Australian Journal of Crop Science

AJCS

AJCS 16(05):637-648 (2022) ISSN:1835-2707
doi: 10.21475/ajcs.22.16.05.p3607

Biological use coefficient of biomass of *Tachigali vulgaris* under phosphorus and potassium fertilization: Management technologies for sustainable production of bioenergy in tropical countries

Pedro Henrique Oliveira Simões*[1], Manoel Tavares de Paula[2], Denmora Gomes de Araújo[1], Luma Castro de Souza[3], Clenes Cunha Lima[4], Lenilson Ferreira Palheta[1], Cândido Ferreira de Oliveira Neto[1], João Olegário Pereira de Carvalho[3]

[1]Federal Rural University of the Amazon, Perimetral avenue, Terra Firme, Belém, PA 66077-830, Brazil
[2]Pará State University, Dr. Eneas Pinheiro Street, Marco, Belém, PA, 66095-015, Brazil
[3]Federal Rural University of the Amazon, Pau Amarelo street, Vila Nova, Capitão Poço, PA, 68650-000, Brazil
[4]Federal Rural University of the Amazon, PA 275 road, Km 13, Zona Rural, Parauapebas, PA, 68515-000, Brazil

***Corresponding author: simoes.florestal@gmail.com**

Abstract

Studies dealing with the behavior, initial development, uptake and nutrient use efficiency of native Amazonian trees as a function of fertilization are extremely important to support actions for the recovery and management of degraded areas. The objective of this study was to evaluate the influence of fertilization with different levels of phosphorus (P) and potassium (K) on growth and nutrient use efficiency in *Tachigali vulgaris* plantation. The experiment was installed in a tropical climate region in eastern Amazonia, Brazil. Three doses of P (0, 65.22 and 130.4 kg ha^{-1}) and three doses of K (0, 100 and 200 kg ha^{-1}) were applied in a 3 x 3 factorial scheme and randomized block design, with 4 repetitions. Growth parameters, nutrient concentration in biomass, nutrient use efficiency (NUE), and biological use coefficient (BUC) were evaluated. *T. vulgaris* responded significantly to fertilization with P and K in the parameters evaluated. It produced two times more biomass at the age of three years. Fertilization with 65.22 kg ha^{-1} of triple superphosphate and 200 kg ha^{-1} of potassium chloride was efficient to increase height growth by 11.1% considering the 24 months of evaluation, compared to unfertilized plants. Mg is the most efficiently utilized nutrient in the biomass components of *T. vulgaris*, followed by P, S, K, Ca and N. The woody compartments of *T. vulgaris* showed the highest BUC values, which is highly desirable and of great interest for forestry.

Keywords: Aboveground biomass; Energy forests; Nutrient use efficiency; Recuperation of degraded areas; Tachi-branco.
Abbreviations: NUE_nutrient use efficiency; BUC_biological use coefficient; DBH_diameter at breast height.

Introduction

The expansion of deforested areas in the Amazon Biome has reached 729000 km². This corresponds to 17% of the territory. However, only a small portion of the deforested area (0.42%) was destined for reforestation programs (Guimarães et al., 2018; Inpe 2018). Among the factors that hinder the implementation of plantations in the Amazon region, the limited knowledge of native species silviculture stands out (Walters et al., 2005).
The use of native flora in reforestations should be implemented, as it would increase the diversity of species, reducing biological and economic risks (Erskine et al., 2005). In addition, the increased use of native species in reforestations provides a replacement of high commercial value wood from natural forests, greater biological and land use diversification (Tonini et al., 2018), which reduces the pressure on the remaining native ecosystem (Farias et al., 2016). Thus, there is an urgency to create a list of potential species that combine high survival and fast growth for plantations in altered areas in the Amazon (Salomão et al., 2014).
There is ample evidence that nutrient use efficiency (NUE) by plants varies between species in the same environment, between different climatic conditions in the same crop, sites and season (Taylor and Willatt 1983). Sustainable ecosystem management depends on the assessment of resource use by plants, their physiological responses and factors governing such mechanisms (Shen et al., 2015; Amaral et al., 2020). In this sense, studies that aim to analyze the behavior, initial development, uptake and NUE of native trees as a function of fertilization, are of extreme importance to subsidize recovery actions and management of degraded areas (Valadão et al., 2014; Reis et al., 2015), besides that the experiments could be replicated for several other native Amazonian forest species.
The influence of NUE on the development of forest plantations has been investigated in recent studies. It has added information about the ecophysiological behavior of

native plant species (Lima Junior et al., 2006; Lenhard et al., 2013; Valadão et al., 2014; Reis et al., 2015). However, although leaf nutrient concentration and NUE are vital functions for the establishment of a plant, there are few scientific studies available on native Amazonian species, especially regarding developmental responses as a function of P and K fertilization.

Given the deforestation scenario in the Amazon and the need to select fast-growing tree species that perform well in degraded areas and initiate secondary succession, we investigated the species *Tachigali vulgaris* L. F. Gomes da Silva & H. C. Lima - Fabaceae, which grows in the Amazon region and in a wide range of climatic and edaphic conditions, with economic and environmental importance (Silva et al., 2002; Saporetti JR et al., 2003). It is a pioneer species that often initiates secondary succession in open areas. It is considered ideal for reforestation due to its high capacity for biomass production (Felfili et al., 1999; Farias et al., 2016). According to Freitas et al. (2012), *T. vulgaris* can be indicated for projects to recover degraded areas, both for full sun and 50% shade conditions for seedlings. Silva et al. (2021) identified moderate basic density and calorific value above 7.95 MJ kg^{-1}, suitable parameters for bioenergy, besides indicating a great potential for genetic improvement of the species.

The objective of this study was to evaluate the influence of fertilization with different levels of phosphorus and potassium on growth and nutrient use efficiency in *T. vulgaris* plantation.

Results

Growth

T. vulgaris growth, height and diameter responded to fertilization with doses of P and K ($p<0.05$) until 24 months post-planting (Figure 4). The evaluations allowed us to identify the effect of fertilization more clearly from 12 months post-planting, after the establishment phase of the plants.

After the first growing season, 12 months post-planting, the fertilized treatments established trees up to 0.41 m (19.2%) taller (K100) and about 41.9 mm (97.1%) thicker (P65.22K100) than the control treatment. During the second year of cultivation, the growth in height and diameter of *T. vulgaris* trees fertilized with the P130.43K200 treatment was about 10.6 % higher than the control. Considering two growing seasons, even increasing competition for light, water and nutrients among trees after canopy closure, the addition to the diameter was up to 57.5 % larger (P65.22K100), raising the biomass productivity of the plantation. Fertilization alone with P or K did not prove advantageous, showing lower height growth when compared to the treatment without fertilization.

Concentration of nutrients in the aboveground biomass

From the results obtained in the analysis of variance (Table 3), it was possible to verify significant interaction ($p<0.05$) for the concentrations of most nutrients between the components of the aerial part, except for the leaf compartment, in which only the concentration of Mg was significant for the interaction of factors. These results indicate the need to study the behavior of the variables considering the factors as a whole.

For the leaf compartment, N was the nutrient in highest concentration, followed by Ca, K, S, Mg and P (Figure 5). The control treatment showed the highest average N concentration in the twig compartment, reaching 6.3 g kg^{-1}. Plants under the P62.22 treatment obtained in the wood+shell compartment 6.64 g kg^{-1} of N, a difference of 18.1% to the unfertilized plants.

Plants under the P130.43K100 treatment showed the highest P concentrations for the twig compartment with 0.83 g kg^{-1} and the wood + bark compartment with 0.95 g kg^{-1}, representing increases of 17% and 20% compared to the control treatment, respectively. Ca concentrations in the leaves of fertilized plants were up to 91.5% higher than the control, with a value of 5.9g kg^{-1} in the treatment with the highest fertilizer doses. The concentrations of Mg and S were also higher among the aerial part compartments in fertilized plants. The treatments P65.22 with 1.29 g kg^{-1} of Mg in leaves, P130.43K100 with 0.60 g kg^{-1} of Mg in wood + bark, P65.22K200 with 1.11 g kg^{-1} of S in branches and P65.22K100 with 1.06 g kg^{-1} of S in wood + bark stand out. Among the components studied, the branches presented the highest contents for all nutrients. This higher content can be attributed to the high production of the biomass of branches in relation to the total biomass, which was approximately 44.4% of the total produced.

Nutrient Use Efficiency – NUE

Through the analysis of variance (Table 4), it was possible to verify significant interaction ($p<0.05$) for the NUE of most of the nutrients evaluated. In general, under the treatments with application of doses of P and K, the plants presented higher values of NUE, when compared to plants without fertilization (Figure 6). The individuals of *T. vulgaris*, under the K100 treatment, used most of the nutrients analyzed efficiently, presenting the highest values for NUE_P, NUE_K and NUE_{Ca}, differing statistically from each other by the Tukey test at 5% probability of error. The highest efficiency in the use of Mg and S was obtained in plants fertilized with the treatments P130.43K100 and P130.43, respectively. There was no statistical difference between the means of the treatments for NUE_N. However, plants fertilized with P130.43 showed an average of 5.4% higher than the plants in the control treatment.

Biological Use Coefficient - BUC

Regarding the analysis of variance of BUC in the aboveground components of *T. vulgaris* fertilized with P and K (Table 5), there was a significant interaction of factors ($P<0.05$) for all nutrients in the twig and wood + bark compartments, providing a differentiated use of nutrients absorbed by *T. vulgaris*. The coefficients of variation were low for some nutrients such as N, P, Mg and S, showing experimental precision. In Figure 7 it can be observed that in the leaf component the nutrient that presented the highest BUC values was Mg, in the K100 treatment, with 1467.1 followed by K with 595.9 (P130.43) and Ca with 348.8 (control).

Among all compartments evaluated, the K100 treatment was the one that showed the highest BUC among all nutrients, being the BUC_{Mg} with 3029.3 (twigs) and 2688.5 (wood + bark). Among the nutrients evaluated, N was used less efficiently by the plants, with the maximum BUC_N value reached in the P65.22K200 treatment, with 233.4 in the wood + bark component. With regard to BUC_P, among the treatments studied, the highest values occurred in the K100 treatments with 1785.1 and 1677.4 for the components twig and wood + bark, respectively. Ca was the nutrient that, after N, the plants also showed low efficiency, especially in the wood + bark, reaching 253.8 in the control treatment. The high Ca content in the bark and the immobilization of this element in the phloem, where it is found in the form of calcium oxalate, may have contributed to this result.

Discussion

The cumulative growth of morphological parameters observed in the first 12 months (3.8 cm in diameter and 1.5 m in height) and later in the second growing season, until 24 months (3.3 cm in diameter and 3.1 m in height). These are within the range of the results of other works with *T. vulgaris* in different regions of Brazil, in which variations from 1.1 m to 3.1 m (height) and 1.2 to 3.4 cm (diameter) were observed (Tonini et al., 2006; Martinoto et al., 2012; Tonini et al., 2018).

The higher height growth observed from 12 months post-planting is justified by competition between trees and greater efficiency in capturing and utilizing primary resources such as water, CO_2, light, and nutrients (Binkley et al., 2017). Schwerz et al. (2019) reported better growth efficiency of *Acacia mearnsii* De Wild. related to canopy densification and consequent higher amount of intercepted radiation, which allows for a higher photosynthetic rate, and consequently, higher radiation utilization efficiency to increase forest biomass.

Despite the variability observed in morphological variables within treatments, which is attributed in part to the non-clonal factor of *T. vulgaris* individuals that were established by native seeds, it is possible to verify the influence of fertilization on height and diameter growth, notably in treatments K100 and P65.22K100 (Figure 4). Such variation was also observed in investigations by Farias et al. (2016) and Silva et al. (2021), in plantings of *T. vulgaris* from seeds without selection. Several studies with application of K doses in forest plantations verified increments in total biomass values and higher growth compared to plants without fertilization (Christina et al., 2015; Bassaco et al., 2018; Gazola et al., 2019).

In the leaves, N was the nutrient in highest concentration, followed by Ca, K, S, Mg and P (Figure 5). Similar results were also found by Alves et al. (2017), in which N was the most accumulated nutrient in leaves, followed by K, Ca, Mg, P and S, evaluating the species *Poincianella bracteosa* (TUL.) L.P. Queiroz, *Mimosa ophthalmocentra* Mart. ex Benth., *Jatropha mollissima* (Pohl) Baill., *Pityrocarpa moniliformis* (Benth.) Luckow & R.W. Jobson and *Thiloa glaucocarpa* (Mart.) Eichler.

Because of the high variability of N concentrations in this compartment, no significant differences were found among treatments. However, the highest average was found in treatment P65.22 with 22.36 g kg^{-1} of N. In the compartment wood + bark, there was an increase of 18.1% of N concentration in the treatment P65.22 compared to the control. In general, leguminous species are highly responsive to phosphate fertilization, particularly in soils where there is low availability of the nutrient, and the nutritional supplementation with P favors the production of leaves and nodules, optimizing photosynthetic efficiency and the biological fixation of atmospheric N (Chuadhary et al., 2008).

The concentration of nutrients in absolute values in the twigs was large, considering the relative biomass of this component. On average, this compartment represented 52% of the total aboveground biomass of *T. vulgaris*. However, it was the second main component in nutrient concentration, mainly due to the high content of Ca, which represents approximately 20% of its nutrient content, second only to N. The treatment P130.43K100 stood out with the highest concentrations of P for the twigs and wood + bark compartments.

The results of the present work are similar to those found by Zhao et al. (2015), reporting 0.99 and 1.74 g kg^{-1} of P in plants of *Erythrophleum fordii* Oliv. which is of the same family as *T. vulgaris* and by Campelo et al. (2018) in adult plants of *Swietenia macrophylla* King. Several authors emphasize the importance of P in the initial growth phase of fast-growing forest species (Maeda and Bognola 2012; Stahl et al., 2013; Dias et al., 2014). The response to the P application was expected due to the low availability of this nutrient throughout the soil profile, besides the acidity contributing to P adsorption, favoring the availability of the nutrient through fertilization, as occurred in the treatment in question.

The concentrations of K, which reached a maximum value of 3.08 g kg^{-1} in the wood + bark compartment with treatment P65.22K200, were considered low compared to other forest species, such as *Handroanthus serratifolius* Vahl. (>10 g kg^{-1}), *Handroanthus impetiginosa* (Mart.) Matos (>6 g kg^{-1}), *Swietenia macrophylla* King (>8 g kg^{-1}) (Campelo et al., 2018) and *Erythrophleum Fordii* Oliver (4.29 g kg^{-1}) (Zhao et al., 2015). The condition of species under low K low concentrations showed no symptoms of water stress throughout the evaluation period that preceded the felling of the trees. Besides, K does not form organic compounds in the plant, making it a nutrient of high mobility in tissues.

The treatments P130.43K200 and P65.22 resulted in Ca and Mg concentrations in the leaves up to 91.5% and 76% higher than the control treatment, respectively. Similar results were found by Rangel-Vasconcelos et al. (2016), in which Ca stock was approximately 132% higher in the aerial biomass of *T. vulgaris* fertilized with P over plants without fertilization, in addition to Mg stock, which was up to 94% higher. The range of results of nutrient concentrations found in this study is comparable to those found in the literature for other leguminous tree species (Queiroz et al., 2007).

The amount of nutrients in the different tree compartments, as a rule, does not follow the distribution of biomass due to the difference in nutrient concentration within the tree compartments. According to Bellote and Silva (2004), the concentration of nutrients in biomass components is related to their functions, generally presenting the following gradient: leaf > bark > branch > trunk (sapwood > heartwood). The leaf is the major metabolic center of the plant, which is evident by the predominance of higher levels of nutrients (Marschner 1995). On the other hand, the lower contents are associated with components that have a more structural or conduction function, as is the case of wood and branches (Binkley 1986). Biomass partitioning suffers strong genetic control. However, it can vary at different growth stages of trees, in addition to the influence of development conditions, such as planting density (Schumacher et al., 2019). Mg is the nutrient most efficiently used in the biomass components, followed by P, S, K, Ca and N. The variation in NUE may be linked to the characteristics of each species.

Table 1. Chemical and physical attributes of the soil in the experimental area (mean values of five collection sites), Igarapé-Açu, Pará, Brazil.

Soil layer	pH	K^+	Ca^{+2}	Mg^+	Al^{+3}	H^+Al^{+3}	SB	CEC	P	V	O.M.	Granulometry		
												Sand	Silt	Clay
(cm)	($CaCl_2$)	(cmolc dm^{-3})							(mg dm^{-3})	%	%	(g kg^{-1})		
0-20	4.1	0.041	0.2	0.1	0.4	2	5.9	2.34	3	15	1.2	170	140	690
20-40	4	0.021	0.2	0.1	0.6	2.2	4.2	2.52	2	13	0.5	230	80	690
40-60	4	0.01	0.2	0.1	0.6	2.2	4.2	2.51	2	12	0.5	270	130	600
60-80	4.1	0.01	0.2	0.1	0.5	2	4.6	2.31	1	13	0.5	270	150	580
80-100	4.1	0.01	0.2	0.1	0.4	2	5.8	2.31	4	13	0.5	290	150	560
100-120	4.1	0.031	0.2	0.1	0.4	1.8	5.3	2.13	1	16	0.5	370	120	510

pH = hydrogen potential; K+ = potassium; Ca^{+2} = calcium; Mg^+ = magnesium; Al^{+3} = aluminum; H^+Al^{+3} = hydrogen and aluminum; SB = sum of bases of percentage of base saturation; CEC = cation exchange capacity; P = phosphorus; V = base saturation; O.M. = organic matter. The soil exchangeable K, Na, Ca and Mg contents were determined by atomic absorption spectrophotometry and flame spectrophotometry (Raij et al., 2000).

Table 2. Amounts of fertilizers applied (commercial products) and amount of nutrients offered, per treatment, to establish the factorial test for the planting of *Tachigali vulgaris,* Igarapé-Açu, Pará, Brazil.

Treatments	Fertilizers applied		Effectively provided nutrients					
	TSP	KCl	P_2O_5	P	K_2O	K	Ca	Cl
	---------- kg ha^{-1}----------		----------- kg ha^{-1}-----------					
Control	0	0	0	0	0	0	0	0
K100	0	100	0	0	50	39.1	0	39
K200	0	200	0	0	100	78.2	0	78
P65.22	65.2	0	26.7	16.6	0	0	6.5	0
P65.22K100	65.2	100	26.7	16.6	50	39.1	6.5	39
P65.22K200	65.2	200	26.7	16.6	100	78.2	6.5	78
P130.43	130.4	0	53.5	33.1	0	0	13	0
P130.43K100	130.4	100	53.5	33.1	50	39.1	13	39
P130.43K200	130.4	200	53.5	33.1	100	78.2	13	78

TSP: Triple superphosphate; KCl: Potassium chloride

Table 3. Analysis of variance of nutrient concentrations in aboveground biomass of leaves, branches and wood with bark (*F* and *P* values), obtained from a *Tachigali vulgaris* plantation under P and K fertilization, Igarapé-Açu, Pará, Brazil.

Nutrients	Block		Phosphorus		Potassium		P x K	
	F	*P (>F)*	*F*	*P (>F)*	*F*	*P (>F)*	*F*	*P (>F)*
Leaves								
N	2.207	0.149	1.812	0.183	0.399	0.674	0.588	0.674
P	1.544	0.225	5.174	0.013*	0.982	0.388	2.174	0.1
K	2.073	0.162	9.054	0.001**	3.763	0.037*	2.465	0.005**
Ca	1.632	0.213	12.369	<0.000***	6.054	0.007*	2.636	0.004**
Mg	0.965	0.335	8.74	0.001**	1.894	0.171	4.724	0.005**
S	2.174	0.152	5.792	0.008	0.638	0.536	0.272	0.893
Branches								
N	0.022	0.885	75.403	<0.000***	142.608	<0.000***	19.23	<0.000***
P	8.936	0.006	84.669	<0.000***	18.973	<0.000***	145.108	<0.000***
K	2.836	0.104	181.726	<0.000***	46.876	<0.000***	82.32	<0.000***
Ca	0.611	0.441	1206.4	<0.000***	42.202	<0.000***	570.134	<0.000***
Mg	0.954	0.338	18.649	<0.000***	29.229	<0.000***	21.13	<0.000***
S	2.146	0.155	28.522	<0.000***	158.671	<0.000***	56.727	<0.000***
Wood + bark								
N	0.45	0.508	0.241	0.788	2.931	0.071	5.631	0.002**
P	0.36	0.554	0.435	0.652	0.9	0.419	16.127	<0.000***
K	0.057	0.813	5.378	0.011*	24.209	<0.000***	1.987	0.126
Ca	0.564	0.473	1.417	0.261	0.305	0.739	3.996	0.012*
Mg	0.599	0.446	6.941	0.004**	0.313	0.734	5.414	0.003**
S	0.465	0.501	23.343	<0.000***	34.225	<0.000***	11.976	<0.000***

Nutrients evaluated in the aerial part biomass: nitrogen (N); phosphorus (P); potassium (K); calcium (Ca); magnesium (Mg); and sulfur (S). *, **, *** imply statistical differences with values of p < .05; p < .01; and p < .001, respectively.

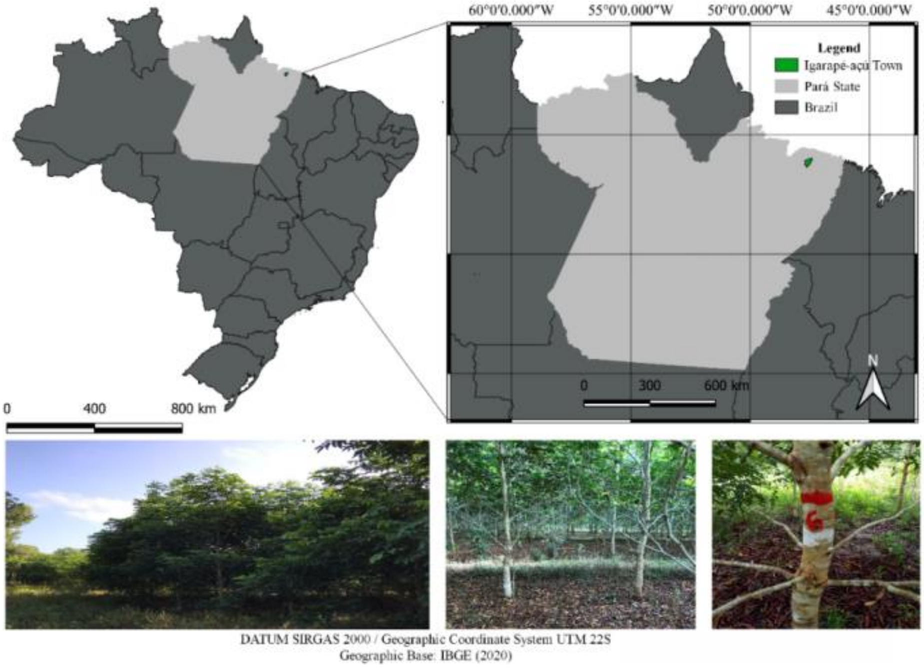

Figure 1. Location of Igarapé-Açu municipality and photos of the Tachigali vulgaris plantation, Pará, Brazil.

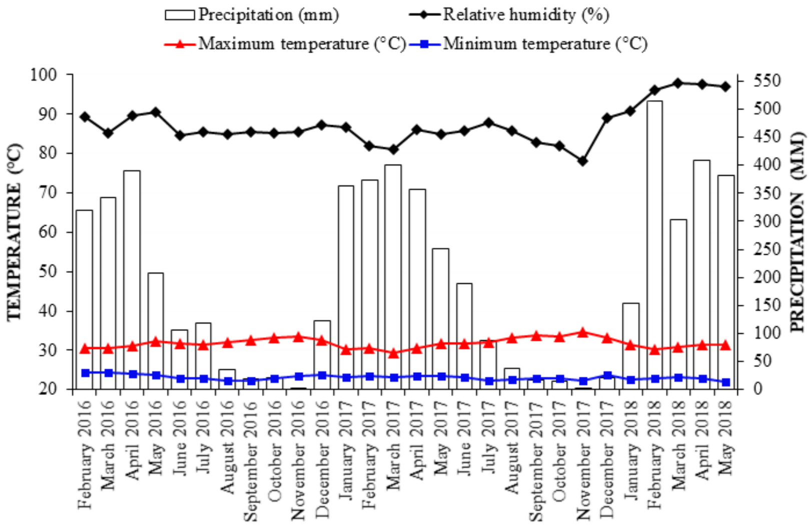

Figure 2. Monthly rainfall (mm), relative humidity (%) and monthly maximum and minimum temperatures (°C) at the experiment site during the evaluation months, Igarapé-Açu, Pará, Brazil.

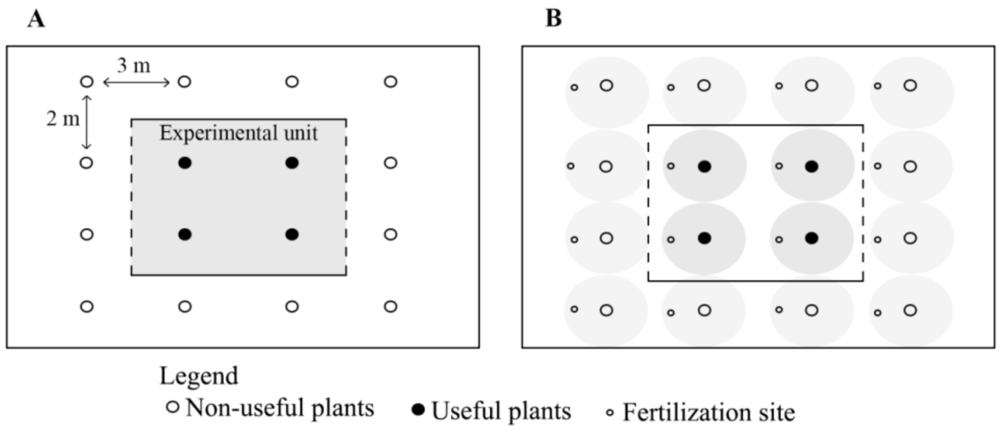

Figure 3. Schematic representation of plots (A) and fertilization sites (B) for evaluation of response of *Tachigali vulgaris* to P and K fertilization, Igarapé-Açu, Pará, Brazil.

Table 4. Analysis of variance of NUE in aboveground biomass (F and p values), in a *Tachigali vulgaris* plantation under phosphorus and potassium fertilization, Igarapé-Açu, Pará, Brazil.

NUE	Block		Phosphorus		Potassium		P x K	
	F	*P (>F)*	*F*	*P (>F)*	*F*	*P (>F)*	*F*	*P (>F)*
NUE $_N$	1.815	0.19	1.043	0.367	0.508	0.608	0.638	0.64
NUE $_P$	0.102	0.752	3.428	0.048	3.797	0.036	4.812	0.005
NUE $_K$	0.133	0.718	3.809	0.035	9.028	0.001	14.983	<0.000***
NUE $_{Ca}$	3.061	0.092	21.132	<0.000***	8.984	0.001**	7.878	<0.000***
NUE $_{Mg}$	0.165	0.688	7.505	0.003**	7.661	0.002**	0.829	0.004**
NUE $_S$	1.394	0.248	5.427	0.011*	2.72	0.085	1.238	0.003**

NUE of nitrogen (N); phosphorus (P); potassium (K); calcium (Ca); magnesium (Mg); and sulfur (S). *, **, *** imply statistical differences with values of p < .05; p < .01; and p < .001, respectively

Table 5. Analysis of variance of BUC of aboveground biomass of leaves, branches and wood with bark (F and p values), for aboveground compartments, obtained in *Tachigali vulgaris* plantation under P and K fertilization, Igarapé-Açu, Pará, Brazil.

BUC	Block		Phosphorus		Potassium		P x K	
	F	*P (>F)*	*F*	*P (>F)*	*F*	*P (>F)*	*F*	*P (>F)*
Leaves								
BUC $_N$	1.906	0.179	0.869	0.431	0.93	0.407	0.817	0.526
BUC $_P$	1.317	0.262	4.304	0.024*	1.147	0.333	2.046	0.117
BUC $_K$	0.444	0.511	6.737	0.004**	1.989	0.17	0.921	0.003**
BUC $_{Ca}$	3.903	0.059	7.475	0.003**	4.931	0.015*	2.115	0.004**
BUC $_{Mg}$	0.487	0.491	5.76	0.008**	1.426	0.259	3.934	0.013*
BUC $_S$	2.027	0.166	3.569	0.043*	0.754	0.481	0.417	0.795
Branches								
BUC $_N$	0.385	0.54	110.371	<0.000***	234.839	<0.000***	22.551	<0.000***
BUC $_P$	9.824	0.004**	104.091	<0.000***	48.718	<0.000***	163.727	<0.000***
BUC $_K$	4.128	0.053	331.958	<0.000***	12.01	<0.000***	66.798	<0.000***
BUC $_{Ca}$	1.137	0.296	1771.83	<0.000***	85.593	<0.000***	1117.64	<0.000***
BUC $_{Mg}$	0.29	0.595	25.726	<0.000***	82.644	<0.000***	57.432	<0.000***
BUC $_S$	1.738	0.199	20.169	<0.000***	139.225	<0.000***	57.598	<0.000***
Wood + bark								
BUC $_N$	0.016	0.901	0.621	0.545	3.052	0.064	5.216	0.003**
BUC $_P$	0.148	0.703	0.223	0.801	2.371	0.113	18.779	<0.000***
BUC $_K$	0.033*	0.857	12.123	<0.000***	26.646	<0.000***	4.557	0.006**
BUC $_{Ca}$	0.045	0.834	0.665	0.523	0.475	0.627	3.054	0.034*
BUC $_{Mg}$	0.014*	0.906	5.757	0.009**	0.413	0.666	3.468	0.021*
BUC $_S$	0.481	0.494	22.449	<0.000***	34.475	<0.000***	10.904	<0.000***

BUC of nitrogen (N); phosphorus (P); potassium (K); calcium (Ca); magnesium (Mg); and sulfur (S). *, **, *** imply statistical differences with values of p < .05; p < .01; and p < .001, respectively.

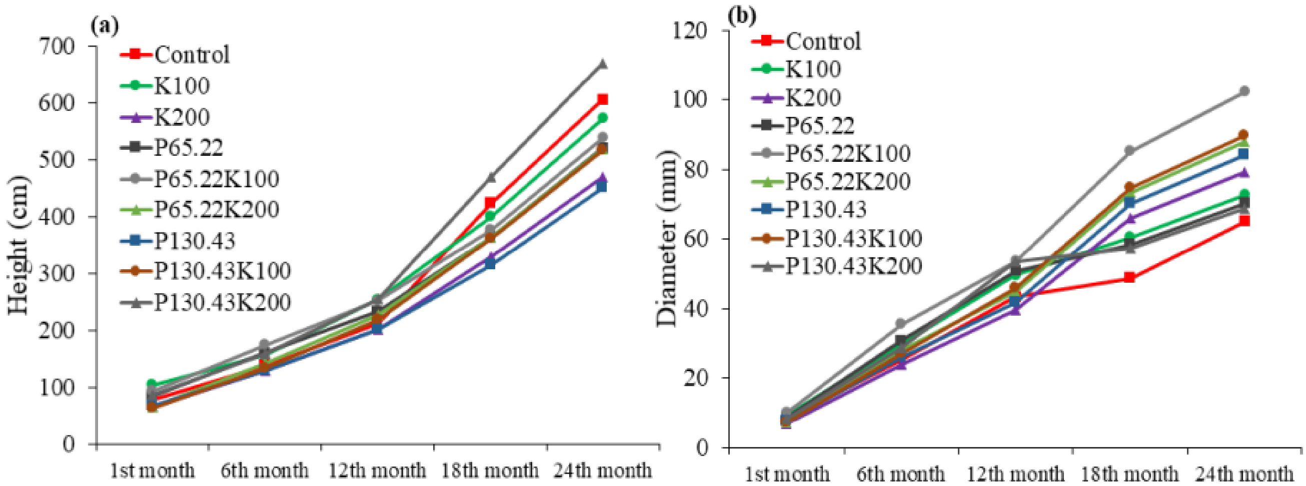

Figure 4. Growth in height (m) (a) and diameter (mm) (b) of *Tachigali vulgaris*, in response to P and K fertilization, Igarapé-Açu, Pará, Brazil.

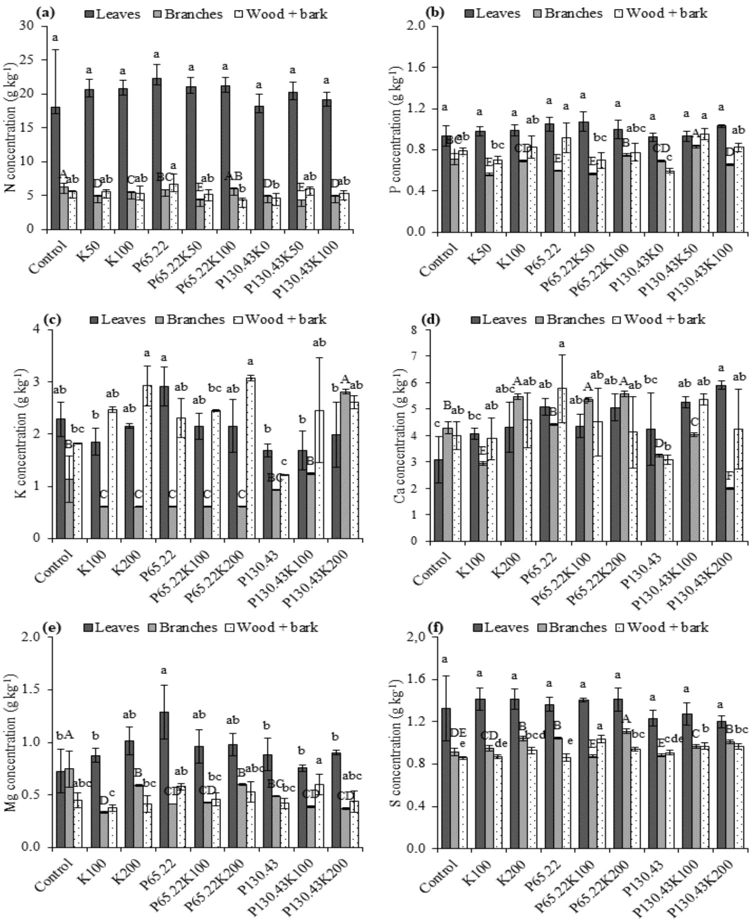

Figure 5. Effect of P and K fertilization on nutrient concentrations of *Tachigali vulgaris*, in the aboveground biomass compartments, Igarapé-Açu, Pará, Brazil. Different letters indicate statistical difference between treatments by Tukey test at 5%.

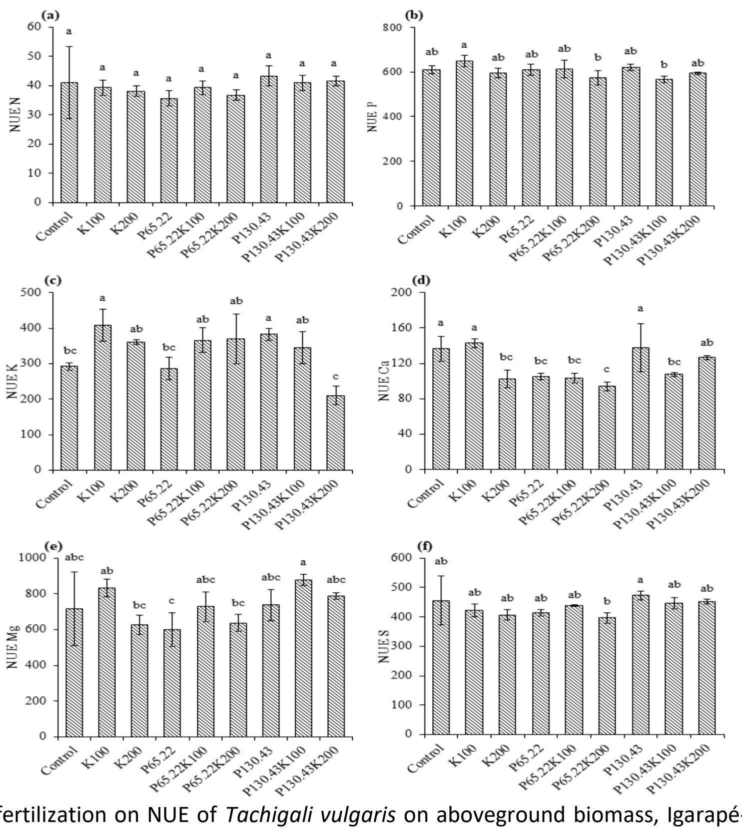

Figure 6. Effect of P and K fertilization on NUE of *Tachigali vulgaris* on aboveground biomass, Igarapé-Açu, Pará, Brazil. Different letters indicate statistical difference between treatments by Tukey test at 5%.

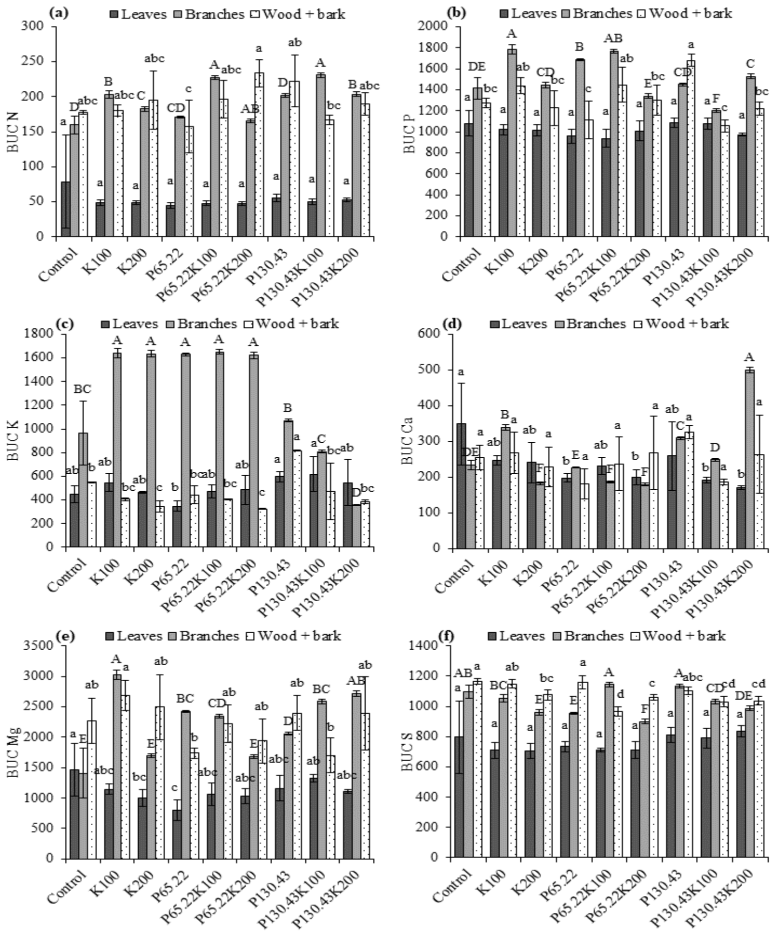

Figure 7. Effect of P and K fertilization on BUC of *Tachigali vulgaris*, in the aboveground biomass compartments, Igarapé-Açu, Pará, Brazil. Different letters indicate difference between treatments by Tukey test at 5%.

The failure to reach the optimal or critical nutritional balance between soil-plant and all other nutrients may result in limitation or excess of one or more available nutrients; and water relations (Santana et al., 2002; Viera et al., 2015). The high efficiency of this species in use of nutrients implies that it has lower nutritional requirements. Therefore, it is a very useful parameter in the selection of species to be used in plantations, especially in soils of low natural fertility (Silva et al., 1983; Viera et al., 2015). Thus, the use of management techniques that opt for more efficient plants in using nutrients is important to maintain the productive capacity of the forest site (Santana et al., 2002).

The K100 treatment promoted the highest values of NUE_P, NUE_K and NUE_{Ca}, and the highest efficiency in the use of Mg and S was obtained in plants fertilized with the P130.43K100 and P130.43 treatments, respectively. Although higher foliar P contents were observed in treatment with phosphate application (P130.43K100), *T. vulgaris* used this element more efficiently in the K100 treatment, suggesting that P is not a limiting factor for the good performance of this species in areas of low fertility. Similar results were found by Silva et al. (2006), evaluating the application of phosphate to pioneer species (*Vismia japurensis* Reichardt, *Bellucia grossularioides* (L.) Triana and *Laetia procera* (Poepp.) Eichler) growing in degraded pastures in central Amazonia.

Illenseer and Paulilo (2002) evaluated the young plants of *Euterpe edulis* Mart. and found that P utilization efficiency was higher with increasing irradiance but was not influenced by the levels of P applied. Safou-Matondo et al. (2005) observed low P utilization efficiency by *Eucalyptus urophylla* x *Eucalyptus grandis* hybrids as a result of the relatively high soil P availability at the cultivation site, demonstrated by the lack of response of the trees to P input.

The high NUE of the sampled trees demonstrates that the species is particularly efficient at producing large amounts of wood despite the low nutrient availability on the site. Thus, NUE may be a relevant index to integrate into species selection strategies, since this parameter provides an indication of the amounts of nutrients exported at harvest. Consequently, the producer now has subsidies to plan the necessary fertilizer inputs to ensure a satisfactory planting yield. These results suggest that *T. vulgaris* presents different strategies for the accumulation and use of nutrients, and that higher accumulation of a given nutrient does not always mean higher NUE.

The woody compartments (twigs and wood + bark) showed the highest BUC values, something very desirable and of great interest for forestry (Viera et al., 2015). The leaves had the lowest BUC values, except for BUC_{Ca}, in which the values were equivalent to the other components of aerial biomass, indicating the importance of maintaining these components in the soil after harvest.

Considering the conditions of natural genetic variability within the stand, it was not possible to observe a tendency of growth of BUC values as a function of fertilization or lack of it. These results suggest the need for further sampling, considering the planting age factor to be able to evaluate the relative export of nutrients in the harvests performed.

Schumacher et al. (2019) found an increasing trend in BUC values as a function of age in *Eucalyptus* spp. stands, indicating greater nutrient export in young stands.

The nutrient stock in forest biomass tends to present an asymptotic behavior at advanced ages, reaching an equilibrium state (Waring and Schlesinger 1985; Schumacher et al., 2019). Biochemical cycling shifts nutrients from senescent tissues to regions with higher metabolic activity (Pallardy 2008), which is especially important in woody tissues in the transformation from sapwood to heartwood (Schumacher et al., 2019). Among all aerial part biomass compartments, the K100 treatment was the one that showed the highest BUC among all nutrients, being the BUC_{Mg} with 3029.3 (twigs), 2688.5 (wood + bark) and 1467.1 (leaves).

Among the nutrients evaluated, N was used less efficiently by the plants, with the maximum BUC_N value reached in the P65.22K200 treatment, with 233.4 in the wood + bark component. Alves et al. (2017) also found lower BUC_N among all nutrients, evaluating the species *Poincianella bracteosa* (Tul.) L.P.Queiroz, *Mimosa ophthalmocentra* Mart. ex Benth., *Aspidosperma pyrifolium* Mart., *Cnidoscolus quercifolius* Pohl. and *Anadenanthera colubrina* (Vell.) Brenan.

With respect to BUC_P, the highest values occurred in the K100 treatments with 1785.1 and 1677.4 for the twig and wood + bark components, respectively. For comparison purposes, the critical BUC values defined for biomass production of the eucalyptus trunk are: P = 12000, K = 1000, Ca = 600 and Mg = 3000 kg of trunk biomass per kg of nutrient (Barros et al., 1995; Novais et al., 2007). Lafetá et al., (2021), evaluating *Eucalyptus grandis* × *Eucalyptus camaldulensis* at different planting spacings, obtained ranges of variation of BUC_P from 7573 to 10450, BUC_K from 948 to 1089, BUC_{Ca} from 657 to 894 and the BUC_{Mg} from 4807 to 6118.

In the analysis of all plant components in general, there was a wide variation in the results of BUCs between the fertilization treatments. This variation resulted from several factors, such as the genetic characteristics of the species. The failure to obtain the optimal or critical nutritional balance between soil, plant and all nutrients, i.e., there may have been a limitation of one or more available nutrients, in addition to water relations. The retranslocation of nutrients from senescing tissues to regions of the plant with greater metabolic activity is an important strategy to increase the efficiency of utilization of nutrients with high mobility in plant tissue and to reduce the outputs in the process of litter deposition (Poggiani and Schumacher 2004).

Materials and methods

Study area

The experiment was conducted in 2016 at the experimental station of the Federal Rural University of the Amazon, located in the municipality of Igarapé-Açu (Geographic coordinates: 01° 07' 33" south latitude and 47° 37' 27" west Greenwich longitude), Pará State, Brazil (Figure 1).

The region's climate falls into the category of humid megathermal, type Am and subtype Am2 of the Köppen classification, with a mean annual temperature of 26.5°C, mean relative humidity of 85% and mean rainfall of 2350 mm, with a strong concentration in the months of January to June and rarer from July to December (Costa et al., 2013; Hohnwald et al., 2019). At the experiment site, a weather station was installed that collected climatic data during the planting evaluation (Figure 2).

The experimental area has flat relief, and the soil was classified as Red-Yellow Latosol of medium texture (266 g kg^{-1} of clay) (Bastos and Pacheco 1999). The chemical and physical soil attributes were characterized up to a depth of 1.2 meters (Table 1) in the Soil Analysis Laboratory of Embrapa Eastern Amazon, in Belém, Pará. Parameters related to degraded soils, such as acidic pH, low cation exchange, low organic matter content, and low base saturation, were observed.

Plant materials, seedling production, planting and experimental design

The seeds of *T. vulgaris* used for seedling production were obtained from a certified producer, collected from seedlings located in the municipality of Santarém-PA (geographical coordinates 2° 26′ 22″S and 54° 11′ 55″W) and placed to germinate in seedbeds with washed sand as a substrate.

Because the species present tegumentary dormancy, a small portion of the tegument was removed at the opposite end to the embryonic axis, to facilitate the process of water entry into the seed and thus start germination. After 30 days from the beginning of germination, the seedlings were transplanted into seedling bags of size 15x25cm, with a volume of 1.9 dm³ of substrate. After 8 months, the seedlings reached 40 cm in height and were ready for planting in the experimental area.

Three doses of P (0, 65.22 and 130.43 kg ha^{-1}, with triple superphosphate) and three doses of K (0, 100 and 200 kg^{-1} ha, with potassium chloride), as well as their combinations, were applied in a 3x3 factorial scheme (Table 2). The fertilizer doses were previously defined according to recommendations for fast growing forest species in medium texture clayey soils (Andrade 2004; Arco-verde et al., 2005). Two applications were made during the first year of cultivation, at 60 days and 12 months post-planting. Fertilization occurred in April and February of the following year, periods favored by the water content in the soil due to rainfall.

The planting area was divided into 4 blocks, 5 meters apart, with the objective of potentiating the effect of the treatments in each plot. Each block was divided into 9 plots (treatments) of 10m wide by 8m long, containing 16 plants at a spacing of 2m between plants and 3m between rows, totaling 36 plots (Figure 3). The outer row of each plot served as a border; thus, each experimental unit was formed by the 4 central trees of each plot.

Growth evaluation

The evaluation of growth in diameter and total height was performed biannually at 6, 12, 18 and 24 months post-planting. For this end, the diameter of the plants was measured in two ways: in the first year the diameter was measured at ground level, using a digital pachymeter, because the individuals did not have the minimum height for measuring the diameter at breast height (DBH). In the second year, we measured the DBH (at 1.3 m from the ground), using a diameter tape graduated in centimeters. To obtain the total height a ruler graduated in centimeters was used, considering the insertion of the last leaf branch.

Chemical analysis of plant tissue

Sampling for the determination of aboveground biomass was performed in all treatments at 24 months post-planting,

collecting 3 trees from each treatment, preferably located on the inner border. The total aboveground fresh mass was subdivided into wood + bark, branches (alive and dead) and leaves. The fresh mass of each compartment was measured on scales with a capacity of 60 kg. Samples were placed in paper bags, weighed on semi-analytical scales and then placed in an oven with forced air circulation at 65º C until they reached constant mass. They were then weighed again to determine the humidity (%), which was used to estimate the dry mass of each compartment.
After drying in greenhouses, the plant tissue samples were processed and chemically analyzed to determine the concentrations of N, Ca, Mg, K, Na and P. The analyses were performed in the Plant Tissue Laboratory of the Escola Superior de Agricultura Luiz de Queiroz (Esalq/USP). The digestions performed were: Sulfuric (N) and nitroperchloric (P, K, Ca, Mg and S). To determine the nutrients in each compartment of the plant (leaves, branches and wood + bark), colorimetry (P), flame emission photometry (K), turbidimetry (S), atomic absorption spectrophotometry (Ca and Mg) were used and total N was determined by the Kjeldhal method after sulfuric digestion, according to the methodology of the Manual of Chemical Analysis of Soils, Plants and Fertilizers (Embrapa 2009).

Nutrient use efficiency (NUE) and biological use coefficient (BUC)
Several indexes for estimating the efficiency of resource use (nutrients, water, light) have been proposed, and there are also adaptations in the form of calculation for the same index (Fageria 2000). Faced with numerous alternatives, the NUE was estimated by dividing the dry biomass of the aboveground part (kg) by the amount of nutrients (N, P, K, Ca, Mg and S) accumulated in the aboveground part (kg), according to Equation 1 (Chapin 1980).

$$NUE = \frac{Aboveground\ dry\ biomass\ (Kg)}{Accumulated\ nutrient\ (Kg)} \qquad (1)$$

To evaluate the conversion rate of nutrients into biomass throughout the plantation development, and consequently, the relative export of nutrients per unit of biomass in each plant compartment, the BUC of the aboveground biomass (leaves, branches and wood + bark) was estimated, obtained by the quotient between the biomass and the nutrient stock in the respective compartment, both with the same unit (Equation 2), as described by Barros et al., (1986).

$$BUC = \frac{Dry\ compartment\ biomass (Kg)}{Accumulated\ nutrient\ (Kg)} \qquad (2)$$

Statistical analysis
The experimental data were evaluated for normality and homogeneity of variances by the Shapiro-Wilk and Bartlett tests, respectively. Subsequently, for parametric variables, the means of the treatments were submitted to analysis of variance and comparisons of means by Tukey's test, using the statistical software SPSS version 27.0 (IBM Corp., 2020). All analyses were evaluated at the 1% significance level.

Conclusion

Fertilization with 65.22 kg ha^{-1} of triple superphosphate and 200 kg ha^{-1} of potassium chloride was efficient to increase height growth by 11.1% considering the 24 months of evaluation, compared to unfertilized plants. Mg is the most efficiently utilized nutrient in the biomass components of *T. vulgaris*, followed by P, S, K, Ca and N. The woody compartments of *T. vulgaris* showed the highest BUC values, something very desirable and of great interest for forestry.

Acknowledgements

The authors would like to thank the Federal Rural University of the Amazon for supporting the researchers. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

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