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Research Article

Dry matter production and nitrogen, phosphorus and potassium uptake in *Crotalaria juncea* and *Crotalaria spectabilis*[1]

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ABSTRACT

There are several benefits in the cultivation of *Crotalaria* spp., including high levels of biomass production and N accumulation, nutrient cycling and antagonistic activity against some nematodes. However, information on nutritional demand is still scarce for these species. This study aimed to determine the dry matter production and macronutrient uptake in shoots of *Crotalaria juncea* and *Crotalaria spectabilis*. Two experiments (one for each species) were carried out in a randomized block design, with three replications, assessing thirteen harvest times for *C. juncea* and ten for *C. spectabilis*. After each harvest, the samples were dried, weighed and submitted to laboratory analysis, in order to determine the nutrient contents in different parts of the plant. The nutrient accumulation on the shoots, for both species, occurred in the order K > N > P, being the stem the main organ of nutrient accumulation. Also for both species, the export of nutrients by the grains followed the order N > K > P. The maximum dry matter accumulation occurred at 135 and 104 days after emergence (DAE), respectively for *C. juncea* and *C. spectabilis*, while the production of viable seeds, in both species, had already begun at 90 DAE.

KEYWORDS: Green manure, nutrient accumulation, phytomass.

RESUMO

Produção de matéria seca e marcha de absorção de nitrogênio, fósforo e potássio em *Crotalaria juncea* e *Crotalaria spectabilis*

Inúmeros são os benefícios do cultivo de *Crotalaria* spp., dentre os quais destacam-se a alta produção de biomassa e acúmulo de N, ciclagem de nutrientes e ação antagônica sobre alguns nematoides. Entretanto, informações sobre a exigência nutricional para essas espécies ainda são escassas. Objetivou-se determinar a produção de matéria seca e a marcha de absorção de macronutrientes na parte aérea de *Crotalaria juncea* e *Crotalaria spectabilis*. Dois experimentos foram conduzidos (um para cada espécie) em delineamento de blocos ao acaso, com três repetições, testando-se treze épocas de colheita para *C. juncea* e dez para *C. spectabilis*. Após cada colheita, as amostras foram secas, pesadas e submetidas a análise laboratorial, para determinação dos teores de nutrientes em diferentes partes da planta. O acúmulo de nutrientes na parte aérea, para ambas as espécies, ocorreu na ordem K > N > P, sendo o caule o principal órgão de acúmulo de nutrientes. Também para ambas as espécies, a exportação de nutrientes pelos grãos seguiu a ordem N > K > P. O máximo acúmulo de matéria seca ocorreu aos 135 e 104 dias após a emergência (DAE), respectivamente para *C. juncea* e *C. spectabilis*, enquanto a produção de sementes viáveis, em ambas as espécies, já havia se iniciado aos 90 DAE.

PALAVRAS-CHAVE: Adubo verde, acúmulo de nutrientes, fitomassa.

INTRODUCTION

Species of the *Crotalaria* genus are characterized by a fast vegetative growth, high levels of biomass production and nutrient extraction, as well as the ability to adapt well to low soil fertility conditions (Fontanétti et al. 2006, Vargas et al. 2011). As such, they are a good option for use in no-tillage production systems. In addition to their use as green manure, some species also stand out for their fiber and forage production (Cazetta et al. 2005). In agricultural systems, the main species are *Crotalaria juncea* and *Crotalaria spectabilis*, which are the most commonly cultivated due to the abundant supply of seeds.

Among the advantages of cultivating species of the Fabaceae family, such as *Crotalaria* spp., the low carbon/nitrogen (C/N) ratio is particularly important, as it results in the quick decomposition

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of plant residues and the consequent rapid release of nutrients, mainly N (Aita et al. 2001), that are made available for subsequent cultivars. Another advantage of cultivating these species is the uptake of high amounts of N, due to the symbiotic relationship with bacteria of the *Rhizobium* and *Bradyrhizobium* genera that fix atmospheric nitrogen (Boddey et al. 2006). In addition, the deep and branched root system of these plants is effective in extracting nutrients from the deepest soil layers (Alcântara et al. 2000), contributing to the cycling and mobilization of nutrients to the soil surface, such as phosphorus (P) and potassium (K).

The cultivation of *Crotalaria* species in crop rotation brings several benefits to no-tillage systems. These plants can be cultivated in the off-season, as part of the production cycle, since the continuous succession of soybean/corn tends to lead to soil physical degradation (Freddi et al. 2017), as well as reductions in the soil nutrient availability and biological activity (Lourente et al. 2010). In addition, a continuous crop succession creates a more favorable environment for the development of diseases, pests and weeds (Garcia et al. 2015), resulting in a decreased crop yield. In light of these benefits, such species have attracted the attention of producers, leading to a significant expansion of their cultivation in grain production areas of the Brazilian Savanna (Costa et al. 2012).

Although there is sufficient knowledge about the phytotechnical aspects of crotalaria cropping (*i.e.*, dry matter production, sowing season, spacing and management in areas with nematodes), and associated improvements in the physical, chemical and biological soil characteristics, little information is available regarding the nutrient management and dynamics within plants of these species. Therefore, research is required to provide information that may contribute to the management of the various cropping systems in which these species are used. For example, studies on the rate of nutrient absorption assist in decision-making processes related to increasing yield (Zobiole et al. 2010, Maillard et al. 2015), since an appropriate and well-timed crotalaria management can provide large N inputs to the soil through biological nitrogen fixation, as well as a satisfactory vegetal coverage. Thus, it may be possible to reduce production costs of economically important crops, while also providing information on the production system of plants of the *Crotalaria* L. genus. Hence, this study aimed to assess the dry matter production and macronutrient uptake in shoots of *Crotalaria juncea* and *Crotalaria spectabilis.*

MATERIAL AND METHODS

The research was conducted at the Embrapa Agropecuária Oeste, in Dourados, Mato Grosso do Sul State, Brazil (22º16'S, 54º49'W and elevation of 408 m above the sea level). According to the Köppen classification, the climate in the region is Am (Alvares et al. 2013). Rainfall and average temperatures recorded during the experimental period (February to August 2017) are shown in Figure 1.

The soil of the experimental area was classified as a Dystroferric Red Latosol (LVDf), with a predominantly clayey texture (630 g kg^{-1} of clay) and the following chemical characteristics: pH ($CaCl_2$) = 5.5; organic matter = 33.3 g dm^{-3}; P = 18 mg dm^{-3}; K = 2.9 mmol$_c$ dm^{-3}; Ca = 36 mmol$_c$ dm^{-3}; Mg = 15 mmol$_c$ dm^{-3}; cation exchange capacity = 97 mmol$_c$ dm^{-3}; and base saturation (V%) = 56.

Two experiments were conducted (side by side), one for each *Crotalaria* species. A randomized complete block design, with three replications, was used, assessing thirteen harvest times or collection episodes (15, 30, 45, 60, 75, 90, 105, 120, 135, 150, 165, 180 and 195 days after emergence - DAE) for *C. juncea* and ten for *C. spectabilis* (15, 30, 45, 60, 75, 90, 105, 120, 135 and 150 DAE).

Sowing was carried out mechanically on February 23, 2017, with no addition of fertilizers, in an area previously cultivated with soybean. The sowing density was 25 kg ha^{-1} of seeds for *C. juncea* and 15 kg ha^{-1} for *C. spectabilis*, for a total of

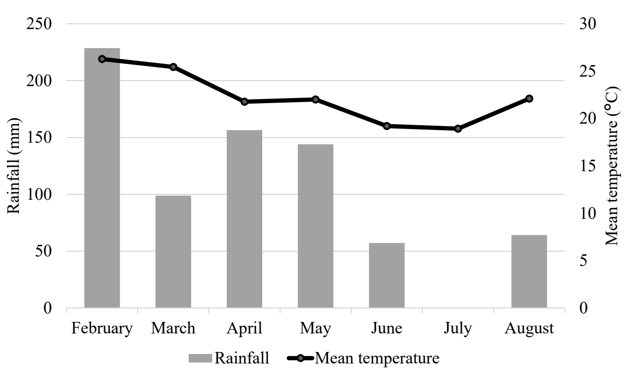

Figure 1. Rainfall and average temperature during the experimental period (February to August 2017), in Dourados, Mato Grosso do Sul state, Brazil.

about 500,000 plants ha^{-1} and 640,000 plants ha^{-1}, respectively.

Each experimental unit consisted of 14 lines, 12 m long, spaced 45 cm apart, for a total area of 75.6 m^2. For the analysis, the 12 central lines of each plot were considered, excluding 1 m at each end, providing a total sampling area of 54 m^2 from which the samples were collected.

To evaluate the accumulation of dry matter and macronutrients, samples were collected at regular intervals of 15 days. In the first harvest or collection episode, at 15 DAE, the samples were collected from the shoots of 15 *C. juncea* and 20 *C. spectabilis* plants. During the second (30 DAE) and subsequent collection episodes, 10 plants of both species were collected. The data were obtained as g $plant^{-1}$ and transformed into kg ha^{-1}.

At each collection, the plants were separated into leaves (blade and petiole) and stems/branches. After the appearance of pods and grains (90 DAE), these structures were also included in the analysis. The various parts of the plants were then washed, stored in perforated paper bags and dried in a forced air convection oven at 65 ºC, for approximately 72 hours, until reaching a constant mass. Subsequently, the shoot dry matter was measured, and samples were ground in a Wiley mill. The N, P and K contents in each part of the plant were determined according to Malavolta et al. (1997).

The adjustment of the dry matter production and nutrient accumulation in the different parts of the plant, as a function of days after emergence, was performed through regression, using the Gaussian model with three parameters (Zobiole et al. 2010).

RESULTS AND DISCUSSION

The shoot dry matter production of the crotalaria plants showed a distinct behavior between the two evaluated species. For *C. spectabilis*, the accumulation was slow until 45 DAE; while, for *C. juncea*, the dry matter production began to intensify from 30 DAE (Figures 2a and 2c), characterizing it as a more accelerated initial starter species, when compared to *C. spectabilis*.

Therefore, the greater amount of dry matter produced by *C. juncea* may be explained by its accelerated growth rate, when compared to *C. spectabilis* (Gitti et al. 2012, Pacheco et al. 2015). Although there is no statistical comparison between the species, the difference in the production levels may be attributed to factors that are inherent to each species, such as architecture, photosynthetic efficiency and root system. In general, *C. juncea* shows a rapid growth until 40 days after sowing (DAS), which slows between 40 and 60 DAS, and then resumes an accelerated growth after 60 DAS. *C. spectabilis*, on the other hand, shows a slow and constant growth rate (Teodoro et al. 2011).

From 45 DAE, the dry matter production in the entire plant intensified, reaching its maximum accumulation at 135 and 104 DAE, respectively for *C. juncea* and *C. spectabilis* (Table 1). At this

Table 1. Estimates of the parameters for the models fitting the dry matter production in different parts of the *Crotalaria* species.

Part of the plant	Estimates[1]			IP (X_0 - b)	Adjusted R^2
	a ($Mg\ ha^{-1}$)	X_0	b		
		DAE			
Crotalaria juncea					
Leaf	2.28	108.44	41.90	66.54	0.8438**
Stem	10.19	142.24	47.23	95.01	0.8904**
Pod	1.12	130.46	28.38	102.08	0.9462**
Grain	1.27	134.05	30.09	103.96	0.9638**
Entire plant	14.20	135.39	44.89	90.50	0.9395**
Crotalaria spectabilis					
Leaf	0.60	72.10	32.91	39.19	0.8746**
Stem	5.82	94.99	33.06	61.93	0.8042**
Pod	1.55	129.55	25.89	103.66	0.9552**
Grain	0.93	135.87	13.67	122.20	0.9611**
Entire plant	7.14	104.41	39.76	64.65	0.8743**

[1] a: maximum accumulation value; X_0: x value in days after emergence (DAE) that provides the maximum in a; b: amplitude in the x value (in DAE) between the inflection point and the maximum point; IP: x value (in DAE) in which the daily accumulation rate, although positive, starts to decrease. ** Significant values for the F-test at 1 % of probability.

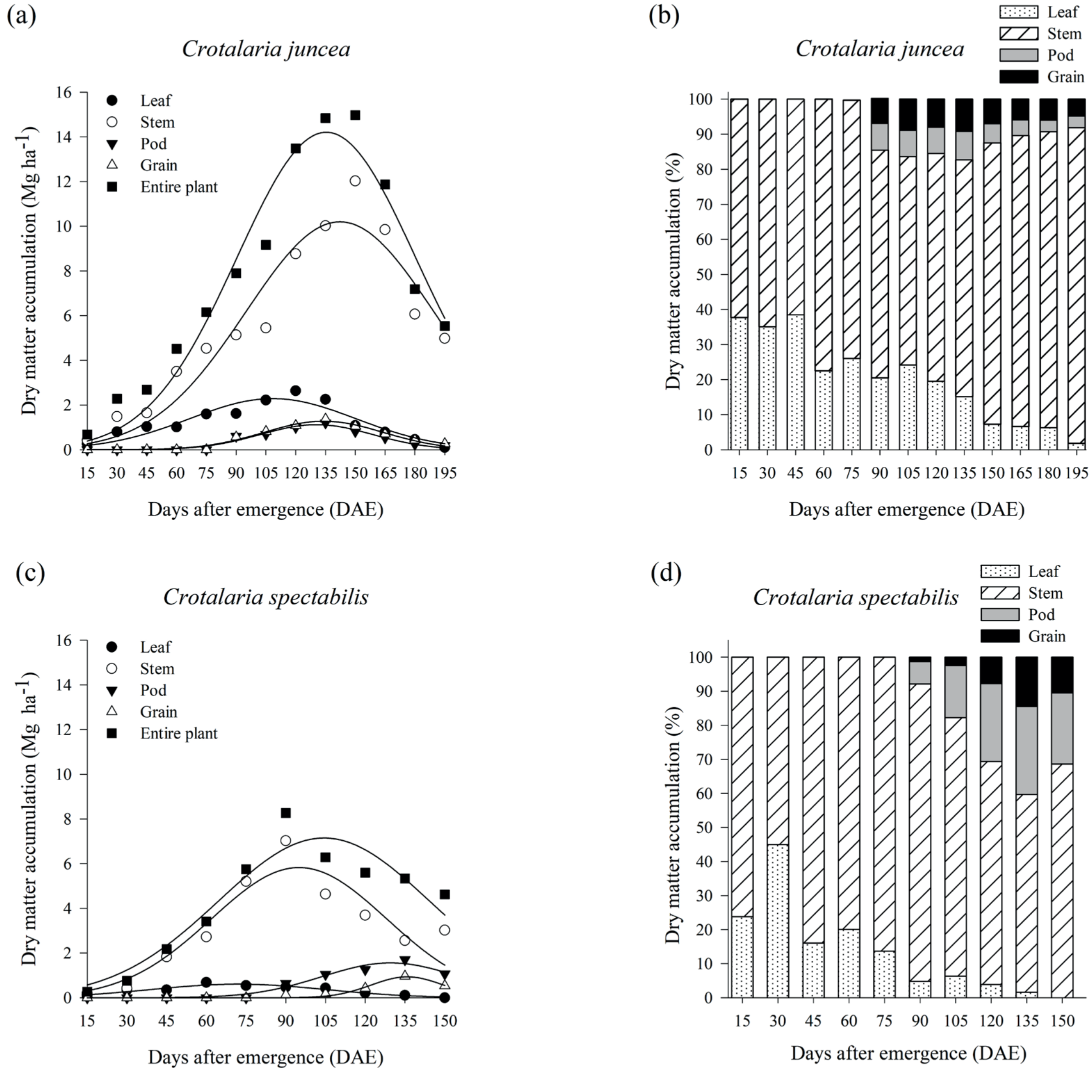

Figure 2. Dry matter accumulation in the shoots of *Crotalaria juncea* (a and b) and *Crotalaria spectabilis* (c and d), as a function of days after emergence.

time (45 DAE), the stems began to contribute more significantly to the dry matter production in the shoots, making them the main sinks of photoassimilates produced during this period.

For *C. juncea*, the maximum dry matter production in the entire plant was 14 Mg ha^{-1}, in which the leaves, stems, pods and grains contributed with about 15 %, 70 %, 7 % and 8 %, respectively (Table 1; Figure 2b). It is important to note that, in comparison to *C. spectabilis*, *C. juncea* presented a greater dry matter production in the shoots, and it also required more time to reach the maximum accumulation point (Table 1). Thus, it may be inferred that *C. juncea* is a promising species as a cover plant for fallow areas, mainly due to the longer period required to reach a maximum dry matter production in the shoots, while also contributing with a large supply of plant residues that can be incorporated into the soil.

In relation to *C. spectabilis*, the maximum accumulated was approximately 7 Mg ha^{-1}, where the leaves, stems, pods and grains corresponded to 8 %, 75 %, 8 % and 9 %, respectively, of the accumulated amount (Table 1; Figure 2d). This species presented lower levels of dry matter accumulation, in relation to *C. juncea*, what may be attributed to its morphological characteristics, such as small size and stems with few branches. Nevertheless, *C. spectabilis* is a viable option for crop rotation systems, as its shorter cycle would not result in delayed sowing of the subsequent crop. In addition, this species helps to manage the main nematodes that occur in grain-producing cultivation areas, by reducing the population and mitigating damages caused by *Pratylenchus brachyurus* in the soybean production (Debiasi et al. 2016).

From the accumulated quantities of dry matter, it is possible to infer that the cover crops should be cut at 135 DAE (*C. juncea*) and 104 DAE (*C. spectabilis*) to obtain the maximum contribution of biomass to the soil. However, at this stage, the plants have already begun to produce viable seeds, what could lead to an invasion of the area by the germination of the green manure seeds, causing problems for subsequent crops. As such, it is advisable to cut the species at up to 90 DAE. In this case, although the plants have lower amounts of dry matter, the nutrient contents in their tissue are high. Another alternative would be the cultivation of the plants until the grains/seeds can be harvested for later use.

The management (cutting) of crotalarias, if performed at 90 DAE, would provide 7.9 Mg ha^{-1} and 7.1 Mg ha^{-1} of straw from *C. juncea* and *C. spectabilis*, respectively, what, according to Alvarenga et al. (2001), is sufficient to provide a good land cover. The 7.9 Mg ha^{-1} of *C. juncea* straw would add about 223 kg ha^{-1} of N, 27 kg ha^{-1} of P and 247 kg ha^{-1} of K to the soil. For *C. spectabilis*, the total of 7.1 Mg ha^{-1} of straw would provide approximately 142 kg ha^{-1} of N, 13 kg ha^{-1} of P and 182 kg ha^{-1} of K.

The N accumulation was insignificant until 30 DAE (Figures 3a and 3b), at which point it began to increase, with leaves being the main organ responsible for the nutrient uptake at that time (Figure 3). The maximum N accumulation in the leaves occurred at 96 and 66 DAE, respectively for *C. juncea* and *C. spectabilis* (Table 2).

The stems presented the greatest N accumulation in both species; however, it is important to note that the accumulated amount was much greater for *C. juncea* than for *C. spectabilis*, with a difference of approximately 42 kg ha^{-1} (Table 2). The maximum amount accumulated in the stems occurred at a later period than for the leaves, with a lag of more than 20 days after reaching the maximum N accumulation in the leaves, in both species.

In pods and grains, the maximum N accumulation occurred in close periods, when comparing the species, where the difference was less than five days (Table 2). This demand may be justified because, in this phase, there is a beginning of pod formation and subsequent grain development, when such structures become the preferred drain of N, since this nutrient is involved in the processes of amino acid and protein synthesis (Helali et al. 2010, Masakapalli et al. 2013). In addition, the nutrient acts directly on cell division and differentiation and tissue constitution (Luo et al. 2017).

The accumulation curves for P (Figures 4a and 4b) show that *C. juncea* had a greater nutrient accumulation than *C. spectabilis* for all evaluated

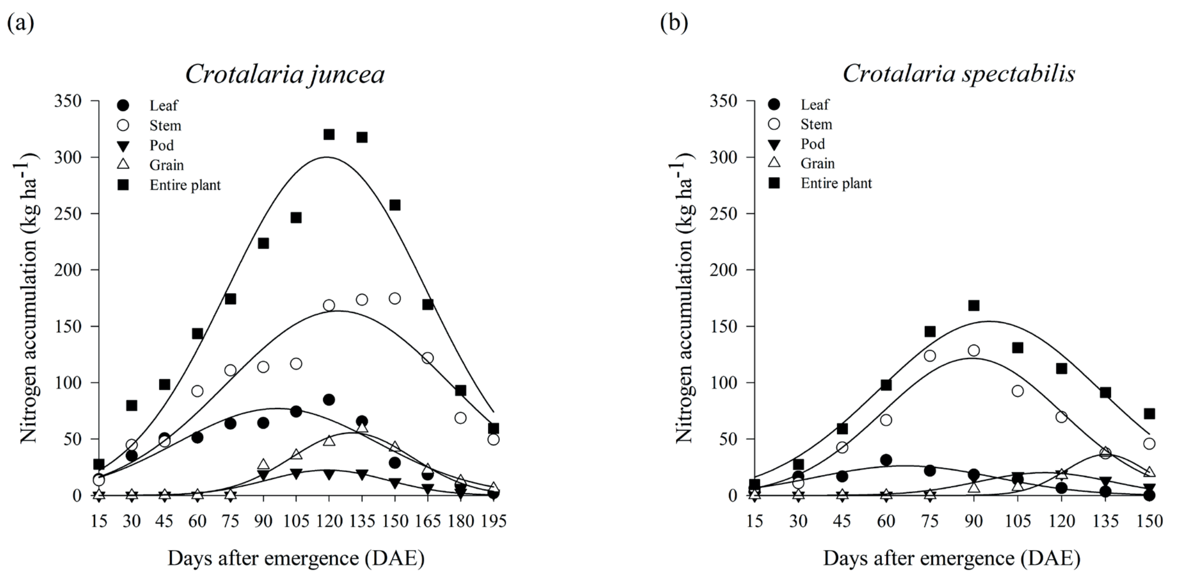

Figure 3. Nitrogen accumulation in the shoots of *Crotalaria juncea* (a) and *Crotalaria spectabilis* (b), as a function of days after emergence.

Table 2. Estimates of the parameters for the models fitting the accumulation of nitrogen in shoots of the *Crotalaria* species.

Part of the plant	Estimates[1] a (kg ha^{-1})	X_0 (DAE)	b (DAE)	IP (X_0 - b) (DAE)	Adjusted R^2
		Crotalaria juncea			
Leaf	77.07	96.34	45.76	50.58	0.8626**
Stem	163.58	124.25	50.92	73.33	0.8580**
Pod	22.47	119.09	27.42	91.67	0.8800**
Grain	55.50	130.44	27.52	102.92	0.9608**
Entire plant	299.98	118.89	45.50	73.39	0.9228**
		Crotalaria spectabilis			
Leaf	26.22	66.48	31.01	35.47	0.8688**
Stem	121.58	89.38	30.64	58.74	0.8830**
Pod	20.17	114.24	22.78	91.46	0.9030**
Grain	36.27	135.13	13.91	121.22	0.9522**
Entire plant	154.34	95.32	37.84	57.48	0.9260**

[1] a: maximum accumulation value; X_0: x value in days after emergence (DAE) that provides the maximum in a; b: amplitude in the x value (in DAE) between the inflection point and the maximum point; IP: x value (in DAE) in which the daily accumulation rate, although positive, starts to decrease. ** Significant values for the F-test at 1 % of probability.

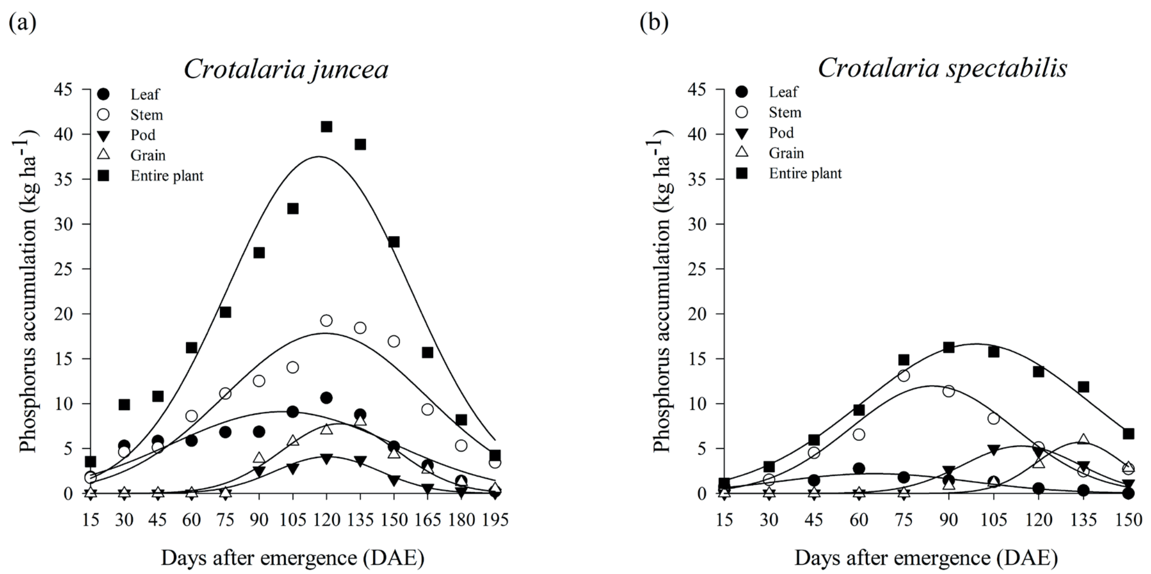

Figure 4. Phosphorus accumulation in the shoots of *Crotalaria juncea* (a) and *Crotalaria spectabilis* (b), as a function of days after emergence.

structures, except pods, with maximum accumulated amounts of 37 kg ha^{-1} (*C. juncea*) and 16 kg ha^{-1} (*C. spectabilis*) found in the entire plant at 116 and 99 DAE, respectively (Table 3).

For the leaves, the greatest accumulation of P was around 100 and 65 DAE, respectively for *C. juncea* and *C. spectabilis* (Table 3). As with the results for N, the greatest accumulation of P in *C. juncea* was identified at a later period, and the maximum amount of the nutrient accumulated in the leaves was higher than for *C. spectabilis*.

For the stem, the maximum quantities of P (18 kg ha^{-1} for *C. juncea* and 12 kg ha^{-1} for *C. spectabilis* at 119 and 84 DAE, respectively) show that the accumulation in this organ occurs at a later period, in relation to the leaves (Table 3).

In pods and grains, the maximum accumulated quantity of P was higher in *C. juncea* than in *C. spectabilis*, and it required a longer period of time to reach the maximum in these organs, resulting in a difference of approximately 7 days between the two species.

Table 3. Estimates of the parameters for the models fitting the accumulation of phosphorus in shoots of the *Crotalaria* species.

Part of the plant	Estimates[1] a (kg ha^{-1})	X_0	b	IP (X_0 - b)	Adjusted R^2
		DAE			
		Crotalaria juncea			
Leaf	9.10	100.47	49.36	51.11	0.7768**
Stem	17.82	119.47	45.06	74.41	0.8932**
Pod	4.09	120.40	23.34	97.06	0.9384**
Grain	7.76	125.73	25.93	99.80	0.9571**
Entire plant	37.50	116.67	40.83	75.84	0.9098**
		Crotalaria spectabilis			
Leaf	2.20	65.17	32.05	33.12	0.8272**
Stem	11.96	84.54	27.47	57.07	0.9145**
Pod	5.28	114.27	19.43	94.84	0.9722**
Grain	5.68	133.70	14.36	119.34	0.9640**
Entire plant	16.64	99.15	38.14	61.01	0.9787**

[1] a: maximum accumulation value; X_0: x value in days after emergence (DAE) that provides the maximum in a; b: amplitude in the x value (in DAE) between the inflection point and the maximum point; IP: x value (in DAE) in which the daily accumulation rate, although positive, starts to decrease. ** Significant values for the F-test at 1 % of probability.

In general, the reproductive organs presented a maximum P accumulation at a later period, in relation to the vegetative organs (Table 3). This nutrient acts directly on the processes of formation, development and maturation of legumes and seeds, and contributes to flowering, seed viability and increases in carbohydrates, oils, fats and proteins (Malavolta 2006), thus justifying its greater remobilization with the onset of inflorescence, and later accumulation in the reproductive organs.

Potassium was the nutrient most accumulated by the crotalaria plants (Table 4). This result is similar to those found by Silva et al. (2002), Pott & Feltrin (2008) and Mauad et al. (2019). In these studies on *Crotalaria spectabilis*, it was also observed that K was the macronutrient with the largest accumulation levels in crotalaria plant tissues.

The maximum K accumulation in the entire plant occurred at 125 (*C. juncea*) and 90 DAE (*C. spectabilis*), respectively for a total of 364 kg ha^{-1} and 199 kg ha^{-1} (Table 4). For *C. juncea*, the stem was the organ that most accumulated K, followed by leaves, pods and grains (Figure 5). For *C. spectabilis*, the stem also showed the highest K accumulation,

Table 4. Estimates of the parameters for the models fitting the accumulation of potassium in shoots of the *Crotalaria* species.

Part of the plant	Estimates[1] a (kg ha^{-1})	X_0	B	IP (X_0 - b)	Adjusted R^2
		DAE			
		Crotalaria juncea			
Leaf	47.53	98.29	46.64	51.65	0.8175**
Stem	288.56	128.54	48.68	79.86	0.8494**
Pod	24.25	126.69	27.45	99.24	0.9128**
Grain	15.23	129.97	29.25	100.72	0.9605**
Entire plant	364.25	124.89	47.16	77.73	0.8919**
		Crotalaria spectabilis			
Leaf	14.89	64.97	31.87	33.10	0.9173**
Stem	186.97	83.46	28.63	54.83	0.8728**
Pod	35.09	128.27	24.35	103.92	0.9634**
Grain	16.36	136.37	13.54	122.83	0.9771**
Entire plant	198.97	90.04	36.23	53.81	0.8412**

[1] a: maximum accumulation value; X_0: x value in days after emergence (DAE) that provides the maximum in a; b: amplitude in the x value (in DAE) between the inflection point and the maximum point; IP: x value (in DAE) in which the daily accumulation rate, although positive, starts to decrease. ** Significant values for the F-test at 1 % of probability.

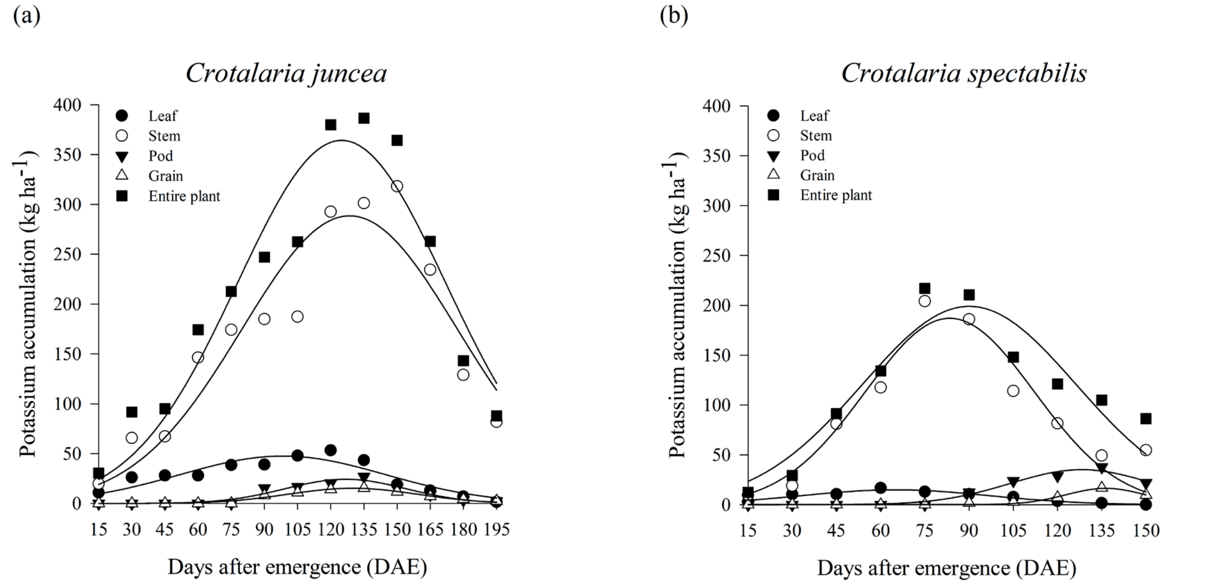

Figure 5. Potassium accumulation in the shoots of *Crotalaria juncea* (a) and *Crotalaria spectabilis* (b), as a function of days after emergence.

followed by pods, grains and, finally, leaves. This corroborates the results obtained by Mauad et al. (2019), who observed the same ranking of K accumulation in *C. spectabilis*.

The second most exported nutrient through grains was K, with values around 15 kg ha^{-1} (*C. juncea*) and 16 kg ha^{-1} (*C. spectabilis*) (Table 4). This nutrient was the most abundant one in the shoots, what makes the *Crotalaria* straw a source of K in no-tillage systems. Previous research has shown that K is the most abundant cation in the cytoplasm of plant cells, forming bonds with organic complexes that are easily reversible and, therefore, capable of a rapid release (Mendonça et al. 2015). Thus, the cultivation of these species provides a large supply of K to the soil during the plant decomposition.

The quantities of K accumulated in the shoots are high, enabling the availability of this nutrient for the successive crop. As such, providing a proportion of potassium fertilization for the commercial crop through crotalaria sowing may be feasible, and could also increase the phytomass production of these cover crop species. It is noteworthy that K represents about 6 % of the total dry matter of plants (Alemán et al. 2011) and acts in the regulation of stomatal opening and closure, providing a higher photosynthetic rate and, consequently, a higher phytomass production.

CONCLUSIONS

1. The maximum accumulation of N-P-K nutrients in the shoots of *Crotalaria juncea* and *Crotalaria spectabilis* follows the order K > N > P;
2. Also for both species, the macronutrient exportation by the grains follows the order N > K > P;
3. The dry matter maximum accumulation occurred at 135 days after emergence (DAE) for *C. juncea* and 104 DAE for *C. spectabilis*. However, the best management time for both species is up to 90 DAE, when they have already produced viable seeds.

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