NUTRIENT EXTRACTION AND EXPORTATION BY COMMON BEAN CULTIVARS UNDER DIFFERENT FERTILIZATION LEVELS: I - MACRONUTRIENTS[1]

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SUMMARY

The use of cultivars with a higher yield potential and the adoption of new technology have achieved high grain yields in common bean, which probably changed the demand for nutrients in this crop. However, there is almost no information about the periods of the cycle in which nutrients are most demanded at which quantities by the main cultivars. The objective of this study was to evaluate the macronutrient extraction and exportation by the common bean cultivars Pérola and IAC Alvorada, under different levels of NPK fertilization, on a dystroferric Red Nitosol, in Botucatu, São Paulo State, Brazil. The experiment was arranged in a randomized complete block (split plot) design with four replications. The plots consisted of six treatments based on a 2 x 3 factorial model, represented by two cultivars and three NPK levels (PD0 - 'Pérola' without fertilization, PD1 - 'Pérola' with 50 % of recommended fertilization, PD2 - 'Pérola' with 100 % of recommended fertilization, AD0 - 'IAC Alvorada' without fertilization, AD1 - 'IAC Alvorada' with 50 % of recommended fertilization, and AD2 - 'IAC Alvorada' with 100 % of recommended fertilization) and subplots sampled seven times during the cycle. At higher levels of NPK fertilization, the grain yield and macronutrient extraction and exportation of both cultivars were higher, but without statistical differences. Macronutrient absorption was higher in the treatments with 100 % of recommended NPK fertilization (average amounts per hectare: 140 kg N, 16.5 kg P, 120 kg K, 69 kg Ca, 17.9 kg Mg, and 16.3 kg S). Regardless of the treatment, the demand for N, P, K, Ca, and Mg was highest from 45 to 55 days after emergence (DAE), i.e., in the R_7 stage (pod formation), while the highest S absorption rates were concentrated between 55 and 65 DAE. More than 70 % of P, between 58 and 69 % of N, 40 and 52 %

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of S, 40 and 48 % of K, and 35 and 45 % of Mg absorbed during the cycle was exported with grains, whereas less than 15 % of Ca was exported.

Index terms: ***Phaseolus vulgaris*****, mineral nutrition, absorption curves, absorption rates, nutrients accumulation.**

RESUMO: *EXTRAÇÃO E EXPORTAÇÃO DE NUTRIENTES EM CULTIVARES DE FEIJOEIRO, SOB NÍVEIS DE ADUBAÇÃO: I - MACRONUTRIENTES*

O uso de cultivares com maior potencial produtivo e a adoção de maior nível tecnológico têm possibilitado a obtenção de elevadas produtividades de grãos da cultura do feijão, o que provavelmente alterou a demanda por nutrientes dessa cultura. No entanto, quase não existem informações sobre as quantidades e as épocas do ciclo em que os nutrientes são mais exigidos pelos principais cultivares utilizados. Objetivou-se, neste estudo, avaliar a extração e a exportação de macronutrientes pelos cultivares de feijão Pérola e IAC Alvorada, sob diferentes níveis de adubação NPK, em um Nitossolo Vermelho distroférrico, no município de Botucatu, SP. O delineamento experimental utilizado foi de blocos casualizados, em esquema de parcela subdividida, com quatro repetições. As parcelas foram constituídas por seis tratamentos referentes a um fatorial 2 x 3, sendo dois cultivares e três níveis de adubação NPK (PD0 - 'Pérola' sem adubação, PD1 - 'Pérola' com 50 % da adubação recomendada, PD2 - 'Pérola' com 100 % da adubação recomendada, AD0 - 'IAC Alvorada' sem adubação, AD1-– 'IAC Alvorada' com 50 % da adubação recomendada e AD2 - 'IAC Alvorada' com 100 % da adubação recomendada) e as subparcelas, por sete épocas de coletas no decorrer do ciclo. Sob maiores níveis de adubação NPK, ambos os cultivares apresentaram as maiores produtividades de grãos, extração e exportação de macronutrientes, porém sem diferirem entre si. Os tratamentos com 100 % da adubação NPK recomendada apresentaram maior extração de macronutrientes, com quantidades médias por hectare de 140 kg de N; 16,5 kg de P; 120 kg de K; 69 kg de Ca; 17,9 kg de Mg; e 16,3 kg de S. Independentemente do tratamento, a época de maior demanda por N, P, K, Ca e Mg ocorreu dos 45 aos 55 dias após emergência (DAE), ou seja, no estádio R7 (formação das vagens), enquanto as maiores taxas de absorção de S concentraram-se entre os 55 e 65 DAE. Mais de 70 % do P, entre 58 e 69 % do N, 40 e 52 % do S, 40 e 48 % do K e 35 e 45 % do Mg absorvidos ao longo do ciclo foram exportados com os grãos, enquanto menos de 15 % do Ca foi exportado

Termos de indexação: Phaseolus vulgaris*, nutrição mineral, curvas de absorção, taxas de absorção, acúmulo de nutrientes.*

INTRODUCTION

Common bean (*Phaseolus vulgaris* L.) is considered a nutrient-demanding crop. Due to its small, shallow root system and short cycle, nutrients must be supplied to the plant at the most appropriate time and location. Thus, knowing the amount and dynamics of nutrient accumulation during the crop cycle will help plan and manage fertilization, as a nutritional imbalance, caused by deficiency or excess of nutrients, would stress the plant (Franco et al., 2007). Furthermore, to establish rational fertilization programs, it is essential to know the nutrient absorption potential of the plant, as well as the nutrient amounts exported from the field.

In recent years, due to the release of new common bean cultivars and the adoption of new technologies, such as the use of higher levels of irrigation and fertilization, a higher grain yield in common bean has been achieved (CONAB, 2012), exceeding 3,000 kg ha^{-1} (Vieira, 2006). Nevertheless, literature information on nutrient absorption by this crop is old, i.e., it was obtained in the 1960's and 1970's in situations where grain yield was lower than 1,000 kg ha^{-1} (Gallo & Miyasaka, 1961; Haag et al., 1967; Cobra Netto et al., 1971).

The amount of extracted and exported nutrients can vary according to the yield potential and growth conditions of a cultivar (Rosolem, 1987), and the amount of nutrients removed from the soil by crops changes according to biomass and grain yield (Haag et al., 1978; Barbosa Filho & Silva, 2000). It is therefore possible that the nutritional requirements of the current common bean cultivars are not the same as those used in the 1960's and 1970's, the period in which nutrient absorption by common bean was studied and described in the literature (Gallo & Miyasaka, 1961; Haag et al., 1967; Cobra Netto et al., 1971).

One of the main common bean cultivars with carioca grains is Pérola, which is one of the most widely grown cultivars in Brazil. It is also a reference cultivar for grain yield and quality (Melo et al., 2006), and preferred by packing companies and the final consumer, defining market standards. The cultivar IAC Alvorada, released in 2007, also has a high yield potential and an excellent quality of carioca grains, as well as moderate tolerance to anthracnose (Carbonell et al., 2008; Soratto et al., 2011). However, there are no studies in the literature on the nutrient absorption and exportation of these cultivars, especially under different fertilization levels.

Thus, more knowledge about nutrient absorption during the development cycle of the main common bean cultivars, under different fertilization levels, is essential for the development of specific fertilization programs for each cultivar and its growing conditions, to fine-tune the management and fertilizer use, as well as reduce costs and environmental risks.

The objective of this study was to evaluate macronutrient extraction and exportation by the common bean cultivars Pérola and IAC Alvorada, under different levels of NPK fertilization.

MATERIALS AND METHODS

A field experiment was conducted on the Experimental Farm Lageado of the College of Agricultural Sciences - São Paulo State University, in Botucatu, São Paulo State, Brazil (48° 26' W, 22° 51' S, 740 m asl), in a dystroferric Red Nitosol (Embrapa, 2006). According to the Köppen classification, the climate is Cwa (tropical highland), with a dry winter and a hot, rainy summer. The experiment was carried out in an area under no-tillage cultivation for several years. Before the installation of this experiment, wheat/maize/pearl millet crops were grown in the area.

Prior to the experiment, a soil sample consisting of 10 subsamples was taken from the 0-20 cm layer to determine the chemical properties (Raij et al., 2001). The results were organic matter = 28 g dm^{-3}; pH ($CaCl_2$ 0.01 mol L^{-1}) = 5.0; P (resin) = 33 mg dm^{-3}; K^+ = 3.0 $mmol_c$ dm^{-3}; Ca^{2+} = 25 $mmol_c$ dm^{-3}; Mg^{2+} = 11 $mmol_c$ dm^{-3}; H+Al = 32 $mmol_c$ dm^{-3}; base saturation = 55 %; S = 6.4 mg dm^{-3}; B = 0.40 mg dm^{-3}; Cu = 12.4 mg dm^{-3}; Fe = 23 mg dm^{-3}; Mn = 5.1 mg dm^{-3}; and Zn = 1.6 mg dm^{-3}.

Fertilization at sowing consisted of 20 kg ha^{-1} N (urea), 40 kg ha^{-1} P_2O_5 (triple superphosphate), and 40 kg ha^{-1} K_2O (potassium chloride), according to soil analysis and following the recommendation of Ambrosano et al. (1997), for an expected grain yield of 3,500-4,500 kg ha^{-1}. The recommendation for topdressing was 90 kg ha^{-1} N (urea), as a strong response to N application in the area was expected (Ambrosano et al., 1997). No S or micronutrients were applied.

The experiment was arranged in a randomized complete block design with split-plots and four replications. Plots consisted of six treatments based on a 2 x 3 factorial model, consisting of two cultivars and three NPK levels (PD0 - Pérola without NPK fertilization, PD1 - Pérola with 50 % of recommended NPK fertilization; PD2 - Pérola with 100 % of recommended NPK fertilization; AD0 - IAC Alvorada without NPK fertilization, AD1 - IAC Alvorada with 50 % of recommended NPK fertilization, and AD2 - IAC Alvorada with 100 % of recommended NPK fertilization). Subplots consisted of seven plant sampling (evaluations) times (Table 1). Each plot consisted of five 12-m-long rows, spaced 0.45 m apart (27 m^2), of which the three central rows of the plot were evaluated, without the borders of 0.5 m at either end of each row (14.8 m). Each subplot was represented by six plants sampled in sequence from each plot. The plants beside a sampled plant were not considered.

Sowing was performed mechanically on 02/15/2011 (15 seeds per meter). In all treatments, the seeds were treated with fungicide carbendazim + thiram (45 + 105 g a.i. per 100 kg of seed) and insecticide thiamethoxam (75 g a.i. per 100 kg of seed). Seedlings emerged on 02/22/2011. Nitrogen topdressing was split into two applications (14 days after emergence - DAE and 24 DAE - V_4 stage). Irrigation and phytosanitary measures during the crop cycle were performed as needed and according to the technical recommendations.

At common bean flowering (37 DAE), leaves were collected as described by Ambrosano et al. (1997), and the concentrations of N, P, K, Ca, Mg, and S were determined according to Malavolta et al. (1997).

At each sampling time, the shoots of six plants without signs of damage caused by pests and diseases and with healthy plants on all sides were collected from each plot. Stems, leaves and reproductive structures (pods + grains) of the sampled plants were separated. The plant parts were dried separately in a forced-air oven at 65 °C for 72 h and weighed. The data from the dry matter (DM) associated with times of plant sampling was used to obtain the curves of DM accumulation.

The samples were ground in a Willey mill and the macronutrient concentrations (N, P, K, Ca, Mg, and S) determined according to Malavolta et al. (1997). Amounts of accumulated macronutrients were estimated for all compartments of the aboveground part of the plant (shoot) separately and together, using data from the macronutrient concentration and amounts of accumulated DM. Accumulation rates of macronutrients in the reproductive structures and the shoot were obtained by the first derivative of the adjustment equations.

At end of the cycle (90 DAE), the grain yield was determined in two 3-m-long rows of each plot, and values were expressed in kg ha^{-1} (13 % of moisture). A sample of grains from each plot was dried in a forced-air oven at 65 °C for 72 h. Afterwards, these grains

Table 1. Description of the common bean growth stages in each time of evaluation

Time of evaluation	Growth stage[1]	Plant characteristics in each time of evaluation
DAE[2]		
14	V_4	Third trifoliate leaf expanded
28	R_5	Pre-flowering (flower buds)
35	End of R_5	Pre-flowering (a little before to full flowering)
42	Early R_7	Beginning of pod formation
55	End of R_7	End of pod formation
70	R_8	Grain filling
90	R_9	Maturation

[1] Fernández et al. (1986). [2] Days after emergence.

were ground and macronutrient (N, P, K, Ca, Mg, and S) concentration was determined according to Malavolta et al. (1997). Macronutrient exportation was obtained using the data of grain yield DM and macronutrient concentration in grains.

Data were subjected to analysis of variance. Means of the treatments at each sampling time were separated by the LSD test at 0.05 probability, using Sisvar software. The effects of times of plant sampling were evaluated by regression analysis, using SigmaPlot 10.0 software.

RESULTS AND DISCUSSION

Analyzing plant nutrition (Table 2), it was found that the NPK fertilization resulted in higher concentrations of N and K in the leaves of common bean cultivars, regardless of the amount of fertilizer applied. Only in the treatments without NPK fertilizer N concentrations in leaves were lower than 30 to 50 g kg^{-1}, the range considered appropriate for common bean by Ambrosano et al. (1997). The K leaf concentrations in all treatments exceeded the range of 20-24 g kg^{-1}, considered adequate by Ambrosano et al. (1997), possibly due to the fact that the availability of this nutrient in the soil (3.0 mmol dm^{-3}) is considered medium (Raij et al., 1997). The P, Ca, and S leaf concentration was not influenced by the treatments (Table 2). The NPK fertilization has no effect on P leaf concentrations because the availability of this nutrient in the soil (33 mg dm^{-3}) is considered medium (Raij et al., 1997). The Mg leaf concentration in the common bean cultivars was not influenced by NPK fertilization, but higher in cultivar Pérola than IAC Alvorada. In general, the P, Ca, Mg, and S leaf concentration in all treatments was in agreement with values considered adequate by Ambrosano et al. (1997), i.e, 2.5-4.0 g kg^{-1} for P, 10-25 g kg^{-1} for Ca, 2.5-5.0 g kg^{-1} for Mg, and 2.0-3.0 g kg^{-1} for S. These results, together with soil nutrient availability, show that the nutrient supply of the plants was sufficient, particularly in treatments with NPK fertilization.

Dry matter accumulation in the stem increased up to 70 DAE (grain filling), with a decrease in the next stage in all treatments (Figure 1a). At each fertilizer level, the DM accumulation in the stems of both cultivars was similar, but DM accumulation increased as the levels of fertilizer increased. In the leaves, DM accumulation was increased from emergence up to 55 and 70 DAE (R7-R8), regardless of the treatment (Figure 1b). In a study about common bean growth, Sant'Ana & Silveira (2008) observed maximum DM accumulation in leaves after a similar period as observed in this study, i.e., 66 DAE. Leaf senescence and abscission probably led to a reduced amount of DM accumulated in leaves at end of the cycle, as also observed by Andrade et al. (2009). Treatments with the recommended NPK fertilization showed higher DM accumulation in the leaf, especially in cultivar IAC Alvorada, which

Table 2. Concentration of N, P, K, Ca, Mg, and S in leaf diagnosis, collected at R_6 stage (37 DAE), of common bean cultivars under different levels of fertilization

Treatment [1]	N	P	K	Ca	Mg	S
	g kg^{-1}					
PD0	26 b	3.1 a	25 b	12.8 a	3.0 a	2.3 a
PD1	37 a	3.3 a	29 a	13.0 a	3.0 a	2.2 a
PD2	41 a	3.4 a	29 a	12.4 a	3.0 a	2.3 a
AD0	24 b	3.1 a	26 b	12.6 a	2.3 b	2.5 a
AD1	35 a	3.3 a	29 a	15.7 a	2.6 b	2.2 a
AD2	40 a	3.3 a	29 a	14.7 a	2.5 b	2.5 a
CV (%)	13.3	14.2	6.0	15.5	9.0	8.1

Values followed by same letter in columns, are not significantly different at $p \leq 0.05$ by the LSD test. [1] PD0: Pérola without NPK fertilization, PD1: Pérola with 50 % of recommended NPK fertilization; PD2: Pérola with 100 % of recommended NPK fertilization; AD0: IAC Alvorada without NPK fertilization, AD1: IAC Alvorada with 50 % of recommended NPK fertilization; AD2: IAC Alvorada with 100 % of recommended NPK fertilization.

showed a higher leaf DM than Pérola, mainly at the end of the cycle (Figure 1b). At the other NPK fertilization levels, the leaf DM was similar between common bean cultivars.

In the early flowering stage, the DM accumulation in reproductive structures was small in all treatments, but increased greatly after 55 DAE (Figure 1c). Once the pods started forming (42 DAE), the reproductive structures became the main sink organs of the plants. According to Andrade et al. (2009), pods and grains act as storage organs for carbohydrates translocated from the leaves. At the end of the cycle, the reproductive structures represented between 77 and 79 % of DM accumulated in the shoot of "Pérola" and between 70 and 74 % of DM accumulated in the shoot of "IAC Alvorada" (Figure 1c,d). In all treatments, shoot DM accumulation was low in the first 28 DAE, but increased, especially after flowering, due to the intense growth of reproductive structures after this period (Figure 1c,d). Brito et al. (2009) also observed a rapid increase in DM accumulation by the common bean cultivar Carioca after the beginning of flowering. In spite of the lower plant population in treatments with cultivar IAC Alvorada, there were no differences in DM accumulation between cultivars, due to plasticity, i.e., the ability of common bean plants type III to environmental adaptation (Jauer et al., 2003). In the treatments with the recommended NPK fertilization (AD2 and PD2), DM accumulation was highest in the shoots (Figure 1d). In treatments with 50 % of recommended NPK fertilization (PD1 and AD1), the DM accumulation of both cultivars was similar and higher than in the unfertilized treatments (PD0 and AD0).

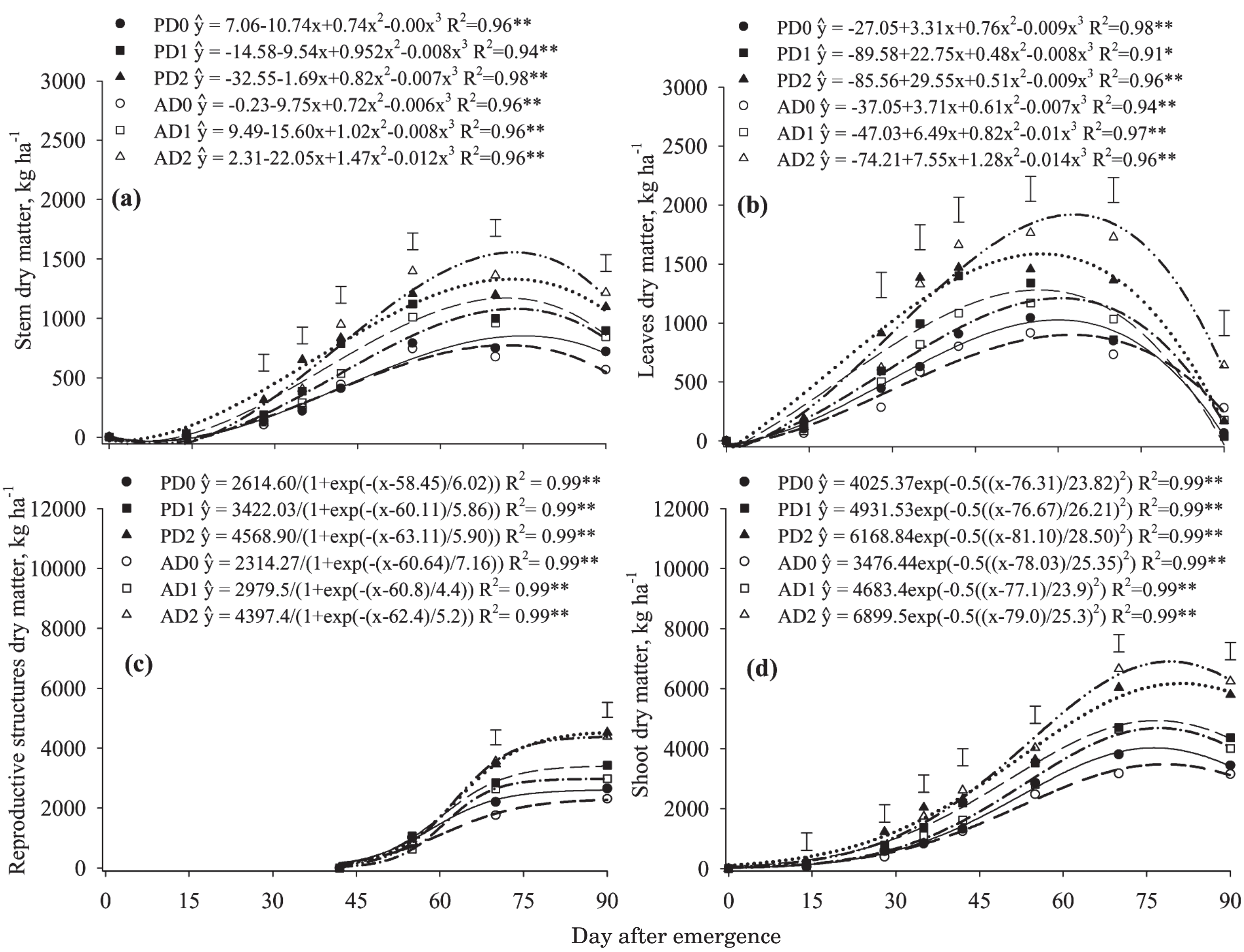

Figure 1. Dry matter accumulation in stem (a), leaves (b), reproductive structures (c), and shoot (d) of common bean cultivars, under different levels of fertilization. ** and * are: significant at $p \leq 0.01$ and $p \leq 0.05$ by the F test. Vertical bars represent the Least Significant Difference (LSD) at $p \leq 0.05$. PD0 = Pérola without NPK fertilization, PD1 = Pérola with 50 % of recommended NPK fertilization; PD2 = Pérola with 100 % of recommended NPK fertilization; AD0 = IAC Alvorada without NPK fertilization, AD1 = IAC Alvorada with 50 % of recommended NPK fertilization; AD2 = IAC Alvorada with 100 % of recommended NPK fertilization.

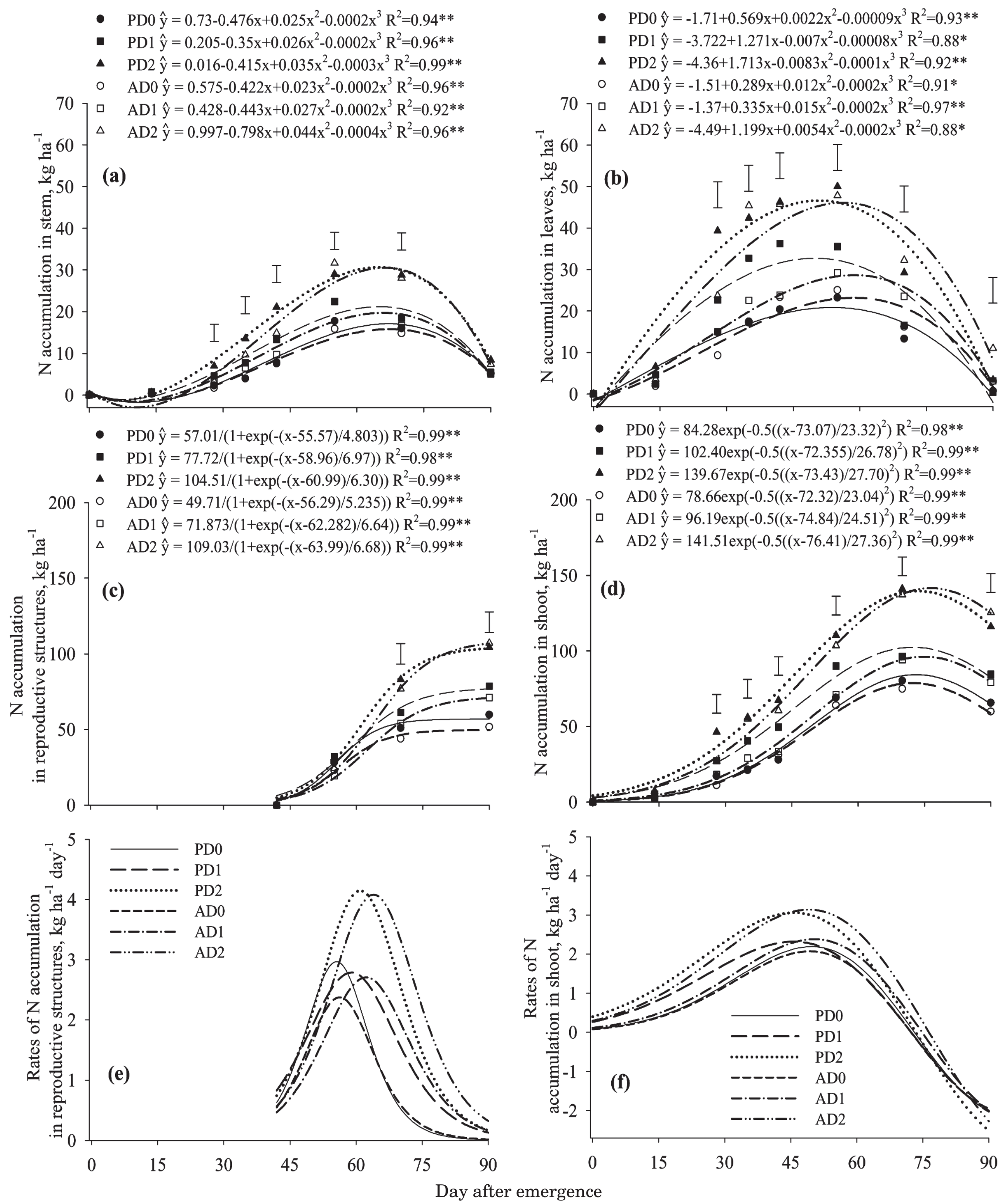

Figure 2. Nitrogen accumulation in stem (a), leaves (b), reproductive structures (c), and shoot (d) and rates of accumulation of N in reproductive structures (e) and shoot (f) of common bean cultivars, under different levels of fertilization. ** and * are: significant at $p \leq 0.01$ and $p \leq 0.05$ by the F test. Vertical bars represent the Least Significant Difference (LSD) at $p \leq 0.05$. PD0 = Pérola without NPK fertilization, PD1 = Pérola with 50 % of recommended NPK fertilization; PD2 = Pérola with 100 % of recommended NPK fertilization; AD0 = IAC Alvorada without NPK fertilization, AD1 = IAC Alvorada with 50 % of recommended NPK fertilization; AD2 = IAC Alvorada with 100 % of recommended NPK fertilization.

With regard to nutrient uptake, it was observed that the amounts of N and P accumulated in the stem increased up to 65 DAE, while the accumulated amounts of K and Mg increased up to 75 DAE and Ca accumulation increased up to 80 DAE (Figures 2a, 3a, 4a, 5a, 6a, and 7a). The nutrient amounts accumulated in the stem did not differ significantly among treatments at the beginning of the cycle. However,

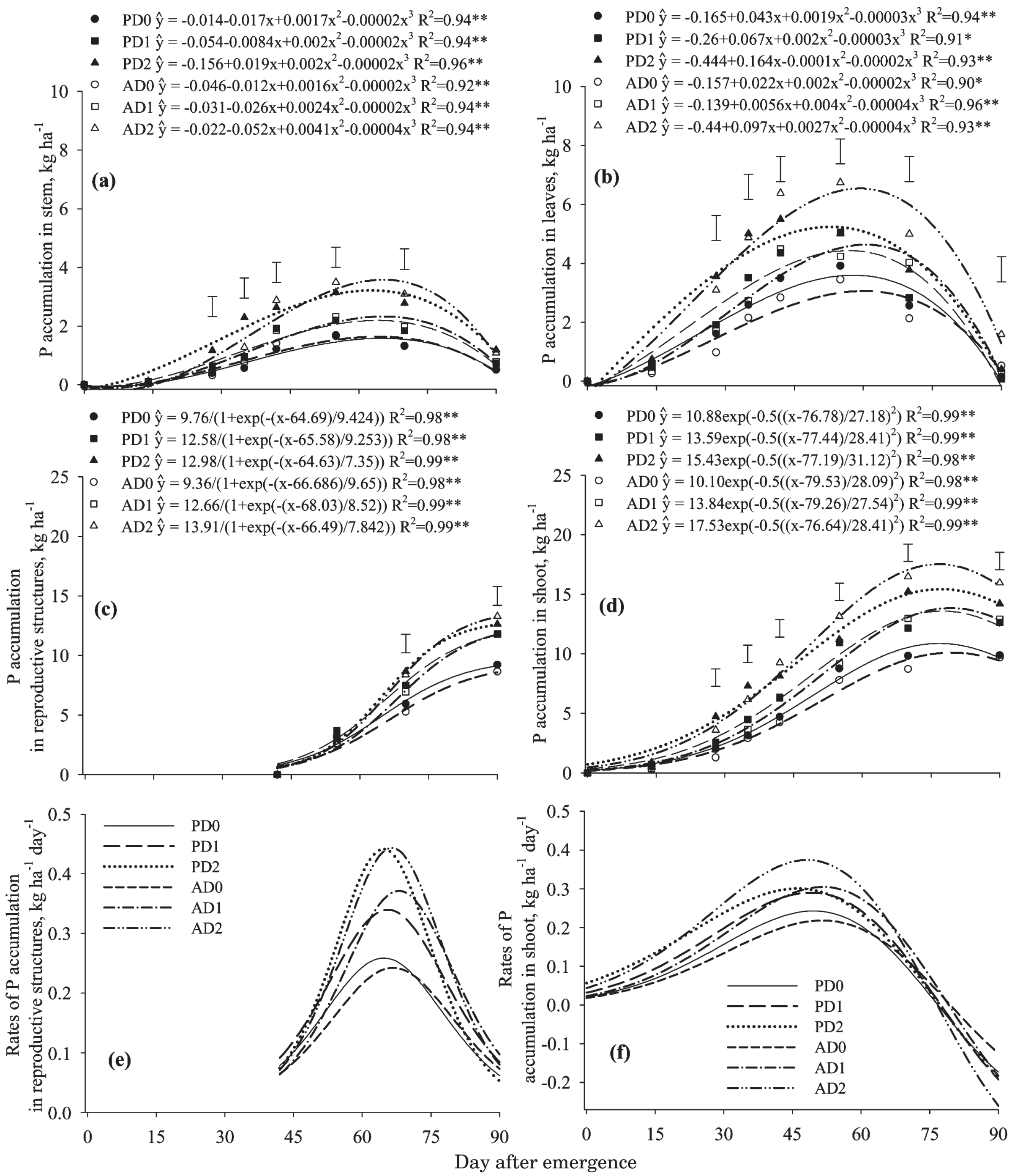

Figure 3. Phosphorus accumulation in stem (a), leaves (b), reproductive structures (c), and shoot (d) and rates of accumulation of P in reproductive structures (e) and shoot (f) of common bean cultivars, under different levels of fertilization. ** and * are: significant at $p \leq 0.01$ and $p \leq 0.05$ by the F test. Vertical bars represent the Least Significant Difference (LSD) at $p \leq 0.05$. PD0 = Pérola without NPK fertilization, PD1 = Pérola with 50 % of recommended NPK fertilization; PD2 = Pérola with 100 % of recommended NPK fertilization; AD0 = IAC Alvorada without NPK fertilization, AD1 = IAC Alvorada with 50 % of recommended NPK fertilization; AD2 = IAC Alvorada with 100 % of recommended NPK fertilization.

after the beginning of flowering (35 DAE), it was observed that at each level of NPK fertilization both common bean cultivars accumulated similar amounts of macronutrient in the stem, but in treatments with 100 % of recommended NPK fertilization the accumulated macronutrient amounts were higher than in treatments without fertilization. In the treatment with 50 % of recommended NPK fertilization,

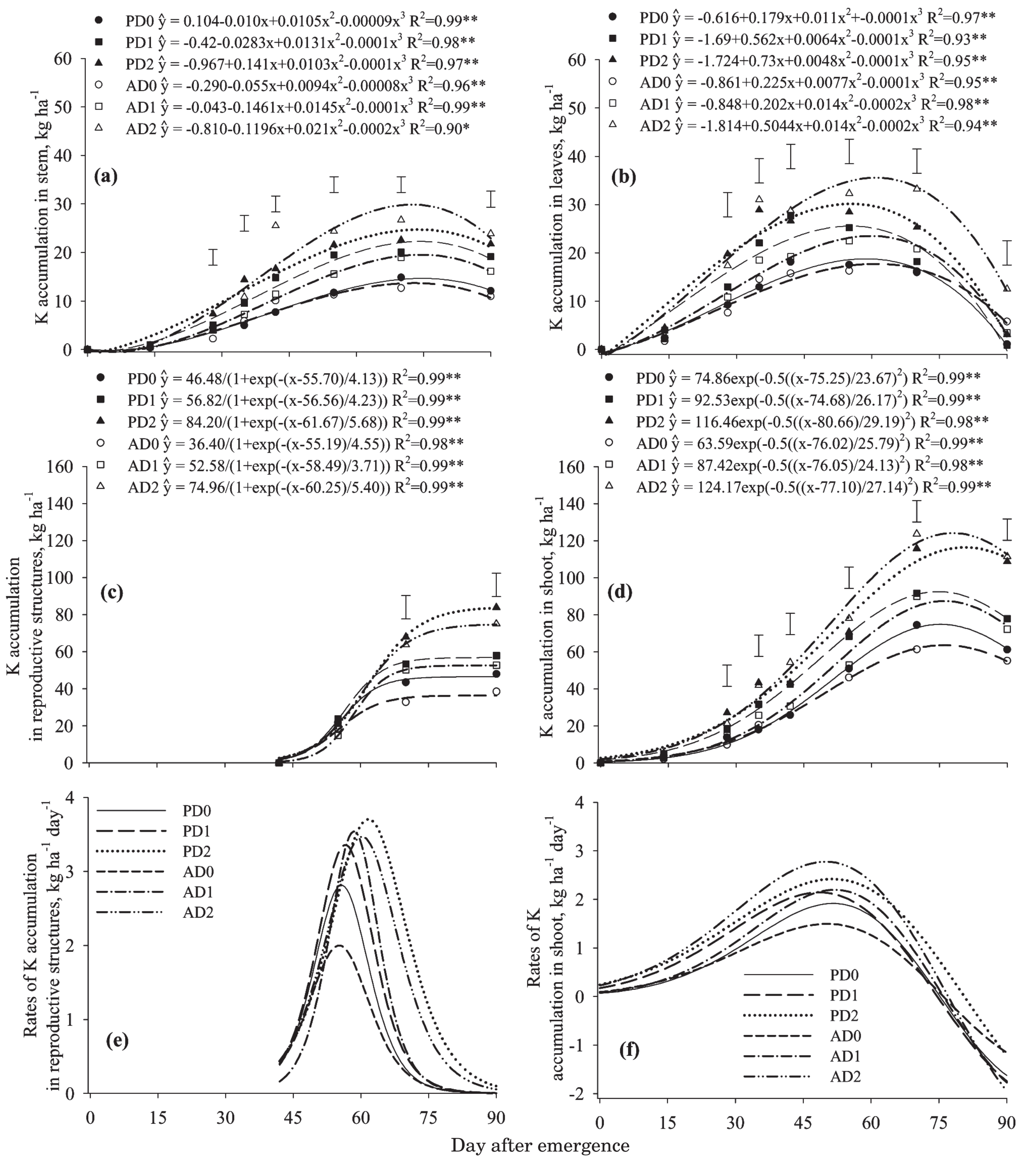

Figure 4. Potassium accumulation in stem (a), leaves (b), reproductive structures (c), and shoot (d) and rates of accumulation of K in reproductive structures (e) and shoot (f) of common bean cultivars, under different levels of fertilization. ** and * are: significant at $p \leq 0.01$ and $p \leq 0.05$ by the F test. Vertical bars represent the Least Significant Difference (LSD) at $p \leq 0.05$. PD0 = Pérola without NPK fertilization, PD1 = Pérola with 50 % of recommended NPK fertilization; PD2 = Pérola with 100 % of recommended NPK fertilization; AD0 = IAC Alvorada without NPK fertilization, AD1 = IAC Alvorada with 50 % of recommended NPK fertilization; AD2 = IAC Alvorada with 100 % of recommended NPK fertilization.

macronutrient accumulation in the stem was intermediate, although N and P accumulation did not differ significantly from treatments without fertilization and K accumulation was similar to treatments with recommended NPK fertilization. In the treatments with 100 % of recommended NPK fertilization the plants accumulated a higher amount of N and P in the stem between 35 and 70 DAE, showing a similar

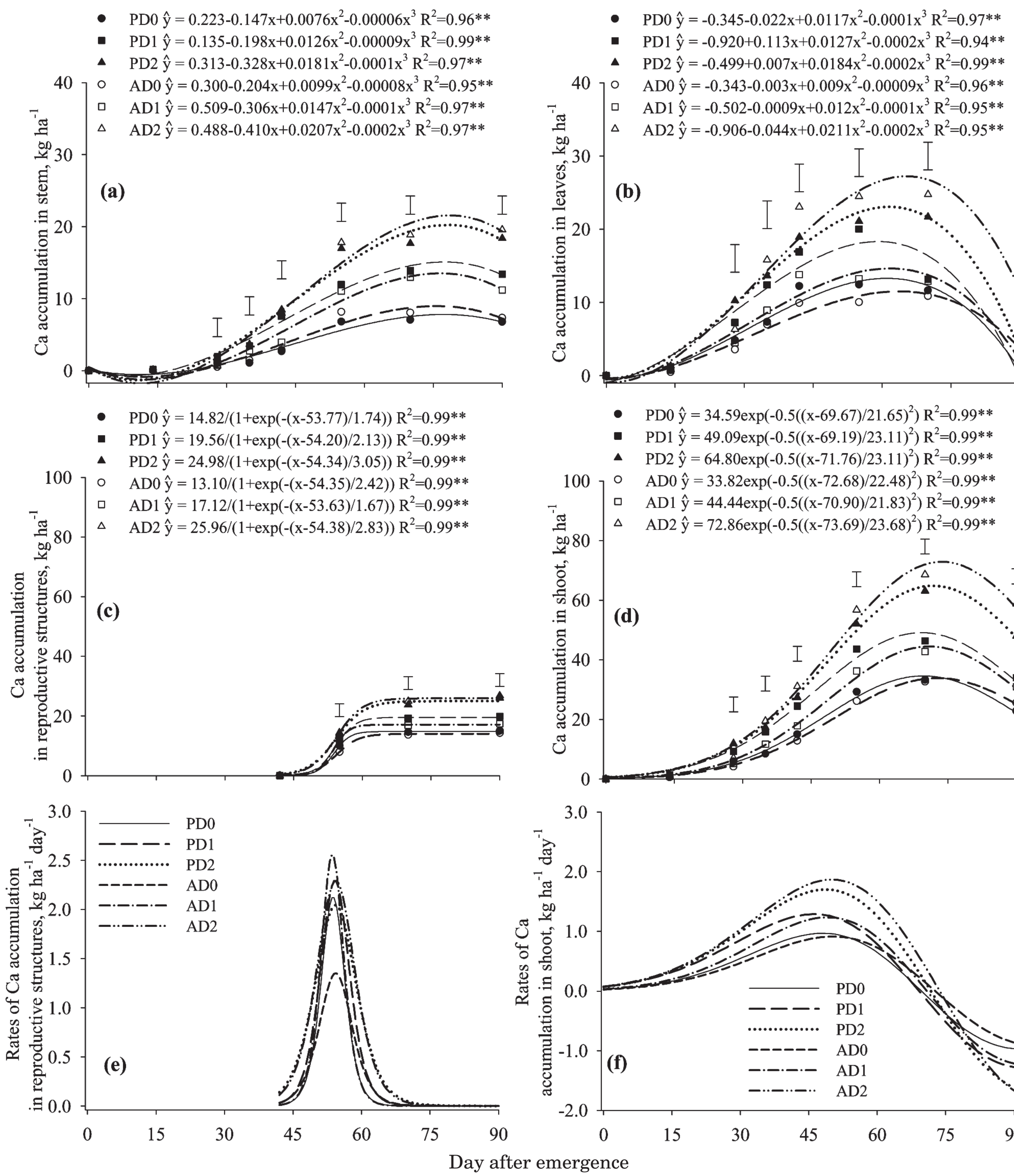

Figure 5. Calcium accumulation in stem (a), leaves (b), reproductive structures (c), and shoot (d) and rates of accumulation of Ca in reproductive structures (e) and shoot (f) of common bean cultivars, under different levels of fertilization. ** and * are: significant at p ≤ 0.01 and p ≤ 0.05 by the F test. Vertical bars represent the Least Significant Difference (LSD) at p ≤ 0.05. PD0 = Pérola without NPK fertilization, PD1 = Pérola with 50 % of recommended NPK fertilization; PD2 = Pérola with 100 % of recommended NPK fertilization; AD0 = IAC Alvorada without NPK fertilization, AD1 = IAC Alvorada with 50 % of recommended NPK fertilization; AD2 = IAC Alvorada with 100 % of recommended NPK fertilization.

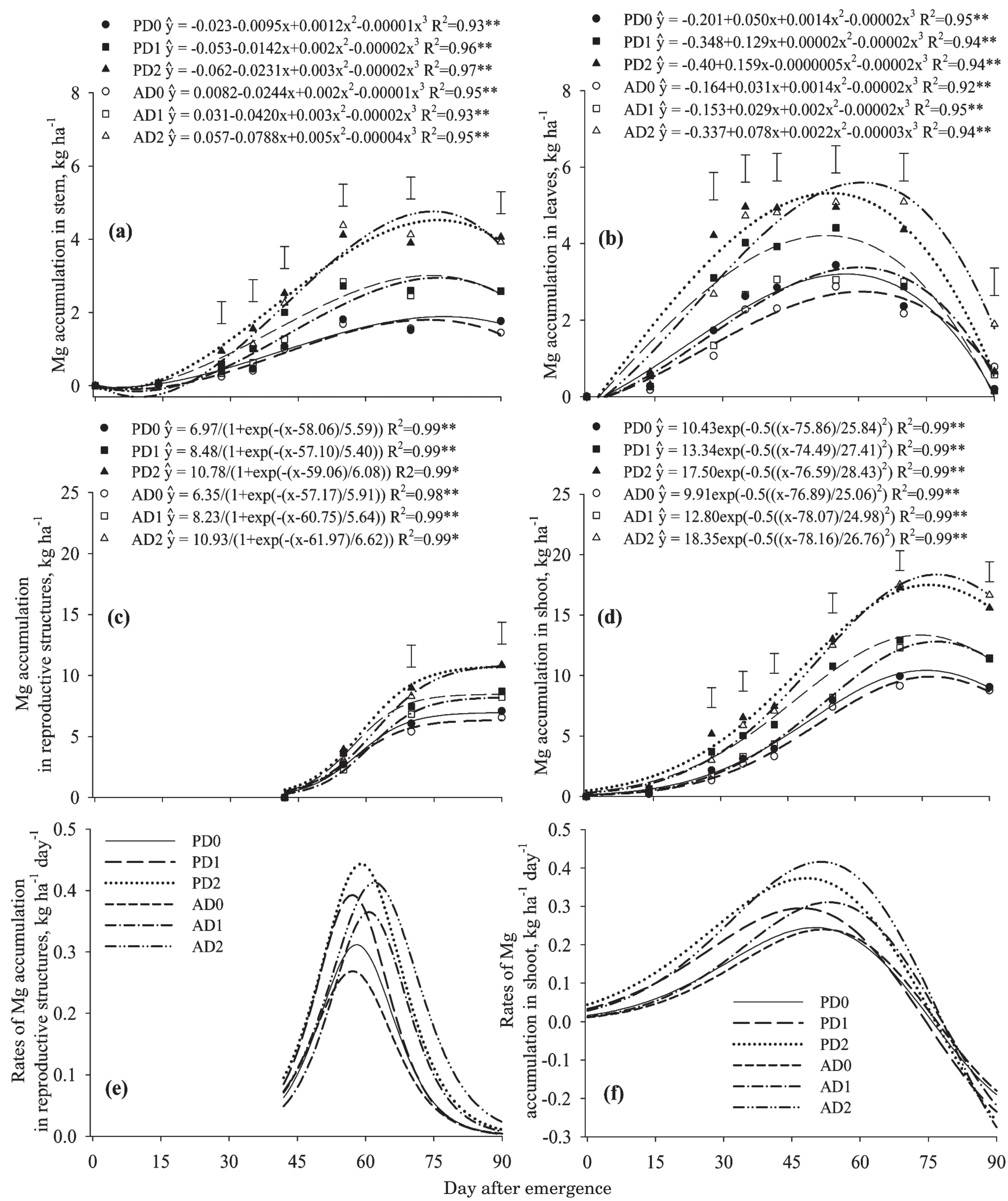

Figure 6. Magnesium accumulation in stem (a), leaves (b), reproductive structures (c), and shoot (d) and rates of accumulation of Mg in reproductive structures (e) and shoot (f) of common bean cultivars, under different levels of fertilization. ** and * are: significant at $p \leq 0.01$ and $p \leq 0.05$ by the F test. Vertical bars represent the Least Significant Difference (LSD) at $p \leq 0.05$. PD0 = Pérola without NPK fertilization, PD1 = Pérola with 50 % of recommended NPK fertilization; PD2 = Pérola with 100 % of recommended NPK fertilization; AD0 = IAC Alvorada without NPK fertilization, AD1 = IAC Alvorada with 50 % of recommended NPK fertilization; AD2 = IAC Alvorada with 100 % of recommended NPK fertilization.

accumulation to the other treatments at the end of the cycle. These results show has an intense N and P accumulation in the stem during the early reproductive stage of common bean, and at the end of the grain filling stage it remobilizes a high proportion of those nutrients for the grains, where these elements are

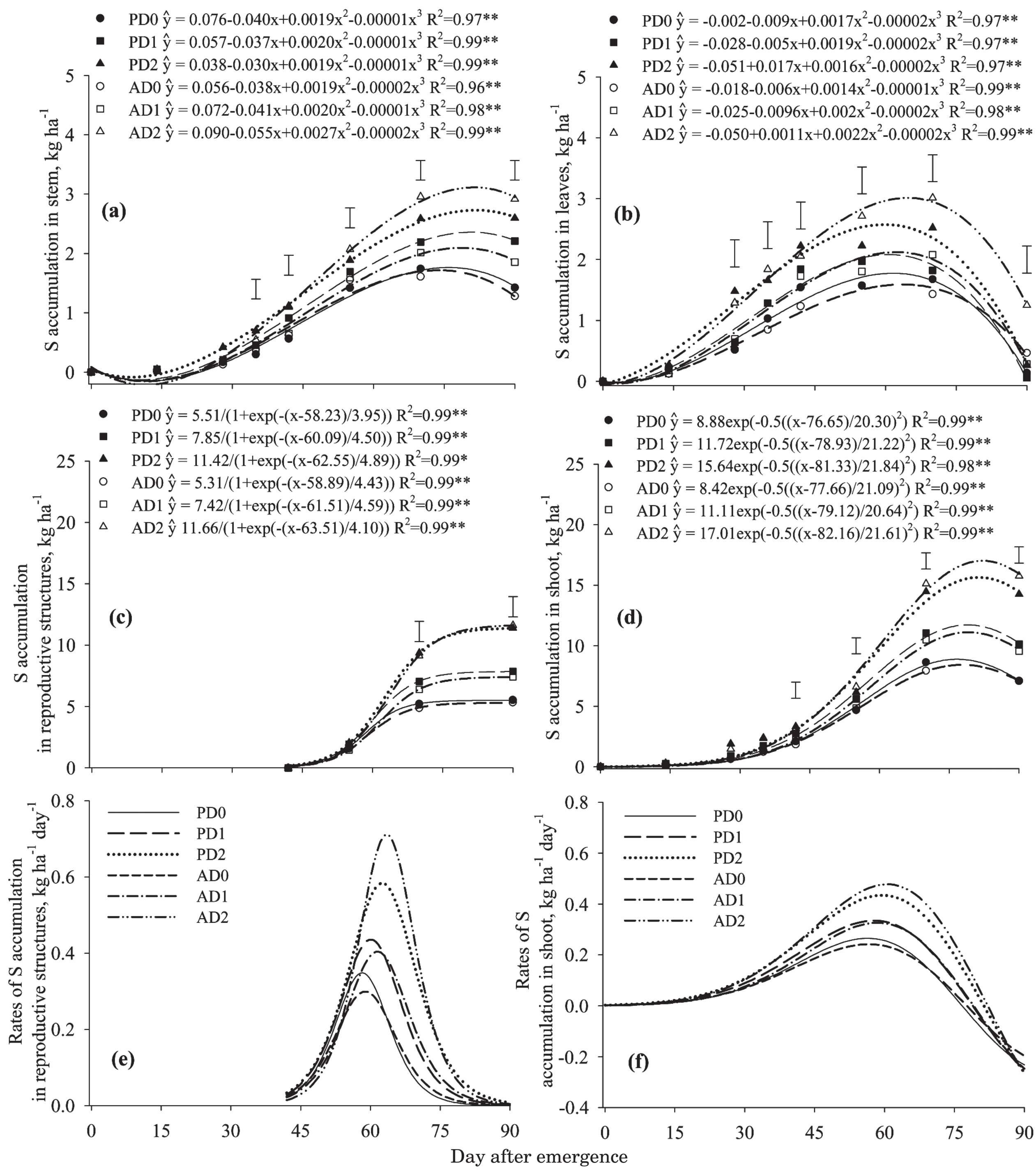

Figure 7. Sulfur accumulation in stem (a), leaves (b), reproductive structures (c), and shoot (d) and rates of accumulation of S in reproductive structures (e) and shoot (f) of common bean cultivars, under different levels of fertilization. ** and * are: significant at $p \leq 0.01$ and $p \leq 0.05$ by the F test. Vertical bars represent the Least Significant Difference (LSD) at $p \leq 0.05$. PD0 = Pérola without NPK fertilization, PD1 = Pérola with 50 % of recommended NPK fertilization; PD2 = Pérola with 100 % of recommended NPK fertilization; AD0 = IAC Alvorada without NPK fertilization, AD1 = IAC Alvorada with 50 % of recommended NPK fertilization; AD2 = IAC Alvorada with 100 % of recommended NPK fertilization.

required in high amounts (Gallo & Miyasaka 1961; Haag et al., 1967). Regardless of the treatment, it was observed that N, K and Ca were the nutrients accumulated in larger amounts in the stem, which was similar to results obtained by Gallo & Miyasaka (1961) and Cobra Netto et al. (1971) in studies with common bean.

The amounts of nutrient accumulated in the leaves were greater and showed a significant difference between treatments from the beginning of the vegetative stage (Figures 2b, 3b, 4b, 5b, 6b, and 7b). However, the maximum nutrient accumulation occurred at similar times during the cycle, with the highest leaf accumulation of N, P, K, and Mg obtained between 50 and 60 DAE (end of pod formation), and the highest leaf accumulation of Ca and S observed from 60 to 65 DAE (early grain filling). At the end of the cycle, the amounts of nutrient accumulated in leaves decreased and became similar in almost all treatments. Elements with high mobility in the plant, e.g., N, P, K, and Mg, were largely redistributed from the leaves to the growing reproductive organs (Figures 2b,c; 3b,c; 4b,c; 6b,c). However, a reduction in the amount of Ca accumulated in the leaves at the end of the cycle was especially due to leaf senescence and abscission (Figure 1b), since Ca remobilization in plant tissue is low (Malavolta et al., 1997), and the amount of this nutrient in reproductive structures increased slightly at the end of the cycle (Figure 5b,c). A reduction in the amounts of N, P, K, Mg, and S accumulated in leaves of common bean during grain filling was observed by Gallo & Miyasaka (1961), who attributed this behavior to the mobilization of nutrients from other plant parts to the reproductive structures. However, these authors also observed a decrease in the amount of Ca accumulated in the leaves, but only in a stage nearer the end of the cycle, showing that this decrease was due to leaf senescence.

During most of the cycle, the treatments with 100 % of recommended NPK fertilization accumulated the largest amounts of macronutrient in the leaves, and the lowest amounts were observed in treatments without fertilization (Figures 2b, 3b, 4b, 5b, 6b, and 7b), which is similar to results given by Gallo & Miyasaka (1961). In treatments PD1 and AD1, the amounts of macronutrient accumulated in leaves were intermediate, but showed no significant difference from unfertilized treatments during most of the cycle, and from treatments with 100 % of recommended NPK fertilization during the vegetative stage. The nutrients which accumulated in greater amounts in the leaves of common bean during the entire development cycle were N, K, and Ca, which was also observed by Gallo & Miyasaka (1961) and Cobra Netto et al. (1971).

The amounts of N, P, K, Mg, and S accumulated in the reproductive structures increased continuously from 42 DAE (beginning of pod formation) until the end of the cycle, in all treatments (Figures 2c, 3c, 4c, 6c, and 7c). The amounts of Ca accumulated in the reproductive structures increased up to 60 DAE (early grain filling) and remained stable in subsequent periods (Figure 5c). This nutrient influences the formation of calcium pectate in the cell walls. Thus, an adequate supply of Ca to plants is essential to normal fruit and seed development (Marschner, 1995). The greater nutrient accumulation in the reproductive structures after flowering occurs because at this stage, pods and grains are growing at the same time (Portes, 1996), which increases DM accumulation in these organs (Figure 1c) and the demand for nutrients.

In the reproductive structures, the highest accumulation rates of N, K, and Mg occurred between 55 and 65 DAE, while the highest accumulation rates of S and P were concentrated between 60-65 and 65-70 DAE, respectively (Figures 2e, 3e, 4e, 6e, and 7e). Calcium was accumulated in the reproductive structures at higher rates in a short period, around 55 DAE (Figure 5e). In treatments with 100 % of recommended NPK fertilization the largest amounts of N, K, Ca, Mg, and S accumulated in the reproductive structures were observed, due to higher accumulation rates of these nutrients (Figures 2c, 4c, 5c, 6c, and 7c). In treatments with 50 and 100 % of recommended NPK fertilization, the amounts of P accumulated in the reproductive structures showed no significant difference, but were higher than in the unfertilized treatments (Figure 3c). The amounts of N, P, and S accumulated in the reproductive structures were lower in unfertilized treatments and intermediate in treatments with 50 % of recommended NPK fertilization, but K, Ca, and Mg accumulation was similar in these treatments. It is important to consider that the K, Ca, and Mg availability in the soil was medium to high (Raij et al., 1997). Even at medium P availability in the soil (Raij et al., 1997), a supply of 9 kg ha^{-1} P (20 kg ha^{-1} P_2O_5) at sowing in the furrow was sufficient to promote higher P accumulation in the reproductive structures of common bean. The greater N accumulation is also explained by the application of this nutrient with the fertilizer. The higher S accumulation in the reproductive structures was probably due to greater root growth provided by NPK fertilization, especially in deeper layers, where this nutrient is normally more readily available (Soratto & Crusciol, 2008).

The amounts of macronutrient accumulated in the shoots of plants were small and showed no significant difference until the beginning of the V4 stage (14 DAE) in all treatments (Figures 2d, 3d, 4d, 5d, 6d, and 7d). After this period, the highest accumulation of all macronutrients in common bean shoot was observed at higher levels of NPK fertilization, but without significant difference between cultivars at the same level of NPK fertilization. The accumulation rates of macronutrients in the shoot were greater after the end of the vegetative stage (28 DAE) and reached maximum values between the beginning (42 DAE) and the end of pod formation (55 DAE) (Figures 2f, 3f, 4f, 5f, 6f, and 7f). The amounts of macronutrient accumulated in the shoot increased up to grain filling

(70-80 DAE). After this time, the accumulation rates of macronutrients in the shoot decreased and became negative, due to leaf senescence and abscission; thus amounts of macronutrients accumulated in the shoot decreased up to the end of the cycle, due to the decrease in DM accumulated, especially in leaves (Figure 1b).

The maximum accumulation of N and Mg occurred 75 DAE (Figures 2d and 6d), which is in agreement with Cobra Netto et al. (1971) and Rosolem (1987), who mentioned that common bean does not absorb the total N requirement in the first 50 DAE. According to Brito et al. (2009), the largest proportion of N absorbed by common bean (around 80 %) was derived by symbiotic fixation, and the highest rate of N symbiotic fixation occurred at the pre-flowering stage. Haag et al. (1967) found that Mg was absorbed up to 70 DAE, i.e., a similar period as observed in this study (Figure 6d). The amount of Ca accumulated in the shoot increased up to 70 DAE, different from results obtained by Haag et al. (1967) and Cobra Netto et al. (1971), who observed Ca absorption by common bean up to 50 and 55 DAE, respectively. The amounts of P, K, and S accumulated in the shoot increased up to 80 DAE (Figures 3d, 4d, and 7d), i.e., P absorption did not increase until the end of the cycle, as observed by other authors (Gallo & Miyasaka, 1961; Haag et al. 1967; Cobra Netto et al., 1971). During the cycle of plant development, K absorption occurred for a longer period than reported by Haag et al. (1967) and Cobra Netto et al. (1971), who observed no K absorption after 50-55 DAE. Sulfur absorption by common bean occurred up to a later stage, as reported by Haag et al. (1967), who observed S absorption only until 60 DAE. However, Cobra Netto et al. (1971) found S absorption by common bean until the end of the cycle. It is important to consider that the research by Haag et al. (1967) was performed in pots, which may have limited plant growth and S absorption, but the study of Cobra Netto et al. (1971) was performed under field conditions.

In all treatments, the time of highest demand for N, P, K, Ca, and Mg occurred between 45 and 55 DAE in both cultivars, while the highest S absorption rates occurred between 55 and 65 DAE (Figures 2f, 3f, 4f, 5f, 6f, and 7f). The periods of highest nutrient demand observed in this study were similar to the periods cited by Rosolem (1987). This author reported that the period of highest nutrient demand by common bean, i.e., when absorption rates were greatest, begins at the time of the maximum number of flowers and ends with the end of flowering (55 DAE), which is also the period of early pod formation.

In all treatments, the macronutrients most absorbed by both common bean cultivars occurred in the following order: N > K > Ca > P > Mg > S (Figures 2d, 3d, 4d, 5d, 6d, and 7d), the same as reported by Vieira et al. (2009), based on the average of four common bean cultivars. Gallo & Miyasaka (1961), Haag et al. (1967), and Cobra Netto et al. (1971) also found that the nutrients most absorbed by common bean plants were N, K, and Ca. At each level of NPK fertilization, the maximum amounts of macronutrient accumulated by the cultivars Pérola and IAC Alvorada, showed no significant difference. Thus, in treatments without NPK fertilization, the cultivars absorbed per hectare on average 82 kg of N, 10.5 kg of P, 69 kg of K, 34 kg of Ca, 10.2 kg of Mg, and 8.7 kg of S, while in the treatments with 100 % of recommended NPK fertilization the absorption was higher with average values of 140 kg ha^{-1} N, 16.5 kg ha^{-1} P, 120 kg ha^{-1} K, 69 kg ha^{-1} Ca, 17.9 kg ha^{-1} Mg, and 16.3 kg ha^{-1} S. It is important to consider that in all treatments, the amounts of N and K absorbed by common bean were higher than those with fertilizer (PD1 and AD1 = 55 kg ha^{-1} N and 16.7 kg ha^{-1} K; PD2 and AD2 = 110 kg ha^{-1} N and 33.4 kg ha^{-1} K), indicating that common bean used the soil reserves and symbiotic fixation to supply its demands.

In treatments with 50 % of recommended NPK fertilization it was observed that, except for S, the amounts of the other macronutrients absorbed by "Pérola" and "IAC Alvorada" (Figures 2d, 3d, 4d, 5d, 6d, and 7d), were very similar to those obtained by Gallo & Miyasaka (1961), Cobra Netto et al. (1971), and Feitosa et al. (1980), using cultivars with lower grain yield and higher levels of fertilization. In the treatments with 100 % of recommended NPK fertilization, the amounts of N, P, K, Ca, and Mg absorbed by the plants were higher than those reported by these authors. They obtained values of absorption per hectare ranging from 81 to 102 kg of N, 7 to 9 kg of P, 62 to 93 kg of K, 34 to 57 kg of Ca, 10 to 18 kg of Mg, and from 6 to 26 kg of S (Gallo & Miyasaka, 1961; Cobra Netto et al., 1971; Feitosa et al., 1980). The amounts of macronutrient absorbed by common bean, observed in this study, are higher than those reported by Vieira et al. (2009) for four common bean cultivars. With the use of recommended NPK fertilization, "Pérola" and "IAC Alvorada" absorbed higher amounts of macronutrients, (especially of N, P, and K) than older cultivars with lower yield, as those studied by Gallo & Miyasaka (1961), Cobra Netto et al. (1971), and Feitosa et al. (1980).

The levels of NPK fertilization induced no difference in grain yield between the common bean cultivars, while grain yield increased significantly with increasing fertilization (Table 3). Increases in grain yield of both cultivars in response to NPK fertilization were the same, showing they have similar characteristics regarding yield potential (Carbonell et al., 2008). Even in treatments without fertilization the grain yield was higher than 1,800 kg ha^{-1}, i.e., almost twice as high as reported in studies from the 1960's and 1970's on nutrient extraction (Gallo & Miyasaka, 1961; Haag et al., 1967; Cobra Netto et al., 1971). This indicates that the nutrients available in the soil alone were sufficient to obtain intermediate yield, since the soil fertility was considered medium (Raij et al., 1997). The results also show a more efficient use of macronutrients of "Pérola" and "IAC

Alvorada" than of the cultivars used in the 1960's and 1970's, because the amounts absorbed in treatments with 50 % of recommended NPK fertilization were similar (Figures 2d, 3d , 4d, 5d, 6d, and 7d), but grain yield was higher (Table 3) than of the old cultivars. The higher grain yield in this study may also be due to the improvement in the cropping system for this particular crop, because in a field with a high level of agricultural technology, which includes irrigation, a suitable plant population and efficient weed control, a grain yield of 3,000 kg ha^{-1} or even higher has been obtained (Vieira, 2006)

Analyzing macronutrients in grains, it was observed that N, K, Ca, Mg, and S concentration was not affected by treatments (Table 3). In treatments with the recommended NPK fertilization (PD2 and AD2), P concentration was lower than in the other treatments. These results are due to a dilution effect, since the use of recommended NPK fertilization resulted in a higher grain yield. In

Table 3. Grain yield, nutrient concentration in grain, nutrient exportation per area, nutrient exportation per ton of grain, and relative nutrient exportation by common bean cultivars, under different levels of fertilization

Treatment(1)	Grain yield	N	P	K	Ca	Mg	S
	kg ha^{-1}	Grain concentration, g kg^{-1}					
PD0	2,033c	29.5a	5.0ab	17.2a	2.6a	2.0a	2.0a
PD1	2,992b	27.3a	4.3bc	16.6a	2.6a	2.1a	2.4a
PD2	3,898a	26.7a	3.6d	16.4a	2.5a	2.2a	2.4a
AD0	1,866c	28.2a	5.0ab	16.6a	2.7a	2.4a	2.4a
AD1	2,572b	28.7a	5.1a	17.1a	2.2a	2.5a	2.5a
AD2	3,657a	29.9a	3.9cd	16.7a	2.8a	2.1a	2.6a
CV (%)	10.0	12.4	10.7	4.5	17.4	15.6	18.3
		Exportation per area, kg ha^{-1}					
PD0	-	52cd	9bc	30cd	4.6c	3.5c	3.8d
PD1	-	70b	11ab	43b	6.5bc	5.5abc	6.0bc
PD2	-	90a	12a	56a	8.3ab	7.5a	8.0ab
AD0	-	45d	8c	27d	4.3c	3.8bc	4.0cd
AD1	-	64bc	11ab	38bc	5.0c	5.8ab	5.3cd
AD2	-	96a	12a	54a	9.0a	6.8a	8.3a
CV (%)	-	13.3	17.8	14.3	25.7	25.4	22.6
		Exportation per ton of grain, kg t^{-1}(2)					
PD0	-	25.7a	4.4a	15.0a	2.3a	1.8b	1.8a
PD1	-	23.8a	3.8ab	14.4a	2.2a	1.8b	2.1a
PD2	-	23.8a	3.3b	14.6a	2.2a	1.9ab	2.1a
AD0	-	25.0a	4.4a	14.5a	2.3a	2.1ab	2.2a
AD1	-	25.0a	4.5a	14.9a	1.9a	2.2a	2.1a
AD2	-	26.7a	3.4b	14.9a	2.5a	1.9ab	2.3a
CV (%)	-	18.1	11.6	8.9	17.1	12.3	18.1
		Relative exportation, %(3)					
PD0	-	62	81	40	13	35	40
PD1	-	69	83	47	14	40	52
PD2	-	65	80	48	13	43	51
AD0	-	58	81	43	13	38	47
AD1	-	66	83	44	11	45	49
AD2	-	68	71	43	12	37	48
Média		65	80	44	13	40	48

Values followed by same letter in columns, are not significantly different at $p \leq 0.05$ by the LSD test. (1) PD0: Pérola without NPK fertilization, PD1: Pérola with 50 % of recommended NPK fertilization; PD2: Pérola with 100 % of recommended NPK fertilization; AD0: IAC Alvorada without NPK fertilization, AD1: IAC Alvorada with 50 % of recommended NPK fertilization; AD2: IAC Alvorada with 100 % of recommended NPK fertilization. (2) Data based on grain yield and the values of maximum nutrient accumulation see figures 2, 3, 4, 5, 6, and 7. (3) Relative nutrient exportation in relation to maximum amounts absorbed see figures 2, 3, 4, 5, 6, and 7.

general, N and Mg concentration in all treatments was similar to that obtained by Haag et al. (1967), but P concentration was higher and K, Ca, and S concentration was lower.

Altogether, macronutrient exportation in both cultivars was increased at higher levels of NPK fertilization (Table 3). In the average of all treatments, nutrient exportation by common bean occurred in the following order: N > K > P > Ca > S > Mg. Barbosa Filho & Silva (2000) also reported a higher exportation of N, K, P, Ca, and Mg, respectively. Except for P and S, in treatments with 50 % of recommended NPK fertilization, the values of macronutrient exportation were similar to those reported by Gallo & Miyasaka (1961). However, the exportation of N, P, and K from all treatments, including those without NPK fertilization, was higher than the 37 kg ha^{-1} N, 4 kg ha^{-1} P, and the 22 kg ha^{-1} K reported by Cobra Netto et al. (1971). Pessoa et al. (2000) observed an exportation per hectare of 72 kg of N, 9.4 kg of P, and 15.3 kg of K in a field of common bean cultivar Ouro Negro with a grain yield of 1,893 kg ha^{-1}. The results showed a higher yield and macronutrient exportation of "Pérola" and "IAC Alvorada", especially when grown with the recommended NPK fertilization, than of the cultivars used in the 1960's and 1970's (Gallo & Miyasaka, 1961; Cobra Netto et al., 1971). This indicates that the cultivars Pérola and IAC Alvorada are highly efficient in photoassimilation and the redistribution of nutrients to grains and respond to higher levels of fertilizers.

Although exportation per area did not increase in the same proportion as the grain yield, for most of the nutrients there is a direct relationship between the increase in grain yield and nutrient exportation, since N, K, Ca, and S exportation per ton of grain yield shows no difference among treatments (Table 3). In treatments PD0, AD0, and AD1 P exportation per ton of grain was higher than in treatments PD2 and AD2, possibly due to the dilution effect caused by higher grain yield in treatments PD2 and AD2. There was a significant difference in Mg exportation per ton of grain only between treatment AD1 and treatments PD0 and PD1.

Analyzing the relative exportation of macronutrients, it was found that of all the P absorbed by the plants, more than 70 % was exported with the grains, while the total accumulated amounts in shoots and the exported proportions of N and S were from 58 to 69 % and 40 to 52 %, respectively, i.e., similar proportions to those reported by Gallo & Miyasaka (1961). This higher relative exportation of P occurs because this nutrient accumulates in higher proportions in the grains than in the whole plant biomass (Haag et al., 1967). Between 40 and 48 % of K and 35 and 45 % of Mg absorbed by plants during the cycle was exported with the grain harvest (Table 3), i.e., more than half of the amounts of K and Mg absorbed throughout the cycle remained in the field. The proportion of Ca exported with the grains was less than 15 % of the total amount absorbed, indicating that of the total amount accumulated in the plants during the cycle, a high proportion returns to the soil with crop residues. Gallo & Miyasaka (1961) reported harvest exportations of only 33 % of K, 27 % of Mg, and 11 % of Ca, from a common bean crop with a grain yield below 870 kg ha^{-1}. According to Pessoa et al. (2000), to maintain soil fertility fertilization must be correct, applying at least the amount of each nutrient absorbed by the plants, or exported with the grain harvest. Moreover, the crop residues should return to the field, which is usually not the case on small farms, where harvesting is done manually. The residues are either burned afterwards or used for animal feed. Thus, mechanized harvesting, after which crop residues are left on the field, contributes to the maintenance of soil fertility.

CONCLUSIONS

1. Higher levels of NPK fertilization increased grain yield and macronutrient extraction and exportation of both "Pérola" and "IAC Alvorada", however with no statistical difference between the cultivars.

2. In the treatments with 100 % of recommended NPK fertilization macronutrient absorption was greater, with average amounts per hectare of 140 kg of N, 16.5 kg of P, 120 kg of K, 69 kg of Ca, 17.9 kg of Mg, and 16.3 kg of S.

3. Regardless of the treatment, the N, P, K, Ca, and Mg demand was highest from 45 to 55 DAE, i.e., in the R_7 stage (pod formation).

4. The highest S absorption rates occurred between 55 and 65 DAE, i.e., between the end of the R_7 stage and the beginning of grain filling (R_8).

5. More than 70 % of P, between 58 and 69 % of N, and 40 and 52 % of S absorbed during the cycle were exported with grains, while higher proportions of the other macronutrients accumulated in the plants returned to the soil with crop residues.

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