only with regard to the P doses used. The 20 pre-germinated genotypes were randomly distributed in the plot; three replications were collected in the flowering stage for biometric assessments and the other three were left for grain production.

Plants were grown in a closed hydroponic system in 3.5 L pots filled with filter sand. The nutrient solutions were placed in 1,000 L capacity boxes and a forced aeration system, with their application in the pots being controlled by a timer, circulating through the system for 15 min, with 30 min intervals between applications

Table 1 – Genotypes used in the study in terms of efficiency of use of P.

Genotype	Cicle	Growth habit	Tegument
1. IAC ALVORADA	92 days	semi-erect (type III)	carioca type
2. IAC CARIOCA TYBATÃ	86 days	semi-erect (type III)	carioca type
3. IAC DIPLOMATA	92 days	erect (type II)	carioca type
4. IAC FORMOSO	85 days	semi-erect (type II)	carioca type
5. IAC IMPERADOR	75 days	semi-erect (typeI)	carioca type
6. IPR UIRAPURU	86 days	erect (type II)	black
7. BAT 477	77 days	erect (type I)	cream
8. SEA 5	75 days	erect (type I)	cream
9. CARIOCA COMUM	92 days	semi-erect (type II)	carioca type
10. IAPAR 81	92 days	erect (type II)	carioca type
11. BRS PONTAL	85-95 days	prostrate (type III)	carioca type
12. BRS ESTILO	85-90 days	erect (type II)	carioca type
13. PÉROLA	90-100 days	semi-erect (type III)	carioca type
14. IPR TANGARÁ	87 days	erect (type II)	carioca type
15. DIAMANTE NEGRO	92 days	erect (type II)	black
16. JALO PRECOCE	72 days	erect (type I)	yellow
17. G 4000	83 days	semi-erect (type II)	brown
18. DOR 364	75-85 days	semi-erect (type II)	red
19. G 2333	95 days	prostrate (type IV)	red
20. BRS ESPLENDOR	85-90 days	erect (type II)	black

in the daytime (8h00 to 18h00) and twice during the nighttime (21h00 to 21h15 and 23h45 to 24h00). The solutions were prepared with deionized water and were composed of 143.0 mg L^{-1} of N; 132.5 mg L^{-1} of K; 121.0 mg L^{-1} of Ca; 25.5 mg L^{-1} of Mg; 33.0 mg L^{-1} of S; 1.81 mg L^{-1} of Fe; 0.45 mg L^{-1} of Cu; 0.18 mg L^{-1} of Zn; 0.45 mg L^{-1} of Mn; 0.45 mg L^{-1} of B; 0.09 mg L^{-1} of Mo and 0.09 mg L^{-1} of Ni. The treatments with P doses applied in the plots (P_A, P_B, P_C and P_D) consisted of 0.05, 2.00, 4.00 and 8.00 mg L^{-1} of P.

In the first two weeks after setting up the experiment, the pots were irrigated with a half-strength nutrient solution, in other words, half the total concentration to be used throughout the growth period of the plants. The nutrient solutions were monitored daily, with the temperature, electrical conductivity and pH parameters being maintained from 25 to 28 °C; 1.8 to 2.0 mS cm^{-1} and 5.8 to 6.0, respectively.

Exchanges of the nutrient solution during the growth period of the plants were made according to the monitoring of electrical conductivity and pH. In addition, water consumed by the plants was replaced. The mean temperature and relative humidity during the day the study was being carried out were 31.8 °C and 82 % and, during the night, they were 14.0 °C and 31 %. Crop treatments were applied according to crop needs.

Two assessments were made on the older leaves with regard to the Relative Chlorophyll Index (RCI) using the non-destructive method (SPAD-502Plus). The first assessment was made at 28 days after transplant (DAT), when the first symptoms of deficiency in the plants were observed, and at 43 days, when they exhibited severe symptoms of deficiency.

At 54 DAT, in the flowering stage, collections of plants were undertaken for assessment of the following biometric traits: plant height; number of nodes per plant; leaf area; fresh matter and dry matter of leaves, stem and roots; surface area, length, total volume and diameter of the root.

Initially, total leaf area was determined using an area meter. The same plants separated into leaves and stem were used for determination of fresh matter (FM) and dry matter (DM) using a precision balance. To obtain dry matter, the samples were dried in a forced air circulation laboratory oven at a temperature of 60 °C until reaching constant weight. Next, the roots, diameter, volume, total length and surface area were assessed. Images of the roots of each plant were obtained from a scanner, and the characteristics of the roots were calculated using the WinRHIZO software. The traits assessed for yield were: number of pods per plant (NPP); number of seeds per plant (NSP); number of seeds per pod (NSPOD); one hundred seed weight in grams (HSW) and grain yield in g per plant (Y).

To determine nutrient content in the leaves, 10-g samples of leaf tissue (dried and ground) were subjected to nitro-perchloric digestion for extraction of K, Ca, Mg and S. In the extracts, the contents of these nutrients were determined by atomic absorption spectrophotometry. To determine total N and P; 0.2-g samples of leaf tissue were subjected to sulfuric digestion. Total N was determined by distillation and P by UV-VIS spectrophotometry (Malavolta et al., 1989).

Results were subjected to analysis of variance and the F test in a split-plot arrangement. Mean values were compared by the Scott-Knott test ($p < 0.05$) for quantification of the effects of the treatments.

Classification of the genotypes for efficiency in the use of P was performed by means of the Parentoni et al. (2011) methodology, plotting the values obtained on a graph in which the yield of the plots under stress is represented on the abscissa axis (x) and yield in the environment without stress on the ordinate axis (y), allowing identification of the genotypes in the following categories: ER, ENR, IR and INR (efficient and responsive, efficient and non-responsive, inefficient and responsive, inefficient and non-responsive) through the two straight lines that cross in the mean values of the environments.

Results and Discussion

The first symptoms of P deficiency in plants were observed at 21 days after transfer of the seedlings to the hydroponic system. In the lowest dose of P (0.05 mg L^{-1}), the plants exhibited smaller size, early yellowing, beginning of abscission and the presence of dark spots on the leaf blade, in accordance with the symptoms described by White and Hammond (2008) for the common bean crop under P deficiency conditions. The development of dark green foliage is among the first symptoms of P deficiency, with the addition of development of pigments in the leaves as a consequence of anthocyanin production for the purpose of protecting the nucleic acids against the incidence of UV light and limitations to photosynthesis, as well as the presence of acute leaf angles, prolonged dormancy, reduction in the number of flowers and buds, with the symptoms first evident in older leaves (White and Hammond, 2008).

In general, analyses of variance regarding all the traits of the shoot (relative chlorophyll index, plant height, number of nodes, leaf area, fresh weight and dry weight of leaves and branches) showed significance for doses, genotype and dose × genotype interaction, and satisfactory values for the coefficients of variation, less than 30 %, which indicates good experimental precision (Table 2).

In the assessment performed at 28 DAT for RCI, the plants differed according to the level of P applied, with the P_A plot showing the lowest relative chlorophyll index in the leaves, followed by the plots P_B, P_C and P_D. In the assessment at 43 DAT, the P_A plot differed from the others, showing the lowest relative chlorophyll index, 31.76 SPAD units, while the other plots had 44.70 SPAD units since severe P deficiencies may result in abnormalities in the chloroplasts, such as a reduction in the number of grana and their morphology, reduction of cell expansion and reduction of photosynthesis and respiration (White and Hammond, 2008). P deficiency may favor excessive fiber synthesis, which may affect leaf senescence by means of the rupture of chloroplasts (Grabau et al., 1986).

Considering only the P_A plot in the second assessment of the RCI, when the symptoms of deficiency were most severe, the amplitude for RCI ranged from 44.43 to 18.82 SPAD units, allowing the genotypes to be separated into four distinct classes. The following cultivars: SEA 5, G 2333, IAC Imperador, IAPAR 81 and IPR Tangará stood out with the greatest mean values for relative chlorophyll index, and the four cultivars Pérola, BAT 477, BRS Estilo and DOR 364 stood out with the lowest values of RCI.

For the plant height trait, high variability was seen among the genotypes, with mean amplitude from 24.75 to 132.00 cm between the genotypes of the plot where the least and greatest dose of P had been applied. The effect of the treatments in relation to plant height led to an approximate reduction of 4, 27 and 81 % in plots P_C, P_B and P_A, respectively, in relation to plot P_D. For genotype effect, the genotypes showed differences with regard to growth habit and cycle. El-gizawy and Mehasen (2009) found an increase of 29 % in plant height in the plots fertilized with 30 kg of P_2O_5 compared to the control without application of the nutrient. P is the key component for energy generation in plants. Thus, growth is the result of the increase in cell division due to the application of P, raising the quantity of ATP in the growth centers (Zafar et al., 2011).

There were differences ($p < 0.05$) for genotypes and plots to the number of plant nodes, with reductions of 4, 13 and 56 % in the P_C, P_B and P_A treatments in relation to P_D. Differences ($p < 0.05$) were observed for dose, genotype and dose × genotype interaction for mean leaf area at the analysis of variance, the P treatments presenting 55.14, 40.44, 16.56 and 2.98 m^2, respectively

Table 2 – Summary of analysis of variance of the components of the shoot of 20 common bean genotypes grown in a hydroponic system.

FV[1]	Mean Square								
	RCI[2]	RCI[3]	PH[4]	NOD[5]	LA[6]	FML[7]	DML[8]	FMB[9]	DMB[10]
P Doses	3179.14**	5044.99**	1.5 E+5**	394.60**	3.3E+8**	1.1E+5**	1469.10**	63378.47**	751.53**
Error (a)	5.54	15.65	436.27	2.78	89194.23	59.57	1.37	18.99	0.81
Genotypes	179.68**	291.20**	18866.20**	17.04**	2.05E+6**	666.68**	9.69**	1206.86**	18.47**
P x G	29.46**	77.71**	1588.39**	2.60	792314.07**	291.68**	4.87**	241.84**	4.75**
Error (b)	12.48	20.18	493.29	1.95	229892.51	110.03	2.59	146.36	2.27
CV (a) %	6	10	22	15	10	14	16	10	17
CV (b) %	8	11	23	13	17	20	22	29	29

[1]Font of variation; [2]Relative chlorophyll index at 28 days; [3]Relative chlorophyll index at 43 days; [4]Plant height (cm); [5]Number of nodes per plant; [6]Leaf area (cm^2); [7]Fresh matter of the leaves (g); [8]Dry matter of leaves (g); [9]Fresh matter of branches (g); [10]Dry matter of branches(g); **Significant at 0.01 % by the F test.

for P_D, P_C, P_B and P_A of with reductions of 26, 70 and 95 % in the P_C, P_B and P_A plots. Considering all the treatments in relation to the dose of P, the following cultivars: BAT 477, Carioca Comum, IAC Alvorada, Diamante Negro and IPR Tangará stood out in their greater showing of leaf area, while the three cultivars G 2333, DOR 364 and BRS Esplendor showed the lowest mean values (Table 3). The authors Zafar et al. (2011), in studies with common bean subjected to P stress, also obtained high reductions, 60 % and 50 %, in total leaf area and in the ATP level in the leaves.

Although leaf area is directly related to photosynthetic processes, when the light capturing area and photoassimilate production was increased, genotypes with greater leaf area were not necessarily the most productive. Processes that save P, thus promoting greater efficiency in its use, involve reduction of growth rate, greater remobilization of internal P_i (inorganic P), modifications in carbohydrate metabolism thereby avoiding the pathways that require high P supply, and the use of alternative breathing passages. Greater efficiency is primarily attributed to efficient retranslocation and reuse of the P stored in the plants (Cavatte et al., 2011).

The mean P concentrations in the leaf tissue in the P_A, P_B, P_C and P_D plots were 1.01, 1.26, 1.75 and 3.58 g kg^{-1}, respectively. Genotype G 2333, considered as efficient for uptake and use of P, had the lowest P leaf content in all the plots, which may also be the result of greater translocation. Hernández-Domíguez et al. (2012) report that the P concentration found in the stressed treatments showed a reduction in relation to the adequately supplied treatments, as well as this content varying according to the position of the leaf on the plant. In the younger leaves, the P content decreased only 34 %, while in the middle leaves the reduction was 83 % on average in relation to the treatments applied.

The values for macronutrient concentration in the leaves were close to those presented by Malavolta (2006) (Table 4); nevertheless, as the experiment was conducted in a hydroponic system and a sample for performing leaf analysis uses all the leaves, the small difference in the results obtained was expected because, in routine analysis, sampling is based on younger leaves.

All the traits evaluated in the root system, except for root diameter, showed significant differences in terms of dose, genotypes and dose × genotype interaction, exhibiting variability among genotypes and good experimental precision, with coefficients of variation less than 20 % for doses and for genotypes ranging from zero to 32 % (Table 5).

The reduction of P doses used resulted in greater root development; nevertheless, at the lowest dose, root development was compromised since the nutrient is essential for providing energy to the plant. The P_C plot that received half of the greatest dose of P used was that which led to the greatest growth and best development of the roots for all the traits assessed, except for mean root diameter, with an increase of 80 % in dry matter production.

The size of the root system is an important trait in assessment of plants tolerant to P deficiency. Nevertheless, severe P deficiency, in addition to limiting total plant growth, also limits root growth. The capacity for development of a root system of large dimensions is of extreme importance to maintain satisfactory rates of root growth in spite of P deficiency, as an alternative, stress tolerance may be obtained by increasing external P uptake efficiency, defined by P uptake per unit of root length (Wissuwa, 2003).

Table 3 – Mean leaf area of 20 common bean genotypes grown in a hydroponic system subjected to doses of 0.05, 2.00, 4.00 and 8.00 mg L^{-1} of P applied in the P_A, P_B, P_C and P_D plots.

Genotype	PA	PB	PC	PD
	m²			
1- IAC Alvorada	4.0 a	19.7 a	48.8 a	64.8 a
2- IAC Carioca Tybatã	2.7 b	13.9 b	41.5 b	67.3 a
3- IAC Diplomata	2.4 b	11.5 b	33.7 b	54.6 b
4- IAC Formoso	3.2 a	23.2 a	34.7 b	43.4 d
5- IAC Imperador	3.2 a	17.1 a	36.4 b	61.3 a
6- IPR Uirapuru	3.4 a	16.5 a	36.9 b	47.8 c
7- BAT 477	2.3 b	17.7 a	53.8 a	68.5 a
8- SEA 5	3.1 a	16.9 a	36.2 b	54.5 b
9- Carioca Comum	2.8 b	18.6 a	52.5 a	66.3 a
10- IAPAR 81	3.8 a	23.0 a	44.7 a	53.5 b
11- BRS Pontal	3.0 b	17.2 a	41.5 b	51.0 c
12- BRS Estilo	2.4 b	14.4 b	40.4 b	57.6 b
13- Pérola	2.3 b	11.2 b	34.6 b	55.3 b
14- IPR Tangará	4.4 a	17.9 a	46.5 a	57.3 b
15- Diamante Negro	2.6 b	21.3 a	51.6 a	55.5 b
16- Jalo Precoce	3.9 a	18.8 a	37.2 b	57.3 b
17- G 4000	2.6 b	13.6 b	46.5 a	53.0 b
18- DOR 364	2.2 b	13.5 b	38.8 b	36.1 d
19- G 2333	3.0 b	9.8 b	23.9 b	43.4 d
20- BRS Esplendor	2.4 b	12.6 b	28.7 b	51.8 c
Mean values of the Plots	3.0 D	16.6 C	40.4 B	55.1 A

*Mean values followed by different lower case letters in the column differ (Scott-Knott test, $p < 0.05$) for cultivars, and mean values with different upper case letters in the line differ (Scott-Knott test, $p < 0.05$) for phosphorus doses applied in the plots.

Table 4 – Macronutrient content in leaf tissue of 20 common bean genotypes grown in a hydroponic system from plots PA, PB, PC and PD with application of 0.05, 2.00, 4.00 and 8.00 mg L^{-1} of P.

Treatment	N	P	K	Ca	Mg	S
	g kg^{-1}					
Adequate*	52-54	4-6	15-35	15-25	4-8	5-10
P_A	40.61	1.44	32.65	14.36	1.95	0.88
P_B	37.54	1.63	41.87	23.02	2.04	0.53
P_C	40.07	2,15	40.63	31.41	2.73	0.67
P_D	45.15	3.93	40.25	35.79	3.03	0.99

*Adequate macronutrient levels in the leaves of common bean sampled at the beginning of flowering and collection of the leaf blade of the highest newly-mature trifoliate leaves (Malavolta, 2006).

Assessments of the root system revealed that the genotypes which stood out through greater root development were SEA-5, BAT 477, IAC Alvorada, IAPAR 81, IPR Tangará and Diamante Negro, while the following genotypes: DOR 364, Pérola, IAC Formoso and Jalo Precoce exhibited the lowest values (Table 6).

There was an increase in root production in relation to the shoot, in proportion to reductions in the dose of P applied in the plots, with the mean ratios of plots P_A, P_B, P_C and P_D being 3.00, 2.73, 2.19 and 0.097, respectively. A common response of plants in relation to P deficiency is an increase in the size of the root system in relation to the shoot. Part of this change from dry matter of the shoot to root formation is allometric, shoot formation ratios normally decrease with root growth since plants with low P supply grow more slowly so that the root may achieve greater indices of development. Some genotypes present a greater coefficient of allometry at low P concentrations. Low P availability reduces leaf expansion and branching (Lynch and Brown, 2008).

The mean squares of the production components had differences for doses and genotypes in all the traits assessed, showing the occurrence of variability and the effect of the treatments. For the dose × genotype interaction, only the grain yield trait did not exhibit a significant effect, showing greater stability of the genotypes to the different doses applied for this trait (Table 7).

According to the limitation of P supply to the plots, there were significant reductions in all the yield components. The decreases observed were: for number

Table 5 – Summary of analysis of variance of the parameters of the root system of 20 common bean genotypes grown in a hydroponic system.

FV[1]	Mean Square					
	RFM[2]	RDM[3]	LEN[4]	RSA[5]	VOL[6]	DIAM[7]
P doses	24854.09**	103.54**	7.84E+09**	99394723**	8237.46**	0.0036[ns]
Error (a)	41.31	0.16	11613739	73215.06	4.71	0.0008
Genotypes	445.85**	2.87**	1.45E+08**	2337101**	374.95**	0.014[ns]
P x G	209.96**	1.32**	69582639	838900.10**	78.02**	0.0015[ns]
Error (b)	103.35	0.51	23384283	294070.56	27.57	0.00
CV (a)%	19	18	16	11	9	8
CV (b)%	30	32	22	22	23	0

[1]Font of variation; [2]Root fresh matter (g); [3]Root dry matter (g); [4]Total root length (cm); [5]Root surface area (cm^2); [6]Total root volume (cm^3); [7]Mean root diameter (mm); *Significant at P 0.05 % by the F test; **Significant at 0.01 % as per the F test; [ns]Not significant as per the F test.

Table 6 – Performance of genotypes for total root length and root surface area subjected to doses of 0.05, 2.00, 4.00 and 8.00 mg L^{-1} of P (P_A, P_B, P_C and P_D).

Genotype	Total root length (m)				Root surface area (m^2)			
	PA	PB	PC	PD	PA	PB	PC	PD
1- IAC Alvorada	87.2 a	310.5 a	447.3 a	272.4 a	11.2 a	36.2 b	48.9 a	33.2 a
2- IAC Carioca Tybatã	65.1 b	254.4 b	357.2 b	161.7 b	6.9 c	26.8 c	37.7 b	18.8 b
3- IAC Diplomata	48.4 c	183.1 c	284.4 b	247.5 a	5.2 c	21.0 d	30.3 b	26.8 b
4- IAC Formoso	68.3 b	287.8 b	261.2 b	211.7 b	7.5 c	32.1 b	27.2 b	21.9 b
5- IAC Imperador	79.2 a	256.0 b	291.7 b	172.2 b	9.0 b	28.2 c	34.4 b	21.5 b
6- IPR Uirapuru	82.6 a	291.0 b	347.1 b	160.7 b	8.6 b	30.6 b	36.2 b	18.5 b
7- BAT477	51.1 c	243.4 b	426.0 a	187.8 b	5.1 c	28.9 c	49.1 a	23.7 b
8- SEA 5	82.6 a	306.6 a	351.4 b	153.9 b	12.0 a	43.4 a	52.0 a	26.3 b
9- Carioca Comum	58.6 b	191.5 c	385.6 a	317.0 a	6.2 c	23.5 c	42.0 a	33.0 a
10- IAPAR 81	88.2 a	332.3 a	503.1 a	244.4 a	10.1 b	40.0 a	56.6 a	26.5 b
11- BRS Pontal	67.9 b	200.2 c	365.6 b	173.3 b	7.7 c	23.4 c	42.1 a	21.8 b
12- BRS Estilo	56.0 c	194.0 c	283.7 b	205.5 b	6.6 c	25.5 c	34.6 b	26.5 b
13- Pérola	48.4 c	147.3 c	340.3 b	230.3 a	5.4 c	17.3 d	36.3 b	24.9 b
14- IPR Tangará	95.1 a	345.6 a	307.4 b	248.7 a	11.7 a	37.8 a	32.3 b	26.9 b
15- Diamante Negro	67.8 b	327.7 a	415.0 a	229.4 a	7.3 c	35.4 b	42.7 a	25.5 b
16- Jalo Precoce	84.2 a	178.9 c	278.4 b	189.9 b	10.2 b	22.7 c	32.3 b	23.4 b
17- G 4000	73.3 a	209.8 c	395.8 a	136.6 b	8.8 b	26.9 c	46.5 a	17.8 b
18- DOR 364	39.5 c	109.9 c	285.1 b	147.0 b	4.1 c	12.7 d	29.5 b	15.4 b
19- G 2333	66.1 b	180.9 c	280.1 b	300.5 a	7.6 c	20.5 d	31.8 b	36.4 a
20- BRS Esplendor	56.0 a	206.8 c	312.8 b	218.2 a	6.5 c	24.7 c	37.5 b	24.8 b
Mean values of plots	68.3 D	237.9 B	346.0 A	210.4 C	7.9 D	27.9 b	39.0 A	24.7 C

*Mean values followed by different lower case letters in the column differ (Scott-Knott test, $p < 0.05$) for cultivars, and mean values with different upper case letters in the line differ (Scott-Knott test, $p < 0.05$) for phosphorus doses applied in the plots.

Table 7 – Summary of analysis of variance of the yield components in 20 common bean genotypes grown in a hydroponic system.

FV[1]	GL	Mean square				
		NPP[2]	NSP[3]	NSPOD[4]	HSW[5]	Y[6]
P doses	3	9563.55**	276965.80**	23.31**	531.77**	22719.71**
Error (a)	6	45.81	874.27	0.39	24.27	38.12
Genotypes	19	233.45**	3984.63**	2.81**	246.91**	184.83**
P * G	57	56.40**	1084.68**	0.75*	20.37*	57.03[ns]
Error (b)	154	22.21	588.35	0.46	12.57	44.93
CV (a) %		36	33	14	20	27
CV (b) %		25	27	15	14	29

[1]Font of variation, [2]Number of pods per plant; [3]Number of seeds per plant; [4]Number of seeds per pod; [5]Hundred seed weight (g); [6]Individual plant yield (g); *Significant at 0.05 % by the F test; **Significant at 0.01 % as per the F test; [ns]Non-significant as per the F test.

of pods per plant of 17, 54 and 90 %; for number of seeds per plant 30, 66 and 92 %; for number of seeds per pod 16, 23 and 25 %; for hundred seed weight 12, 25 and 14 % and, for grain yield, reductions of 39, 74 and 93 %, for P_C, P_B and P_A respectively, in relation to the control plot P_D. The effectiveness of stress induction may be able to reduce productive potential from 40 to 60 %, in reference to the environment without stress (Parentoni et al., 2011). Very drastic reductions may also lead to the reduction of genetic variability through loss of plants or yield restriction. If the environment with a low level of P leads to little reduction in productive potential, the correlation between the genetic materials assessed, with and without stress, will tend to be relatively high. Nevertheless, it is expected that the greater the intensity of the stress, the greater the effect of the genotype × environment interaction, resulting in changes in genotype classification in contrasting environments.

Genotypes G 4000, Carioca Comum, IAPAR 81 and IAC Carioca Tybatã had the greatest mean values for number of pods per plant, on average 25 pods per plant, while the genotypes IPR Tangará, SEA 5, DOR 364 and Jalo Precoce showed the lowest values for this trait, an average of 12 pods per plant. The assessment of number of seeds per plant revealed that the following cultivars: Carioca Comum, IAPAR 81, IAC Imperador, and IAC Carioca Tybatã exhibited greater performance with an average of 110 seeds per plant and the following genotypes: IAC Alvorada, SEA 5, DOR 364 and Jalo Precoce exhibited lower performance, with an average of 43 seeds per plant. Genotypes SEA 5, BRS Esplendor, BRS Pontal and IAC Formoso exhibited an average of 5.2 seeds per pod, going beyond the genotypes G 4000, BAT 477, Jalo Precoce and Pérola with an average of 3.8.

The Jalo Precoce cultivar had a greater hundred seed weight (38.8g), followed by the two cultivars Pérola, IAC Alvorada and IAC Carioca Tybatã (28.8g) and the four genotypes G 4000, BRS Esplendor, BAT 477 and IAC Diplomata with lower mean values (18.8g). The reduction in doses of P had an effect of decreasing grain weight; nevertheless, this difference was attributed primarily to the morphological differences among the genotypes. According to Yan et al. (1995), Andean genotypes that have large seeds tend to be more efficient when phosphorus deficiency is present than Mesoamerican genotypes that have small seeds. Nevertheless, the Mesoamerican genotypes are more responsive to applications of the element.

IAPAR 81, IAC Carioca Tybatã, Carioca Comum and IAC Imperador stood out as the highest grain yielding, with an average of 28 g per plant. DOR 364, Jalo Precoce and IAC Diplomata were the the lowest yielding, with an average of 17 g per plant (Table 8).

Carrying out assessments of agronomic traits allowed changes to be verified in the classification of the genotypes in relation to the doses of P applied for most of the traits. In addition, the dose applied to the P_C plot, 50 % less in relation to the highest dose (P_D), resulted in a reduction of 60 % in yield, an increase of 64 % in root growth and reduction in dry matter production of the shoot. Therefore, the dose for the P_C plot may be considered as the ideal dose for inducing P stress with a view toward classification and selection of materials that are efficient and responsive in the use of the nutrient.

The classification of genotypes according to the methodology of Parentoni et al. (2011) allowed the genotypes to be classified into the four groups proposed by Fageria (1998) (Figure 1). In this classification, the following genotypes: IAPAR 81, Carioca Comum, IAC Carioca Tybatã, IAC Imperador and G 2333 stood out as efficient and responsive, proving to be more adapted to P stress conditions, and the two cultivars DOR 364 and Jalo Precoce, which had the lowest mean values for most of the traits, proved to be inefficient and non-responsive.

The classification of these genotypes opens the way for selection of divergent genotypes for inducing crosses directed toward obtaining more efficient lines and molecular studies, as well as for recommendation of genotypes that are efficient in environments with low soil fertility and those that are responsive in more technically advanced locations that make use of adequate application of fertilizers.

Table 8 – Mean yield per plant of 20 common bean genotypes grown in a hydroponic system subjected to doses of 0.05, 2.00, 4.00 and 8.00 mg L^{-1} of P (P_A, P_B, P_C and P_D).

Genotype	PA	PB	PC	PD	Mean
	g				
1- IAC Alvorada	4.5 a	8.9 a	27.4 a	53.8 a	23.7 b
2- IAC Carioca Tybatã	4.1 a	17.8 a	34.2 a	60.1 a	29.1 a
3- IAC Diplomata	2.3 c	10.0 a	19.5 a	42.9 b	18.7 b
4- IAC Formoso	3.0 b	16.1 a	29.1 a	42.6 b	22.7 b
5- IAC Imperador	3.2 b	11.5 a	37.9 a	53.9 a	26.6 a
6- IPR Uirapuru	3. 8 a	15.2 a	28.5 a	48.9 a	24.1 b
7- BAT 477	1.3 c	11.6 a	22.4 a	41.8 b	19.3 b
8-SEA 5	3.1 b	14.1 a	28.6 a	43.9 b	22.43 b
9- Carioca Comum	2.7 b	16.5 a	35.5 a	63.7 a	29.63 a
10- IAPAR 81	4.6 a	12.0 a	41.1 a	62.0 a	29.93 a
11- BRS Pontal	2.8 b	13.2 a	25.8 a	49.5 a	22.83 b
12- BRS Estilo	2.9 b	13.5 a	28.3 a	43.6 b	22.1 b
13- Pérola	1.8 c	12.3 a	24.6 a	53.6 a	23.11 b
14- IPR Tangará	5.1 a	15.2 a	32.6 a	42.2 b	23.8 b
15- Diamante Negro	3.9 a	9.7 a	31.0 a	45.9 b	22.7 b
16- Jalo Precoce	3.6 a	11.9 a	25.7 a	29.9b	17.8 b
17- G 4000	3.6 a	7.5 a	25.9 a	36.6 b	18.4 b
18- DOR 364	1.9 c	14.1 a	21.2 a	37.5 b	18.6 b
19- G 2333	3.1 b	9.9 a	29.3 a	54.0 a	24.1 b
20- BRS Esplendor	3.7 a	5.9 a	30.3 a	42.3 b	20.5 a
Mean value of plots	3.3 A	12.3 B	28.9 C	47.4 D	22.9

*Mean values followed by different lower case letters in the column differ (Scott-Knott test, $p < 0.05$) for cultivars, and mean values with different upper case letters in the line differ ((Scott-Knott test, $p < 0.05$) for phosphorus doses applied in the plots.

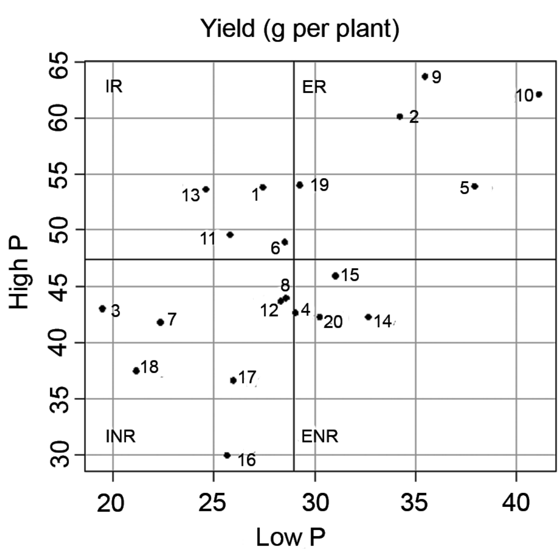

Figure 1 – Performance of the 20 common bean genotypes in regard to efficiency in use of phosphorus, classified in four categories: IR – inefficient and responsive; INR – inefficient and non-responsive; ER – efficient and responsive; ENR - efficient and non-responsive. The axis of the abscissas is represented by the grain yield values under P stress (Low P), and the axis of the ordinates, by the grain yield values under ideal P conditions (High P), 4.00 and 8.00 mg L^{-1} of P respectively.

Conclusions

The dose of 4.00 mg L^{-1} of P applied in the P_C plot was the most efficient in inducing P stress for discriminating cultivars with regard to uptake efficiency and use of the nutrient.

The following genotypes: IAPAR 81, Carioca Comum, IAC Carioca Tybatã, IAC Imperador and G 2333 stood out as efficient and responsive, while the two cultivars DOR 364 and Jalo Precoce stood out as inefficient and non-responsive to P.

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