

The potential of nutrient cycling in cover plants in response to phosphate fertilization

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Abstract

Residues of crops and cover crops contain considerable amounts of phosphorus (P) in their tissues, which through their mineralization can meet much of the requirement of crops. In this context, the present study aimed to evaluate the biomass production, P absorption and use of different cover crops subjected to phosphate fertilization, and its effects on the absorption and use of nitrogen (N), phosphorus (P) and potassium (K). The experiment was conducted in a protected environment from August to December 2019. The experimental design was completely randomized, arranged in a 7 x 3 scheme, consisting of the planting of seven species of cover crops (*Crotalaria spectabilis*, *Crotalaria breviflora*, *Crotalaria ochroleuca*, *Mucuna aterrima*, *Mucuna pruriens*, *Dolichos lablab* and *Canavalia ensiformis*), three P rates (0, 80 and 160 kg ha⁻¹ of P₂O₅) and four replicates. At the time of full flowering, the cover species were cut and divided into root and shoot for subsequent determination of dry mass production, nutrient content and absorption efficiency and nutrient utilization. The results showed that *Canavalia ensiformis* promoted higher yield of shoot fresh and dry mass, P content in the shoots and higher N and P absorption efficiency. N and P contents in *Dolichos lablab* roots were higher at the highest P rates (160 kg ha⁻¹ of P), without close relationship with the supply of shoot dry mass. The P dose of 160 kg ha⁻¹ had an increasing and significant effect on the production of shoot fresh mass and dry mass, N, P and K contents in the shoots, N, P and K contents in the roots and efficiency of N, P and K use by the different cover crops. The P rates of 80 kg ha⁻¹ increased the N, P and K contents in the shoots of *Crotalaria ochroleuca*, *Crotalaria breviflora* and *Crotalaria spectabilis*; and at higher P rates, there was a reduction in nutrient accumulation. The species *Mucuna pruriens* and *Mucuna aterrima* were efficient in the use of N, P and K at P rates of 160 kg ha⁻¹.

Keywords: Green manure; Legume species; Nutrient cycling; Phosphorus; P use efficiency; Soil sustainable management.

Introduction

The supply of phosphorus (P) represents a significant portion of the production cost of crops, especially in tropical regions, because in addition to having low P availability, almost all soils are weathered, acidic, clayey and oxidic, characteristics that favor P fixation by the soil (Silva et al., 2011). The practical implication of this is that, although P requirement by plants is not high, large amounts of the nutrient must be supplied through fertilization to promote some soil saturation and originate a surplus that meets the nutritional requirements of crops (Novais and Smyth, 1999).

Most of the cost in the establishment of a plantation in the southern region of the Rondônia state is related to the correction of soil acidity and phosphate fertilization. Thus, considering the essentiality of P for plant development, and phosphates as a non-renewable natural resource, it is necessary to search for ways to use it efficiently. One

practice that results in increased recovery of P added to the soil is the implementation of soil conservation practices, including species with high efficiency in extracting and using P. Based on this premise, plants that have structural, biochemical and physiological mechanisms enable a greater use of soil P, which can be used to achieve a high agronomic efficiency of phosphate fertilization (Fernandes and Muraoka, 2002)

Residues of crops and cover crops contain considerable amounts of P in their tissues, which through their mineralization can meet much of the requirement of crops. In the process of mineralization of organic residues, organic forms of P that are less susceptible to adsorption reactions are formed. The soil can adsorb organic acids with great energy, competing with the P adsorption sites and increasing

the availability of this nutrient for plants (Oliveira et al., 2002; Andrade et al., 2003).

Studies have shown that plants with greater capacity to extract P are those that have abundant root system and produce exudates capable of acidifying the rhizosphere, favoring the solubilization of the less reactive, water-insoluble natural phosphates, when they need acidity for some dissolution. Another factor that favors the solubility of natural phosphates is the sink of P and Ca by plants. A greater removal of Ca and P increases the dissolution rate of natural phosphate (Silva et al., 2011). Thus, conditions that favor the increase cation exchange capacity (CEC) with a higher content of organic matter and liming, besides the crop itself, can play a major role in the efficiency of natural phosphates, as they would act as Ca sink (Silva et al., 2009). Together, P cycling by plants gains importance, because they have different levels of adaptation to access soil P (Hall et al., 2010). It is essential to identify the ones with the greatest potential to absorb and cycle soil P and to optimize the use of soil P by plants in agricultural systems, as the access mechanisms vary with the plant species, especially those that can be used commercially or as soil cover crops cultivated in succession and/or rotation with commercial species. The synchronization between plant species, soils and P is an indispensable tool for the best use of this element by different species, maximizing the plant's response to phosphate fertilization in most tropical soils (Andrade et al., 2003; Soares et al., 2007).

Thus, studying the effect of different crop systems and soil managements on the forms of P accumulation in soil is the way to select agricultural practices to improve the dynamics of this nutrient in soil and as a management alternative that contributes to the maintenance or improvement of soil quality. The indication of diversified cover crops associated with a system of crop succession and/or rotation in the Amazon Biome is relevant for the deepening of scientific knowledge and for a new technological process aimed at agricultural production in the Amazon region, with lower costs due to the reduction in the use of chemical fertilizers. In view of the above, the present study aimed to evaluate the biomass production, P absorption and use by different cover crops subjected to phosphate fertilization, and its effects on the absorption and use of N, P and K.

Results and discussion

The results showed significant effects ($p \leq 0.05$) of the double interaction between cover crops and P rates on N, P and K contents in the shoots (Table 6), N, P and K contents in the root (Table 7) and efficiency of N, P and K use (Table 8). However, the other results did not show significant effect of the interaction and are independently presented for the different cover crops (Table 3, 4 and 5) and P rates (Figure 2, 3, 4 and 5).

Fresh and dry mass production Dry by cover crops

Canavalia ensiformis was statistically superior ($p \leq 0.05$) to the other cover crops in terms of shoot fresh and dry mass production, while root dry mass production had one of the lowest values recorded among the different cover crops (Table 3). It is observed that even with low root dry mass production, which may be closely related to the soil volume

available for root development, *Canavalia ensiformis* was able to absorb the largest amount of N by the root (16.52g kg⁻¹) (Table 4). In contrast, lower amounts of N were accumulated in the shoots (Table 4), as an inverse relationship between the variables. Pereira et al. (2017), studied nutrient cycling by different cover plants and found that *Canavalia ensiformis* led to better results regarding shoot fresh and dry mass production at the phenological stage of flowering, while Bortoluzzi et al. (2019) verified that *Canavalia ensiformis* has high potential for biomass supply in different sowing periods. Barros et al. (2017) and Teodoro et al. (2011) suggested *Canavalia ensiformis* as an excellent cover species because it has rapid initial growth, large cotyledonary leaves, good soil cover and high dry mass production capacity, besides performing biological N fixation.

The lowest values of shoot fresh mass and dry mass production were verified for the cover crop *Dolichos lablab* (Table 3), with a direct correlation between shoot fresh and dry mass production and the lowest N accumulation in the shoots (17.72 g kg⁻¹) (Table 4). However, the species had the highest P contents in the shoots (1.66 g kg⁻¹), not differing statistically from *Crotalaria breviflora* and *Crotalaria spectabilis* (Table 4). N and P contents in *Dolichos lablab* roots were significantly higher than those found in the other cover plants, making it possible to infer the ability of this species to accumulate N and P in its root tissues, without close relationship with the supply of shoot dry mass.

Among the cover plants, for the production of root dry mass and total dry mass, the species *Mucuna aterrima*, *Mucuna pruriens* and *Crotalaria ochroleuca* stood out and did not differ statistically from one another (Table 3).

Nutrient content in shoot and root by cover crops

Regarding the K contents in shoots and roots, the species *Crotalaria spectabilis* was superior to the others, while the lowest K contents in shoots and roots were accumulated by *Canavalia ensiformis* (Table 4). K absorption by the respective cover crops ranged between 17.18 g kg⁻¹ for *Crotalaria spectabilis* and 10.57 g kg⁻¹ for *Canavalia ensiformis*. These significant K contents in the shoots of *Crotalaria spectabilis* corroborate those found by Pereira et al. (2017) and Mauad et al. (2019). In areas with low K levels, it is important to use soil cover plants due to their capacity for cycling, accumulation and supply of nutrients to subsequent crops, favoring the entire agricultural system (Teodoro et al., 2011). The difference of response between species regarding the production and absorption of nutrients is confirmed in the literature, due to the existence of nutritional behavior differentiated by genetic factors of adaptability. In terms of N and P absorption efficiency, *Canavalia ensiformis* stood out with values of 65.45 for N absorption and in the order of 4.43 for P absorption, mg of dry weight per g of N and P absorbed, not differing statistically from the species *Crotalaria breviflora* and *Crotalaria spectabilis* (Table 5). This higher efficiency of N and P absorption by *Canavalia ensiformis* tended to follow the shoot dry mass production, but it was not correlated with the highest N contents in the shoots (Table 3 and 4). The species *Crotalaria breviflora* and *Crotalaria spectabilis* besides being efficient in the absorption of N and P were significantly efficient in terms of K absorption (Table 5).

These data corroborate the K contents found in the roots of both species (Table 4). It is important to highlight that, in addition to the capacity of the species, as a legume crop to fix atmospheric N by the symbiotic association with bacteria of the genus *Rhizobium*, they have high efficiency for cycling and immobilization of nutrients. In the same premise of nutrient absorption efficiency, *Canavalia ensiformis* had the highest efficiency in the use of nutrients, such as P and K (Table 5). Thus, it is possible to affirm that the efficiency of P absorption by the species is directly correlated with the P use efficiency, but the K use efficiency is not consistent with the K absorption efficiency. This information points out *Canavalia ensiformis* as an alternative for adaptation to different edaphoclimatic conditions, soils of low fertility as it can absorb the nutrients from deeper layers, and use them in the shoots.

The species *Mucuna pruriens* and *Mucuna aterrima* were significantly efficient regarding the use of N, P and K (Table 5). The branched and deep root systems of these legume crops promote an increase in the efficiency of fertilizer use, since they bring up to the surface soil layer nutrients that had been lost by leaching, mainly potassium, calcium, magnesium and nitrate. They also functioning as a 'mining agent' of nutrients of low availability such as P, enabling them more available to subsequent crops (Padovam et al., 2011). In addition to the root system morphology, the efficiency of P use per root unit, the acid phosphatase activity and P contents in the roots and shoots explain the dynamics of P absorption and acquisition by the different cover crop species. Barros et al. (2017), evaluated the nutrient extraction and potential of different plant species, aiming at the supply of nutrients to the subsequent crop. They verified that *Mucuna aterrima* had the highest accumulations of all macronutrients, especially N, P, K and Mg, which demonstrates the high capacity of the species in the absorption and use of nutrients.

Fresh and dry mass production in response to phosphorous rates

P doses exerted an increasing and significant effect ($p \leq 0.05$) on the production of shoot fresh mass (Figure 2A), shoot dry mass (Figure 2B), root dry mass (Figure 2C) and total dry mass (Figure 2D) of the different cover crops. The highest yields were obtained at a P dose of 160 kg ha^{-1} , which reveals a positive effect of phosphate fertilization on the growth and development of cover crops. This demonstrates that these crops are very efficient in the use of soil P from mineral phosphate fertilization. In the present study, triple superphosphate was used as source of P. It is known that the reactivity characteristics of P sources are extremely important in relation to their short-term efficiency. Phosphates of greater reactivity, being more readily available, which favored the absorption and use of the nutrient by plants (Silva et al., 2011). Another aspect is that the higher availability of P can trigger changes in photosynthesis, due to the greater capture of solar radiation and increase in the production of photoassimilates, because P acts as a forming agent of the ATP molecule and, under conditions of low ATP production, plant growth is directly affected (Rocha, 2016). In the present study, the P content in the soil considering the clay percentage was 5 mg dm^{-3} . This is considered very low, which justifies the increasing

response of the variables shoot and total dry mass production as a function of increasing doses of P_2O_5 applied at sowing.

Nutritional content and efficiency in response to phosphorous rates

The N contents in the shoots (Figure 3A) and in the root (Figure 4A) responded significantly ($p \leq 0.05$) to the increment of P doses, with maximum N contents in leaves and roots of 22.90 g kg^{-1} and 12.55 g kg^{-1} , respectively. At the P rates of 160 kg ha^{-1} , they were statistically different from the control treatment and from the P rates of 80 kg ha^{-1} . This increase in leaf and root N contents with the application of phosphate fertilization corroborates the higher efficiency of N use by cover plants (7.03 g mg^{-1}) (Figure 5A). N is one of the nutrients that most limit plant growth in the tropics. Therefore, the use of green manures capable of efficiently performing biological N fixation can represent considerable contributions to the economic viability and sustainability of production systems (Boddey et al., 1997), through the total or partial replacement of the N fertilization of the subsequent crop.

For P and K contents in shoots and roots, there was no significant difference between the P rates of 80 and 160 kg ha^{-1} applied at sowing (Figure 3B, 3C, 4B, 4C), but the P and K use efficiencies were higher at the P rates of 160 kg ha^{-1} . The values were 94.3 g mg^{-1} and 16.55 g mg^{-1} , respectively, differing statistically from the control treatment and from the P rates of 80 kg ha^{-1} (Figure 5B and 5C). From the data, it is possible to infer that there were increments in P and K use efficiency of 31% and 106%, respectively, compared to the control (0 kg ha^{-1} of P), under P dose of 160 kg ha^{-1} was applied.

Unfolding of the interaction between cover crops and phosphorous rates

The analysis of the double interaction was carried out with the objective of quantifying the nutrients recycled by the cover species, without considering phosphate fertilization (0 kg ha^{-1} of P). We found that *Crotalaria ochroleuca*, *Crotalaria breviflora* and *Crotalaria spectabilis* were statistically superior to the other cover crops in the accumulation of N, P and K in the shoots; thus, promoting the potential return of nutrients to the soil through biomass mineralization (Table 6). At P rates of 80 kg ha^{-1} , the above-mentioned species continued to respond positively to phosphate fertilization by increasing the contents of N, P and K in their tissues, differing statistically ($p < 0.05$) from the control (0 kg ha^{-1} of P). At higher P rates, there was a reduction in the accumulation of nutrients in the shoots, although there was no statistically significant difference between the P rates of 80 and 160 kg ha^{-1} (Table 6). The average increase in N, P and K contents in the shoots for *Crotalaria ochroleuca*, *Crotalaria breviflora* and *Crotalaria spectabilis* were on the order of 18.50%, 16.55% and 12.63%, respectively, when compared to the control treatment and fertilized with 80 kg ha^{-1} of P. Thus, the positive effect of phosphate fertilization is evident at moderate P rates and the species of crotalaria have significant tolerance to soils of low fertility and with low levels of P.

We observed that *Dolichos lablab*, *Mucuna pruriens*,

Table 1. Chemical attributes of the soil before installing the experiment at different depths.

Depth	MO	pH	P	K	C	M	H+Al	Al	SB	CTC	V	m
	g/dm ⁻³	H ₂ O	mg/dm ⁻³		a	g		cmolc/dm ⁻³			-----%	
0-20	20.4	6.0	5	18	6	1.	4.3	0	8.2	12.5	66	0
			0			7						

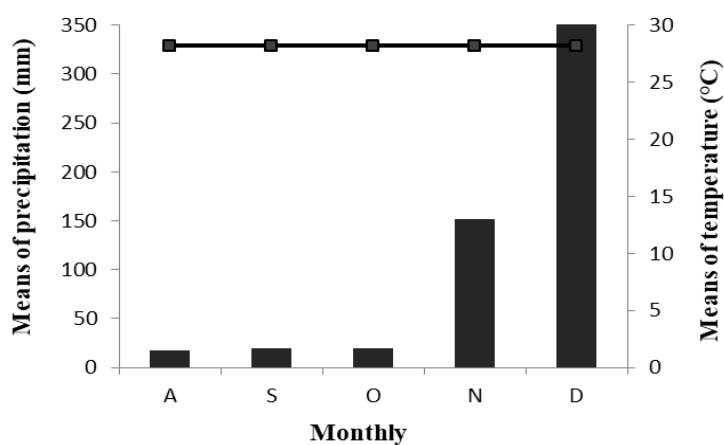


Fig 1. Monthly means of precipitation (mm) and temperature (°C), recorded in the weather station of the National Institute of Meteorology, from August to December of the 2019 agricultural year.

Table 2. Species of cover crops (treatments of plots) and their respective C/N ratios indicated in the literature.

Species	Family	C/N ratio
<i>Crotalaria ochroleuca</i>	Fabaceae	25-29 ²
<i>Crotalaria spectabilis</i>	Fabaceae	10-16 ¹
<i>Crotalaria breviflora</i>	Fabaceae	11-18
<i>Mucuna aterrima</i>	Fabaceae	12-21 ¹
<i>Mucuna pruriens</i>	Fabaceae	12-21 ¹
<i>Dolichos lablab</i>	Fabaceae	23-28 ³
<i>Canavalia ensiformis</i>	Fabaceae	10-16 ¹

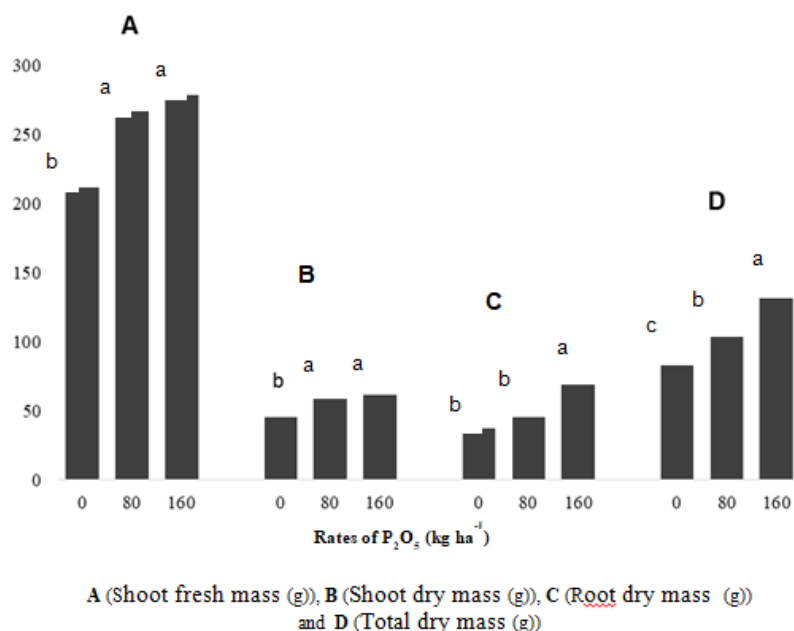


Fig 2. Production of shoot fresh mass (A), shoot dry mass (B), root dry mass (C) and total dry mass (D) of cover crops in response to phosphate fertilization. Means followed by the same letter on the bars do not differ statistically by Tukey test at 5% probability level.

Table 3. Shoot fresh mass (SFM), shoot dry mass (SDM), root dry mass (RDM) and total dry mass (TDM) of different cover crops cultivated in protected environment.

Cover crops	SFM	SDM (g.vase ⁻¹)	RDM	TDM
<i>Canavalia ensiformis</i>	310.26 a	77.05 a	32.06 c	109.11 bc
<i>Dolichos lablab</i>	219.53 c	45.59 d	43.95 b	93.54 cd
<i>Mucuna pruriens</i>	223.29 c	57.97 b	83.80 a	141.78 a
<i>Mucuna aterrima</i>	236.91 bc	59.59 b	74.27 a	133.86 ab
<i>Crotalaria ochroleuca</i>	256.25 bc	51.65 d	66.44 a	118.10 abc
<i>Crotalaria breviflora</i>	249.30 bc	45.48 d	25.44 c	70.92 d
<i>Crotalaria spectabilis</i>	271.38 b	49.60 d	28.11 c	75.72 d
CV (%)	12.53	13.38	29.93	21.52

Means followed by the same letter in the column do not differ statistically by Tukey test at 5% probability level. CV (Coefficient of variation).

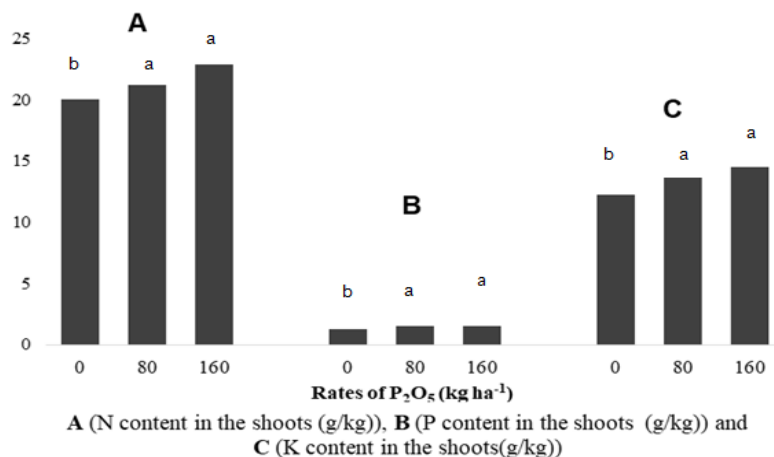


Fig 3. N content in the shoots (A), P content in the shoots (B) and K content in the shoots (C) of cover plants in response to phosphate fertilization. Means followed by the same letter on the bars do not differ statistically by Tukey's test at 5% probability level.

Table 4. Nitrogen content in the shoots (N), phosphorus content in the shoots (P), potassium content in the shoots (K), nitrogen content in the root (NR), phosphorus content in the root (PR) and potassium content in the root (KR) of different cover crops cultivated in protected environment.

Cover crops	N	P	K
	g/kg ⁻¹		
<i>Canavalia ensiformis</i>	19.15 c	1.16 c	10.57 e
<i>Dolichos lablab</i>	17.72 c	1.66 a	13.72 b
<i>Mucuna pruriens</i>	21.65 b	1.19 c	11.43 e
<i>Mucuna aterrima</i>	22.69 b	1.28 c	12.63 d
<i>Crotalaria ochroleuca</i>	26.64 a	1.46 b	15.29 b
<i>Crotalaria breviflora</i>	22.62 b	1.57 a	14.08 b
<i>Crotalaria spectabilis</i>	21.46 b	1.62 a	17.18 a
CV (%)	8.21	9.74	9.75
Cover crops	NR	PR	KR
g/kg ⁻¹			
<i>Canavalia ensiformis</i>	16.52 a	1.32 bc	7.15 c
<i>Dolichos lablab</i>	14.07 ab	1.54 a	7.75 c
<i>Mucuna pruriens</i>	15.24 ab	1.27 bc	7.28 c
<i>Mucuna aterrima</i>	15.11 a	1.26 c	8.80 b
<i>Crotalaria ochroleuca</i>	14.14 ab	1.15 d	4.88 d
<i>Crotalaria breviflora</i>	13.02 b	1.34 bc	11.18 a
<i>Crotalaria spectabilis</i>	15.25 ab	1.37 b	11.79 a
CV (%)	12.22	6.37	21.22

Means followed by the same letter in the column do not differ statistically by Tukey's test at 5% probability level. CV (Coefficient of variation).

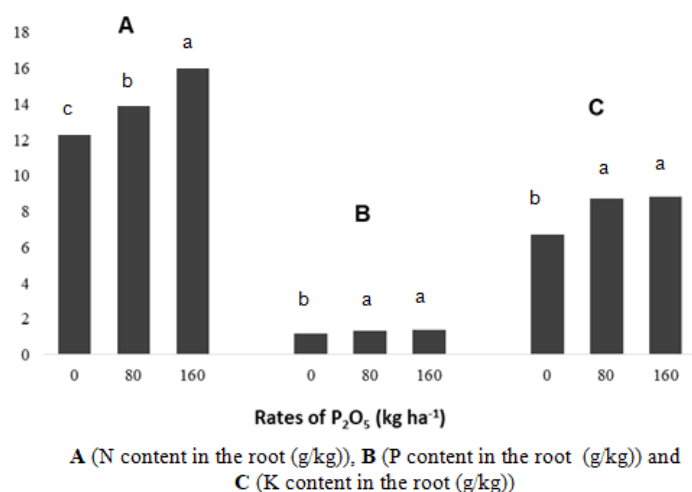


Fig 4. N content in the root (A), P content in the root (B) and K content in the root (C) of cover plants in response to phosphate fertilization. Means followed by the same letter on the bars do not differ statistically by Tukey's test at 5% probability level.

Table 5. Efficiency of absorption and use of macronutrients by different cover crops cultivated in a protected environment.

Cover crops	Efficiency of absorption		
	mg g ⁻¹		
	N	P	K
<i>Canavalia ensiformis</i>	65.45 a	4.43 a	28.49 bc
<i>Dolichos lablab</i>	36.08 cd	3.59 b	24.23 bc
<i>Mucuna pruriens</i>	33.36 d	2.27 c	16.46 c
<i>Mucuna aterrima</i>	36.17 cd	2.44 bc	20.18 c
<i>Crotalaria ochroleuca</i>	44.02 cd	2.82 bc	24.39 bc
<i>Crotalaria breviflora</i>	57.44 ab	4.47 a	39.01 a
<i>Crotalaria spectabilis</i>	53.77 ab	4.37 a	42.29 a
CV (%)	30.76	28.63	30.80
Cover crops	Efficiency of use		
	g.mg ⁻¹		
	N	P	K
<i>Canavalia ensiformis</i>	6.11 b	92.00 a	11.04 a
<i>Dolichos lablab</i>	5.81 b	57.56 b	6.64 b
<i>Mucuna pruriens</i>	8.20 a	114.75 a	10.79 a
<i>Mucuna aterrima</i>	7.14 a	106.26 a	14.35 a
<i>Crotalaria ochroleuca</i>	5.87 b	92.26 a	5.09 b
<i>Crotalaria breviflora</i>	3.80 c	48.22 b	4.22 b
<i>Crotalaria spectabilis</i>	3.98 c	49.37 b	4.10 b
CV (%)	26.48	23.49	38.76

Means followed by the same letter in the column do not differ statistically by Tukey's test at 5% probability level. CV (Coefficient of variation).

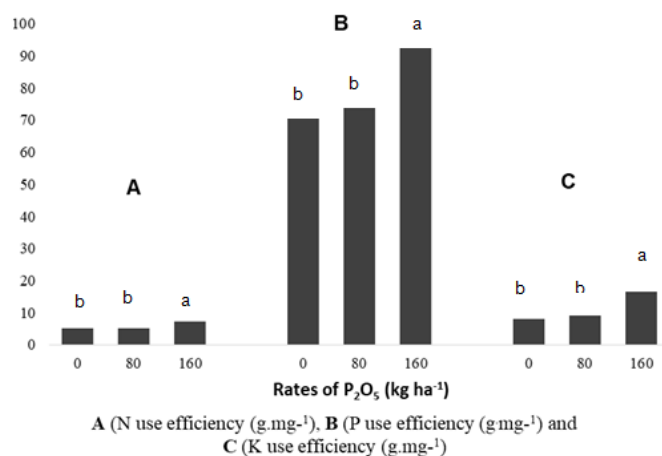


Fig 5. N use efficiency (A), P use efficiency (B) and K use efficiency (C) by cover plants in response to phosphate fertilization. Means followed by the same letter on the bars do not differ statistically by Tukey's test at 5% probability level.

Table 6. Analysis of the interaction between cover plants and phosphorus doses for nitrogen, phosphorus and potassium contents

in the shoots.

Cover crops	N content in the shoots (g/kg ⁻¹)		
	Rates of P ₂ O ₅ (kg ha ⁻¹)		
	0	80	160
<i>Canavalia ensiformis</i>	17.53 cdA	19.55 bA	20.36 bcA
<i>Dolichos lablab</i>	16.78 dA	18.12 bA	18.26 cA
<i>Mucuna pruriens</i>	18.36 cdB	23.63 abA	22.97 bA
<i>Mucuna aterrima</i>	21.84 abB	25.22 aA	21.02 bcB
<i>Crotalaria ochroleuca</i>	23.70 aB	26.77 aA	29.43 aA
<i>Crotalaria breviflora</i>	21.18 abB	25.62 aA	21.08 bcB
<i>Crotalaria spectabilis</i>	20.62 abcB	25.41 aA	22.36 bB

Cover crops	P content in the shoots (g/kg ⁻¹)		
	Rates of P ₂ O ₅ (kg ha ⁻¹)		
	0	80	160
<i>Canavalia ensiformis</i>	0.90 bB	1.26 dA	1.32 cA
<i>Dolichos lablab</i>	1.49 aB	1.66 abAB	1.84 aA
<i>Mucuna pruriens</i>	0.98 bB	1.31 cdA	1.28 cA
<i>Mucuna aterrima</i>	0.96 bB	1.41 cdA	1.48 bcA
<i>Crotalaria ochroleuca</i>	1.35 aB	1.61 abA	1.51 bcA
<i>Crotalaria breviflora</i>	1.62 aA	1.60 abA	1.48 bcB
<i>Crotalaria spectabilis</i>	1.39 aB	1.86 aA	1.61 abB

Cover crops	K content in the shoots (g/kg ⁻¹)		
	Rates of P ₂ O ₅ (kg ha ⁻¹)		
	0	80	160
<i>Canavalia ensiformis</i>	10.75 cA	12.65 cA	11.33 bcA
<i>Dolichos lablab</i>	11.93 cC	15.64 abA	13.59 bB
<i>Mucuna pruriens</i>	9.98 cB	12.45 cA	8.86 cB
<i>Mucuna aterrima</i>	12.21 bcA	13.61 bcA	12.05 bA
<i>Crotalaria ochroleuca</i>	18.80 aA	15.56 abB	11.49 bcC
<i>Crotalaria breviflora</i>	15.05 aA	14.35 abA	12.83 bB
<i>Crotalaria spectabilis</i>	19.12 aA	17.12 aAB	15.31 aB

Lowercase letters separate the means within each column, and uppercase letters separate the means within the row. Equal letters do not differ by Tukey test at 5% probability level.

Table 7. Analysis of the interaction between cover crops and phosphorus doses for nitrogen, phosphorus and potassium contents in the root.

Cover crops	K content in the root (g/kg ⁻¹)		
	Rates of P ₂ O ₅ (kg ha ⁻¹)		
	0	80	160
<i>Canavalia ensiformis</i>	10.23 bB	18.02 aA	18.32 aA
<i>Dolichos lablab</i>	13.66 aA	14.18 bA	14.38 bA
<i>Mucuna pruriens</i>	13.61 aB	18.51 aA	13.59 bcB
<i>Mucuna aterrima</i>	13.82 aC	18.25 aA	16.27 abB
<i>Crotalaria ochroleuca</i>	9.53 bC	17.14 abA	15.74 abB
<i>Crotalaria breviflora</i>	13.17 aAB	15.55 abA	10.33 cB
<i>Crotalaria spectabilis</i>	13.87 aB	16.36 abA	15.53 abA

Cover crops	P content in the shoots (g/kg ⁻¹)		
	Rates of P ₂ O ₅ (kg ha ⁻¹)		
	0	80	160
<i>Canavalia ensiformis</i>	1.09 cB	1.39 bA	1.48 abA
<i>Dolichos lablab</i>	1.36 aB	1.63 aA	1.64 aA
<i>Mucuna pruriens</i>	1.22 bA	1.34 bA	1.25 cdA
<i>Mucuna aterrima</i>	1.05 cB	1.34 bA	1.38 bcA
<i>Crotalaria ochroleuca</i>	1.18 bA	1.10 cA	1.16 dA
<i>Crotalaria breviflora</i>	1.34 aA	1.29 bA	1.39 bcA
<i>Crotalaria spectabilis</i>	1.22 cB	1.41 bA	1.49 abA

Cover crops	K content in the root (g/kg ⁻¹)		
	Rates of P ₂ O ₅ (kg ha ⁻¹)		
	0	80	160
<i>Canavalia ensiformis</i>	6.48 cA	8.87 bA	7.17 abA
<i>Dolichos lablab</i>	7.91 bcA	8.00 bA	5.53 bcA
<i>Mucuna pruriens</i>	7.77 bcAB	9.11 bA	4.96 bcB
<i>Mucuna aterrima</i>	6.69 bcB	11.32 aA	8.39 abB
<i>Crotalaria ochroleuca</i>	7.49 bcA	4.27 cB	2.87 cB
<i>Crotalaria breviflora</i>	12.87 aA	10.86 aB	9.81 aB
<i>Crotalaria spectabilis</i>	10.36 abA	10.70 aA	8.32 abB

Lowercase letters separate the means within each column, and uppercase letters separate the means within the row. Equal letters do not differ by Tukey test at 5% probability level.

Table 8. Analysis of the interaction between cover crops and phosphorus doses for the efficiency of use N, efficiency of use P and efficiency of use K.

Cover crops	Efficiency of use nitrogen (g.mg ⁻¹)		
	Rates of P ₂ O ₅ (kg ha ⁻¹)		
	0	80	160
<i>Canavalia ensiformis</i>	6.76 abA	5.72 aA	6.86 bcA
<i>Dolichos lablab</i>	4.30 bcB	6.00 aAB	7.14 bA
<i>Mucuna pruriens</i>	6.18 abB	5.85 aB	12.57 aA
<i>Mucuna aterrima</i>	7.47 aA	6.47 aA	7.50 bA
<i>Crotalaria ochroleuca</i>	3.86 cC	5.29 aB	8.46 bA
<i>Crotalaria breviflora</i>	3.25 cA	3.36 bA	4.79 cA
<i>Crotalaria spectabilis</i>	3.65 cA	3.53 bA	4.76 cA

Cover crops	Efficiency of use P (g.mg ⁻¹)		
	Rates of P ₂ O ₅ (kg ha ⁻¹)		
	0	80	160
<i>Canavalia ensiformis</i>	105.11 aA	85.54 abB	85.35 cB
<i>Dolichos lablab</i>	46.45 cA	59.12 cdA	67.11 dA
<i>Mucuna pruriens</i>	91.55 abB	92.08 abB	160.61 aA
<i>Mucuna aterrima</i>	95.57 abA	101.15 aA	122.06 aA
<i>Crotalaria ochroleuca</i>	51.38 bcC	89.50 abB	135.92 bA
<i>Crotalaria breviflora</i>	39.29 cA	49.54 dA	55.83 dA
<i>Crotalaria spectabilis</i>	48.04 cA	40.38 dA	59.70 dA

Cover crops	Efficiency of use K (g.mg ⁻¹)		
	Rates of P ₂ O ₅ (kg ha ⁻¹)		
	0	80	160
<i>Canavalia ensiformis</i>	11.04 abA	9.46 aA	11.65 bA
<i>Dolichos lablab</i>	6.64 abA	7.91aA	12.39 bA
<i>Mucuna pruriens</i>	10.79 abB	12.27 aB	33.41 aA
<i>Mucuna aterrima</i>	14.35 aA	11.50 aA	13.70 bA
<i>Crotalaria ochroleuca</i>	5.09 abB	11.75 aB	30.22 aA
<i>Crotalaria breviflora</i>	4.22 bA	5.67 aA	7.01 bA
<i>Crotalaria spectabilis</i>	4.10 bA	4.72 aA	7.47 bA

Lowercase letters separate the means within each column, and uppercase letters separate the means within the row. Equal letters do not differ by Tukey test at 5% probability level.

Mucuna aterrima, *Crotalaria breviflora* and *Crotalaria spectabilis* were statistically superior to the other cover crops in terms of N accumulation in the root, in the absence of phosphate fertilization (Table 7). After, fertilization with 80 kg ha⁻¹ of P, the species *Mucuna pruriens* and *Mucuna aterrima* responded to phosphate by increasing the N contents in the roots by 36% and 32%, respectively, compared to the non-fertilized control statistically (p<0.05) from the P rates of 160 kg ha⁻¹ of P. The greatest increment in K content in the root was observed for *Mucuna aterrima*, *Crotalaria breviflora* and *Crotalaria spectabilis* at P rates of 80 kg ha⁻¹ (Table 7). Regarding the P contents in the root, *Dolichos lablab* had the highest increment of the nutrient in comparison to the control, at the highest P rate (160 kg ha⁻¹ of P) (Table 7), corroborating the results found individually for the species, as shown in Table 4. The species *Mucuna pruriens* and *Mucuna aterrima* were significantly efficient regarding the use of N, P and K at P dose of 160 kg ha⁻¹ (Table 8), corroborating the results found and presented in Table 5 and Figure 5, besides having the highest root dry mass production, which gives these species greater root volume.

However, the use of these soil cover crops for green manure in crop succession or rotation systems has a great capacity to supply significant amounts of dry mass to the soil. The cycling and accumulation of nutrients in the shoots can reduce the use of chemical fertilizers applied in the subsequent crop and contribute to the development of a more sustainable agriculture in the Amazon region, with the premise of preserving the production environment.

Material and Methods

Experimental area

The experiment was conducted in a protected environment from August to December 2019, in the experimental area of the Federal Institute of Education, Science and Technology of Rondônia, Campus of Colorado do Oeste, in the municipality of Colorado do Oeste, RO, Brazil, at geographic coordinates of 13° 06' S and 60° 29' W, with an average altitude of 407 meters. According to Köppen's classification, the climate is Awa, tropical hot and humid, with two well-defined seasons. Mean data of temperature and precipitation along the experiment were obtained from the National Institute of Meteorology (Inmet) database. Chemical characterization of the soil was performed in the 0-20 cm layer, in samples collected before installing the experiment (Table 1).

Experimental design

The experimental design was completely randomized, arranged in a 7 x 3 scheme, consisting of the planting of seven species of cover crops (*Crotalaria spectabilis*, *Crotalaria breviflora*, *Crotalaria ochroleuca*, *Mucuna aterrima*, *Mucuna pruriens*, *Dolichos lablab* and *Canavalia ensiformis*) (Table 2), three P rates (0, 80 and 160 kg ha⁻¹ of P₂O₅), using triple superphosphate (TSP) as soluble source of P₂O₅ (45% P₂O₅), and four replicates, totaling 84 experimental units. The amount of each P dose was calculated based on the total P₂O₅ content of phosphate fertilizers, and converted to pot conditions.

Experimental methods

Concomitantly with P application, basal fertilization with N and K was performed at doses of 30 kg ha⁻¹ of N and 60 kg ha⁻¹ of K₂O, using urea (45% N) and potassium chloride (56% K₂O), respectively, incorporated into the soil for better standardization. The experimental units were composed of plastic pots with a capacity of 10 dm⁻³, filled with air-dried soil, passed through a 4-mm-mesh sieve. The P rates converted to the volume of experimental unit were 0.40 and 0.80 mg dm⁻³, while those of N and K corresponded to 0.015 and 0.03 mg dm⁻³, respectively. Moisture level of pots was controlled daily, always aiming to maintain the soil with 60% of field capacity. The seeds were placed to germinate directly in the pots eight days after emergence (DAE). Thinning was performed, leaving only one plant per experimental unit, considering the vigor and uniformity of the seedlings. Upon the full flowering of the cover species, the different plant parts were cut and divided into roots and shoots, and all the collected plant material was washed in running water and deionized water, weighed to determine the fresh mass. They subsequently dried in a forced air circulation oven at 65 °C for 72 hours, and then weighed again to determine the dry mass. After the plant material was dried and weighed, shoot and root dry masses were ground in a Wiley-type mill, and the samples were subjected to sulfuric digestion to determine N contents and to nitric-perchloric digestion to determine P and K contents in the different plant parts (roots and shoot), according to the methodology described in Embrapa (2009).

The indices of nutrient absorption efficiency, ratio between the total nutrient content in the plant and root dry mass, were calculated according to Swiader et al. (1994), while the indices of nutrient use, ratio between the total dry mass produced and the total nutrient content in the plant were calculated according to Siddiqi and Glass (1981).

Statistically analyzed

The data were subjected to the normality test (Shapiro-Wilk) and analysis of variance. The effects between cover plants and P doses were evaluated by Tukey test at 5% probability level, and the correlations between the variables were determined using the statistical program Sisvar.

Conclusions

Canavalia ensiformis provided higher yield of shoot fresh and dry mass, P content in the shoots and higher N and P absorption efficiency. N and P contents in *Dolichos lablab* roots were higher at the highest P rate (160 kg ha⁻¹ of P), without close relationship with the supply of shoot dry mass. The P rate of 160 kg ha⁻¹ exerted an increasing and significant effect on shoot fresh mass and dry mass production, N, P and K contents in the shoots, N, P and K contents in the root and N, P and K use efficiency by the different cover crops. The P rate of 80 kg ha⁻¹ increased the N, P and K contents in the shoots of *Crotalaria ochroleuca*, *Crotalaria breviflora* and *Crotalaria spectabilis*. At a higher P rate, there was a reduction in the accumulation of nutrients. The species *Mucuna pruriens* and *Mucuna aterrima* were efficient regarding the use of N, P and K at P rate of 160 kg

ha⁻¹. The use of these cover crops is a potential method to improve nutrient dynamics in soil and an alternative management that contributes to the maintenance and improvement of soil quality in the Amazon biome.

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