

Doses of N, P and K in the cultivation of eucalyptus in soil originally under Cerrado vegetation

Doses de N, P e K na cultura do eucalipto em solo originalmente sob Cerrado

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Abstract

Many eucalyptus plantations in Brazil are in areas of soil with low fertility, with little phosphorous (P) and potassium (K) availability and with low organic matter (OM) content, resulting in a low supply of nutrients to plants, directly reflected in reduced yield. Thus, our objective was to evaluate the effects of nitrogen (N), P and K fertilization on the growth of eucalyptus plants, with the aim of achieving nutritional balance and high yield. The experiment was conducted on Renascença Farm, an agricultural property administered by Cargill Agrícola S.A., located in the city of Três Lagoas, Mato Grosso do Sul state, Brazil. The experimental design consisted of randomized blocks with ten treatments and five replicates. The treatments were composed of doses of N (0, 70, 105 and 140 kg ha⁻¹), doses of P (0, 40, 70 and 100 kg ha⁻¹ of P₂O₅) and doses of K (0, 90, 135 and 180 kg ha⁻¹ of K₂O). The doses of N and K were applied at planting and as top dressing, and the doses of P were applied only at planting. The diameter at breast height (DBH), plant height and timber volume with bark were assessed, and the concentrations of macronutrients in the leaves were determined. DBH and volume were positively affected by N fertilization, and eucalyptus growth in DBH, height and volume increased with P and K fertilization. The maximum yield of eucalyptus at 21 months of age was obtained with the application of 71 kg ha⁻¹ of N, 100 kg ha⁻¹ of P₂O₅ and 125 kg ha⁻¹ of K₂O. The concentrations of macronutrients were adequate even in the absence of the application of N, P and K. With increasing doses of K, there was an increase in leaf concentrations of K and a decrease in those of calcium and magnesium.

Key words: Nutritional state of plants, *Eucalyptus*, fertilization, macronutrients

Resumo

Grande parte do plantio da cultura do eucalipto no Brasil encontra-se em área de solo de baixa fertilidade, com pouca disponibilidade de fósforo (P) e potássio (K), e baixo teor de matéria orgânica (M.O.), o que

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implica em baixo fornecimento de nutrientes à planta, refletindo diretamente na redução da produtividade. Neste sentido, objetivou-se avaliar a adubação nitrogenada, fosfatada e potássica no crescimento das plantas de eucalipto visando equilíbrio nutricional e alta produtividade. O experimento foi executado na Fazenda Renascença, fundo agrícola administrado pela Cargill Agrícola S/A, localizado no município de Três Lagoas/MS. O delineamento experimental foi o de blocos casualizados com dez tratamentos e cinco repetições. Os tratamentos foram constituídos por doses de nitrogênio (N) (0, 70, 105 e 140 kg ha⁻¹), doses de P (0, 40, 70 e 100 kg ha⁻¹ de P₂O₅) e doses de K (0, 90, 135 e 180 kg ha⁻¹ de K₂O). As doses de N e K foram aplicadas no plantio e em cobertura e as doses de P somente no plantio. Foram avaliados: o diâmetro à altura do peito (DAP), a altura de plantas, o volume de madeira com casca e determinados as concentrações de macronutrientes nas folhas. O DAP e o volume foram influenciados positivamente pela fertilização nitrogenada, já o crescimento do eucalipto em DAP, a altura e o volume aumentaram com a adubação fosfatada e potássica. A máxima produtividade do eucalipto aos 21 meses de idade foi obtida com aplicação de 71 kg ha⁻¹ de N, 100 kg ha⁻¹ de P₂O₅ e 125 kg ha⁻¹ de K₂O. As concentrações dos macronutrientes estiveram adequadas mesmo na ausência da aplicação de N, P e K. Com o aumento das doses de K houve incremento das concentrações foliares de K e diminuição das de cálcio e magnésio.

Palavras-chave: Estado nutricional de plantas, *Eucalyptus*, fertilização, macronutrientes

Introduction

In 2012, the area occupied by *Eucalyptus* plantations in Brazil was 5.1 million hectares, representing an increase of 4.7% compared to 2011. This growth was spurred by investments made by domestic companies in the paper and pulp sector, with the greatest expansions occurring in the states of Tocantins (39.9%) and Mato Grosso do Sul (19.0%) (ABRAF, 2013). In the latter, the areas occupied by *Eucalyptus* plantations are concentrated in the eastern part of the state due to the low relative value of land, spanning the municipalities of Três Lagoas and Ribas do Rio Pardo (SANTOS, 2011). Thus, eucalyptus cultivation has occupied new regions of the country beyond the traditional regions, such as the south and southeast (SANTANA et al., 2008).

Afforestation has expanded in regions with naturally low-fertility soils and frequent and pronounced water deficits, as in the Cerrado (Brazilian tropical savanna) biome (GAVA et al., 1997; OLIVEIRA NETO et al., 2010; ALVES, 2011). These soils are characterized by a high degree of weathering and consequently have high levels of Fe and Al oxides and reactive acids, increasing their permeability and capacity for phosphorus (P) fixation. In addition to creating low base saturation and low levels of organic matter (OM), human

action on these soils, including the long-term impoverishment caused by extensive ranching, has modified their chemical properties, causing nutrient depletion without the necessary replenishment, which negatively affects the yield of newly forested populations.

Eucalyptus species are considered nutrient-demanding. Nutrient accumulation in the trunk and in shoots proceeds in the following order: N > Ca > K > Mg > P (ANDRADE et al., 2006; FARIA et al., 2008). Benatti (2013) observed the following order in six and a half-year-old eucalyptus clones: Ca > N > K > Mg > P; however, the author noted that the amount of accumulated Ca and N was practically equal. Vieira et al. (2012) observed the same sequence obtained by Benatti with the hybrid *Eucalyptus urograndis* at 18 months of age.

The effect of nitrogen (N) fertilization has been contradictory in eucalyptus plantations. The gains in yield of these plantations in response to fertilization have been relatively low or absent, indicating that the soil has been able to supply the plants most of the demand for this nutrient, which may be attributed to the larger amount of N mineralized from soil OM (GAMA-RODRIGUES, 1997; GAMA-RODRIGUES et al., 2005). According to Gonçalves et al. (1997), the recommendation for doses of N in eucalyptus plantations is based on the

content of OM of the soil, assuming that the N stock is greater in soils with higher OM content, with the lowest dose recommended for this condition. However, Gava et al. (2003) evaluated the growth of *Eucalyptus* clones with regard to the application of N in soils with high OM content ($> 50 \text{ g dm}^{-3}$ of OM) and suggested that there is potential for response by eucalyptus to N application even in soils with higher OM content.

Among the primary macronutrients, P is the least extracted yet most limiting of production in the Cerrado region because its levels in soil solution are generally low. Furthermore, these soils have high adsorption and precipitation capacity because they are extremely acidic and have high levels of exchangeable Al (SOUSA et al., 2004; SILVEIRA; GAVA, 2004). One way to compensate for this low availability is the application of high amounts of P fertilizers, but such practice greatly burdens the planting costs of eucalyptus; rational fertilization practices, which optimize the use of financial and environmental resources, depend on careful calibration studies (BOGNOLA et al., 2011; MAEDA; BOGNOLA, 2012).

Potassium (K) is one of the elements that most limits *Eucalyptus* yield in Brazil (SILVEIRA; MALAVOLTA, 2000) and is the second or third most accumulated nutrient, at times behind N and Ca (SILVEIRA et al., 2005). The use of K fertilizers has permitted significant increases in yield in most planted areas, due to the low levels of this nutrient found in soils (ALMEIDA et al., 2007). Rational recommendations for fertilization with K, both in the field and greenhouse, and for the location of species in planted areas with regard to nutritional characteristics and levels of K in the soil are of great importance (TEIXEIRA et al., 2006).

The calibration of NPK fertilization acts as a foundation for suitable fertilization recommendations, which is of great relevance for eucalyptus cultivation due to the lack of more current recommendations, given that the

recommended amounts are well below those currently used by companies. According to Silva (2011), greater eucalyptus yield with increased fertilizer doses has been demonstrated in several experiments. These results changed fertilization management in commercial plantations, which in the past did not apply fertilizers, or applied small amounts, while currently plantations receive high doses of fertilizers.

The evaluation of doses of NPK avoids the application of high doses of fertilizers, resulting in lower production costs. Castro (2011) reports that fertilization holds a unique importance among the eucalyptus cultivation factors because fertilization comprises a significant portion of the production costs.

Recommendations for fertilization should be defined at the regional level for the most representative species and soil types (FERREIRA, 2011) because yield, according to Stape et al. (2008), is governed by environmental conditions, and the availability of water is one of the main factors that limits the growth of eucalyptus. Thus, the appropriate fertilizer dose varies with the environment.

In addition to environmental factors such as climate and soil, the adoption of more productive and most likely more nutritionally demanding genetic materials, such as clones, should be considered. Clones are characterized as plants with accelerated development that are tolerant to diseases or adverse climatic conditions and that produce quality products (BENATTI, 2013). Alves (2011) stresses that specific fertilization recommendations should be made for each genetic material due to the marked and differentiated nutrient requirements among them. According to Silva (2011), the recommendation in the literature needs to be reevaluated, especially due to the use of more productive and likely more demanding genetic materials than those used to produce the original recommendation.

The objective of this study was to evaluate the effect of doses of N, P₂O₅ and K₂O on the cultivation of eucalyptus, given the importance of these nutrients and their limitations in the soil of the Cerrado region.

Materials and Methods

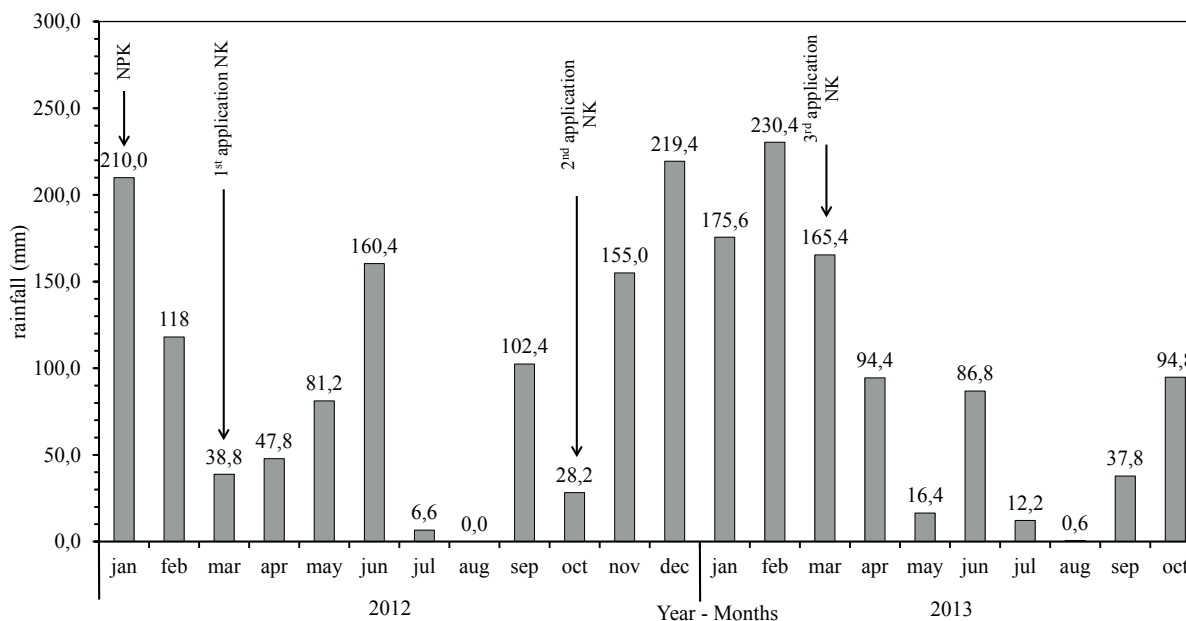
The experiment was conducted from September 2011 to November 2013 at Renascença Farm, an agricultural property administered by Cargill Agrícola S.A., located at latitude 20° 34' S, longitude 51° 50' W and a mean altitude of 305 m, in the municipality of Três Lagoas, Mato Grosso do Sul state, Brazil.

Preceding the installation of the experiment, soil samples were collected at depths of 0 to 20 and 20 to 40 cm to determine the chemical attributes of the soil following the method described by Raij et al. (2001). At a depth of 0 to 20 cm, the chemical

attributes were as follows: pH of 4.2 in CaCl₂; 7.4 g dm⁻³ of OM; 1 mg dm⁻³ of P in resin; levels of K, Ca, Mg, H+Al and Al of 0.2, 4.2, 1.9, 17.0 and 4.3 mmol_c dm⁻³, respectively; and a base saturation (V) of 27%. At a depth of 20 to 40 cm, the following chemical attributes were found: pH of 4.2 in CaCl₂; 6.8 g dm⁻³ of OM; 1 mg dm⁻³ of P in resin; levels of K, Ca, Mg, H+Al and Al of 0.3, 1.6, 1.1, 18.0 and 4.5 mmol_c dm⁻³, respectively; and V of 14%. The experimental area was occupied by natural vegetation (plants of the Cerrado biome) and, before the installation of the experiment, by degraded pasture with a slope of 4%. The soil is classified as orthic quartzarenic neosoil (EMBRAPA, 2013).

According to the Köppen system, the climate of the region is classified as Aw, defined as humid tropical with a rainy season in the summer and a dry season in the winter. The rainfall data recorded during the execution of the experiment are presented in Figure 1.

Figure 1. Monthly rainfall during the experimental period. Três Lagoas, Mato Grosso do Sul, Brazil, 2012/13.



In September 2011, the operational activities to install the experiment were begun: a) initial control of leaf-cutting ants: 10 to 12 September 2011, with

the application of a granulated formicide bait (1.5 g ha⁻¹ of the active ingredient [a.i.] sulfluramid); b) liming: 24 September 2011, with the application

of 1500 kg ha⁻¹ of 80% relative power of total neutralization lime cast over the total area; c) application of gypsum: 25 September 2011, with the application of 500 kg ha⁻¹ of gypsum cast over the total area; d) pre-planting control of leaf-cutting ants, in two stages: 5 to 7 December 2011 and 2 to 4 January 2012, with the application of granulated formicide bait (0.9 and 0.6 g ha⁻¹ of a.i. sulfluramid, respectively); e) chemical control in the total area through “desiccation”: 20 January 2012, with application of 2880 g ha⁻¹ of a.i. glyphosate; f) soil preparation: 27 January 2012, subsoiling in the planting rows, using a subsoiler, to an average depth of 45 cm; g) planting of seedlings and demarcation of experimental plots: 28 January 2012; h) base fertilization: 29 January 2012, with manual application of fertilizers in a continuous stream in the furrow row, simulating commercial application, in which the amounts applied conform with the treatments; i) manual irrigation of seedlings: 28 to 31 January 2012; j) replanting of dead seedlings: 20 February 2012; k) irrigation: 20 to 23 February 2012; and l) top-dressing: performed at 2, 9, and 14 months after planting of seedlings, with fertilizers applied manually between rows (canopy projection) and distributed in a half-moon shape on the

upper part of the row in amounts according to the treatments.

The experiment was implemented in January 2012, and the experimental design was randomized blocks with ten treatments and five replications. Each plot was composed of 56 plants, distributed in seven rows of eight plants each, totaling 420 m². Seedlings of the clone I144 (*Eucalyptus urophylla*) were spaced at 2.5 m in the planted rows and at 3 m between rows. Only the 30 central plants were considered as the useful plot area, disregarding the border, with the effective area of the sample totaling 225 m² per plot.

Treatments 2, 3, 4 and 1 corresponded to doses of N of 0, 70, 105 and 140 kg ha⁻¹; treatments 5, 6, 1 and 7 to doses of P of 0, 40, 70 and 100 kg ha⁻¹ of P₂O₅; and treatments 8, 9, 10 and 1 to K doses of 0, 90, 135 and 180 kg ha⁻¹ of K₂O, respectively (Table 1). For the fertilization at planting, urea, triple superphosphate, and potassium chlorate were used as sources of N, P₂O₅ and K₂O, respectively. At 2, 9 and 14 months, ammonium nitrate and potassium chloride were used as sources of N and K₂O, respectively, in the top-dressings. The amounts applied of each nutrient are provided in Table 1.

Table 1. Partial and total amounts of nutrients applied in treatments. Três Lagoas, Mato Grosso do Sul, Brazil, 2012/13.

Treatments		Amounts of nutrients (kg ha ⁻¹)											
		Total			planting fertilizing			top-dressing					
		N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O	2 month		9 month		14 month	
							N	K ₂ O	N	K ₂ O	N	K ₂ O	
1	Control	140	70	180	15	70	15	37	49.5	37.5	49.5	50	66
2	N-0	0	70	180	0	70	15	0	49.5	0	49.5	0	66
3	N-1	70	70	180	15	70	15	16.5	49.5	16.5	49.5	22	66
4	N-2	105	70	180	15	70	15	27.0	49.5	27	49.5	36	66
5	P-0	140	0	180	15	0	15	37.5	49.5	37.5	49.5	50	66
6	P-1	140	40	180	15	40	15	37.5	49.5	37.5	49.5	50	66
7	P-2	140	100	180	15	100	15	37.5	49.5	37.5	49.5	50	66
8	K-0	140	70	0	15	70	0	37.5	0	37.5	0	50	0
9	K-1	140	70	90	15	70	15	37.5	22.5	37.5	22.5	50	30
10	K-2	140	70	135	15	70	15	37.5	36	37.5	36	50	48

The following micronutrients were applied at planting in all the treatments: 1 kg ha⁻¹ of B (boric acid), 1 kg ha⁻¹ of Zn (zinc sulfate) and 1 kg ha⁻¹ of Cu (copper sulfate). In the top-dressings with N and K, performed at 9 and 14 months after planting, 1 kg ha⁻¹ of B (boric acid) was applied in all treatments.

At 12, 15, 18, and 21 months after planting, tree measurements (dendrometry) were conducted, evaluating the height and DBH of trees in the useful plot areas of the five blocks of the experiment, totaling 30 trees per plot, with the timber volume estimated following the method described by Aguiar et al. (2005). For the height measurement, a Forestor Vertex hypsometer was used, and a metric tape was used for the DBH measurement. The determination of the total timber volume with bark was estimated using the following equations:

$$V_{tc} = \sum V_i/A_i * 10000$$

$$V_i = \frac{\pi * (DAP_i)^2 * ff * H}{4}$$

V_i = timber volume with tree bark; A_i = useful plot area (225 m²); V_{tc} = total volume with bark (m³ ha⁻¹); DBH_i = diameter at breast height of each tree (m); ff = form factor—in this case, due to the absence of regionally defined factors for the clone studied, a value of 0.5 was assigned; and H_i = total height of each tree (m).

When the plants reached 18 months of age, the concentrations of macronutrients in the eucalyptus leaves were determined, with samples collected from the upper third of the canopy of eight medium trees present within the useful plot area of each

treatment. These samples were sent for an analysis of macronutrients following the method described by Malavolta et al. (1997).

The results were analyzed by regression analysis for doses of N, P₂O₅ and K₂O using the program SISVAR (FERREIRA, 2008).

Results and Discussion

Nitrogen fertilization

Doses of N increased DBH at 18 and 21 months of age. Doses of 63 and 67 kg ha⁻¹ of N resulted in the maximum diameters (8.9 and 9.9 cm, respectively), and at these doses, there was an increase of 4.7% (63 kg ha⁻¹ of N) and 5.0% (67 kg ha⁻¹ of N) in relation to the control (Figure 2). Greenhouse experiments omitting nutrients for the hybrid clone *Eucalyptus grandis* x *Eucalyptus urophylla* (SGARBI et al., 1999) and for *Eucalyptus citriodora* (MAFFEIS et al., 2000) showed that the absence of N application reduced the growth of the plant diameter. Costa and Tonini (2011) found that the DBH of *Eucalyptus camaldulensis*, at 16 months of age, increased linearly with increases in doses of N (0, 50, 100 and 200 kg ha⁻¹). In contrast to the results found for DBH, there was no significant effect on plant height associated with the application of N fertilizer in the present study (Figure 2).

In addition to diameter, the increase in doses of N caused increases in timber volume with bark of 9.2 and 15.3%, evaluated in the same seasons, with the maximum volumes (52.1 and 65.2 m³ ha⁻¹) obtained with applications of 59 and 71 kg ha⁻¹ of N (measured at 18 and 21 months, respectively) (Figure 3).

Figure 2. Diameter at breast height (DBH) (A) and mean height (B) of eucalyptus at 12, 15, 18 and 21 months of age as a function of doses of nitrogen (N). Três Lagoas, Mato Grosso do Sul, Brazil, 2012/13.

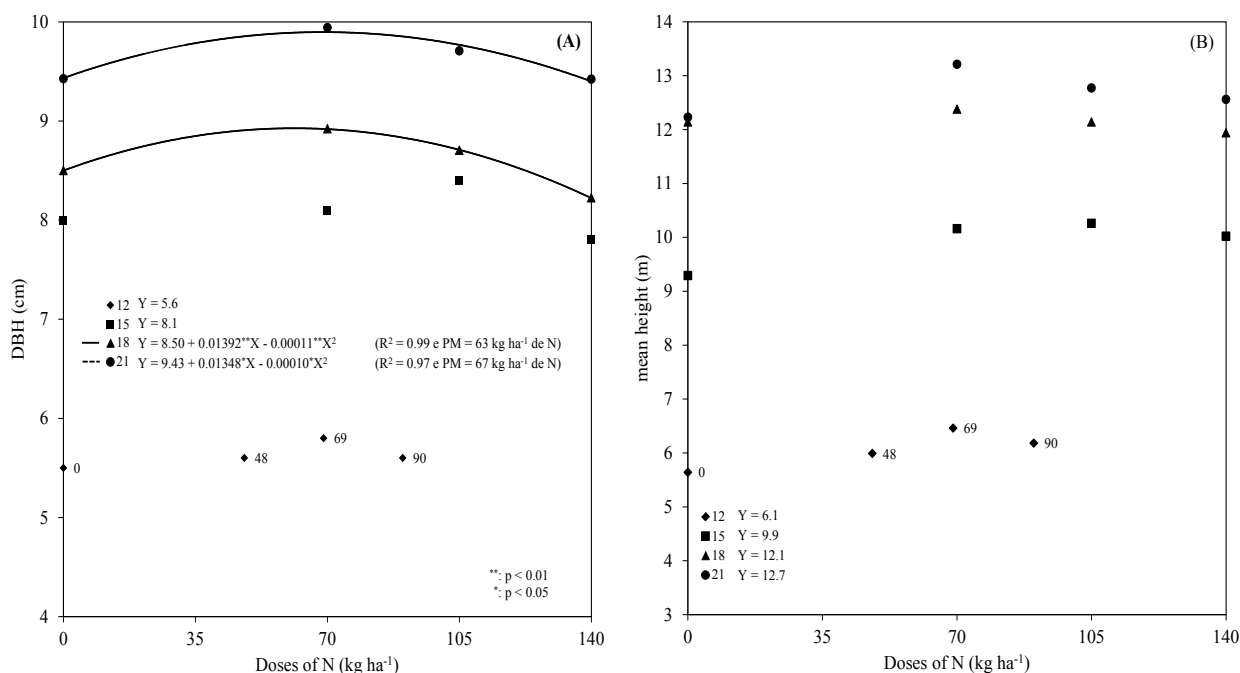
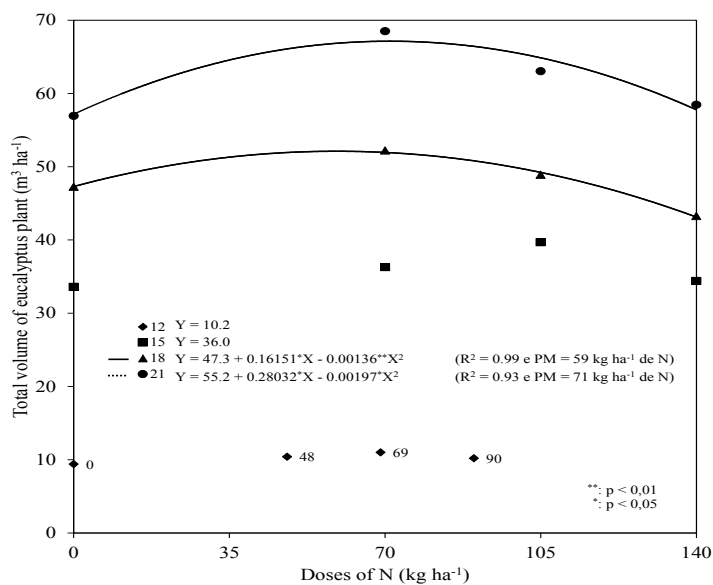


Figure 3. Total volume of eucalyptus plant timber with bark at 12, 15, 18 and 21 months of age as a function of doses of nitrogen (N). Três Lagoas, Mato Grosso do Sul, Brazil, 2012/13.



These results reinforce the importance of N fertilizer in soils with a low OM content, such as those in this study (7 g dm⁻³ of OM). For N fertilization in eucalyptus cultivation based on soil OM and clay content, Gonçalves et al. (1997)

proposed a recommended dose of 60 kg ha⁻¹ of N in soil with OM content between 0 - 15 g dm⁻³. In the present study, the results obtained were close to those recommended by those authors.

Pulito (2009) evaluated the response of *Eucalyptus* to N fertilizer and bioavailable N stock in soils and found that in the first two years, the yield relative to the control was, on average, 16% lower in the treatments that received fertilization in sandy soils, 9% lower in soils of medium texture and 10% lower in clayey and very clayey soils. The greatest potential for response to fertilization at a young age occurred in the soils where the lowest levels of total N and mineralizable N were found.

While in the present study the crop responded to the levels of N tested, the gains as a function of N fertilization were of a low magnitude. According to Barreto et al. (2011), in areas recently forested with eucalyptus, the mineralization of organic reserves of N can meet the demand of the trees throughout the crop cycle. Gama-Rodrigues et al. (2005) reported that the gains in yield of eucalyptus plantations as a function of N fertilization have been relatively low, which indicates that the soil has been able to meet most of the plants' demand for this nutrient.

In a study of the *Eucalyptus urophylla* clone in Cerrado soil with doses of N parceled over three

seasons, Jesus et al. (2012) observed that at 30 months after planting, the dose of 154 kg ha⁻¹ of N provided the maximum volume of timber, with growth 58.1% superior to production without N fertilizer. To obtain 90% of maximum production, the estimated dose was 74 kg ha⁻¹. In addition to treatments with doses of N, these authors used a treatment consisting of the application of 120 kg ha⁻¹ of N (ammonium nitrate) and found that this treatment did not differ from the same dose of N with ammonium sulfate, which indicated that the response is due to the supply of N and not to the supply of sulfur (S).

The leaf concentrations of N, P, K, Mg and S were not affected by the doses of N, with the N effect confirmed only in the concentration of Ca (Table 2). The values of P, K, Mg and S were within the range described by Dell et al. (2001), while that of N was slightly below the adequate range. These authors propose the following ranges, considered adequate for eucalyptus in the initial phase of growth: N from 18 to 30 g kg⁻¹; P from 1 to 3 g kg⁻¹; K from 6 to 18 g kg⁻¹; Ca from 3 to 8 g kg⁻¹; Mg from 1 to 3 g kg⁻¹ and S from 1.5 to 3 g kg⁻¹.

Table 2. Concentrations of macronutrients (nitrogen - N, phosphorous - P, potassium - K, calcium - Ca, magnesium - Mg and sulfur - S) in eucalyptus at 18 months of age as a function of nitrogen doses (N). Três Lagoas, Mato Grosso do Sul, Brazil, 2013.

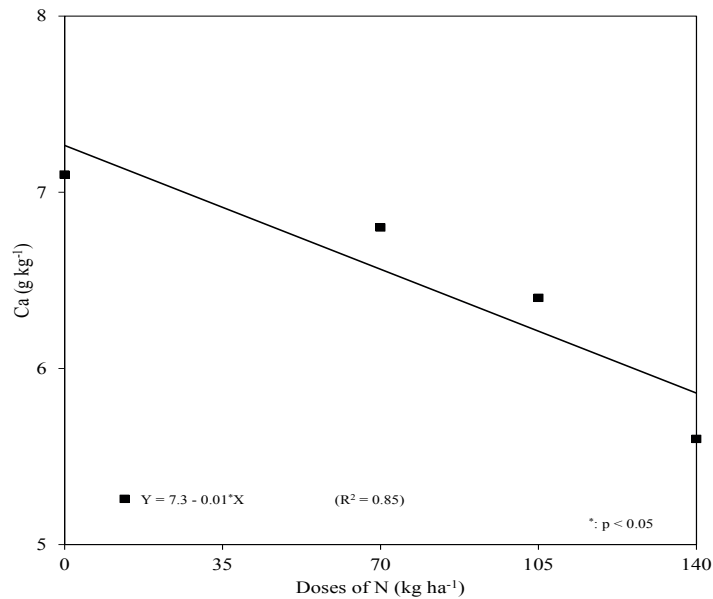
Doses of N (kg ha ⁻¹)	N	P	K	Ca	Mg	S
	g kg ⁻¹					
0	16.0 ^{ns}	1.2 ^{ns}	7.3 ^{ns}	7.1*	2.2 ^{ns}	1.4 ^{ns}
70	16.0	1.2	6.7	6.8	2.0	1.5
105	15.2	1.2	7.3	6.4	1.9	1.4
140	16.2	1.1	7.3	5.6	2.1	1.4
C.V. (%)	5.86	7.29	13.95	10.34	12.26	7.46

ns; * - not significant and significant by the F test, at 5% probability.

The concentrations of Ca decreased as a function of the increase in doses of N (Figure 4), likely due to the dilution effect of this nutrient in the leaf because there was greater plant growth in both diameter and volume with an increase in doses of N (Figures 2 and 3). Andrade et al. (2006) found

a positive correlation between Ca and Mg contents in bark with the volume of the tree, indicating that trees with greater volume have higher levels of these nutrients in the bark. Benatti (2013) reported that Ca displayed greater accumulation in bark, representing 60.6% of the total amount in the plant.

Figure 4. Concentrations of calcium (Ca) in eucalyptus leaves at 18 months of age, as a function of doses of nitrogen (N). Três Lagoas, Mato Grosso do Sul, Brazil, 2013.

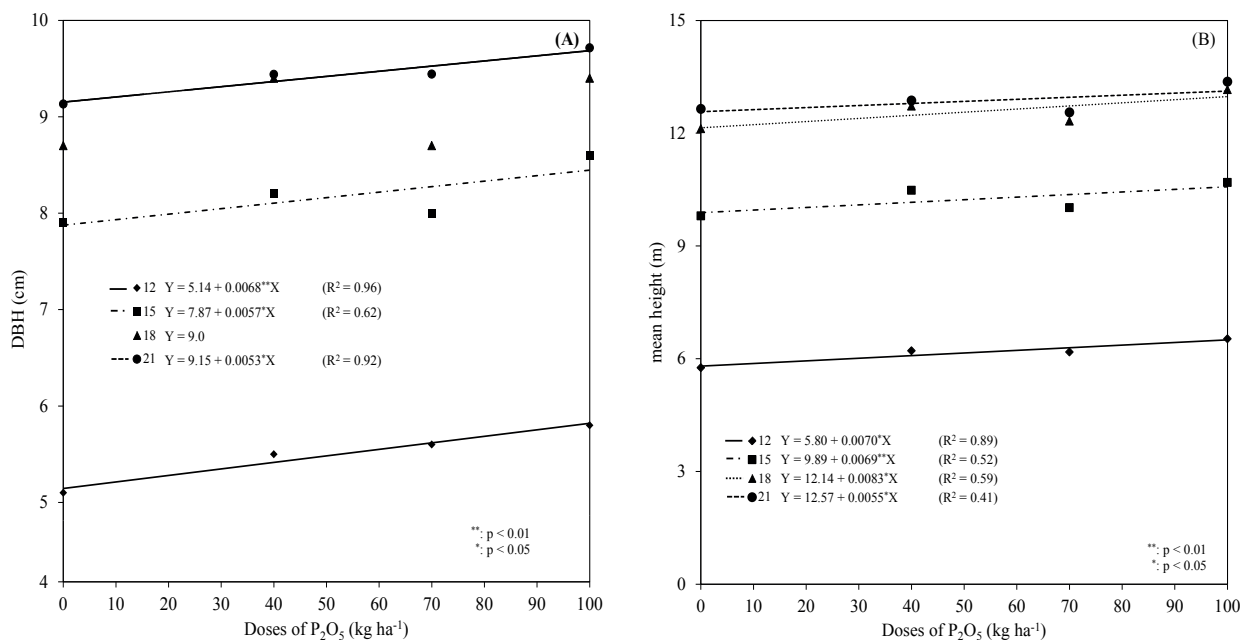


Phosphorous fertilization

Doses of P positively affected growth in DBH and height, with the greatest dose (100 kg ha⁻¹ of P₂O₅) causing an increase on the order of 13.7, 8.9

and 6.6% in the diameter at 12, 15 and 21 months, respectively, and increases of 13.4, 9.1, 9.1 and 5.9% in the height of the plant at 12, 15, 18 and 21 months, respectively, compared to the absence of P in fertilization (Figure 5).

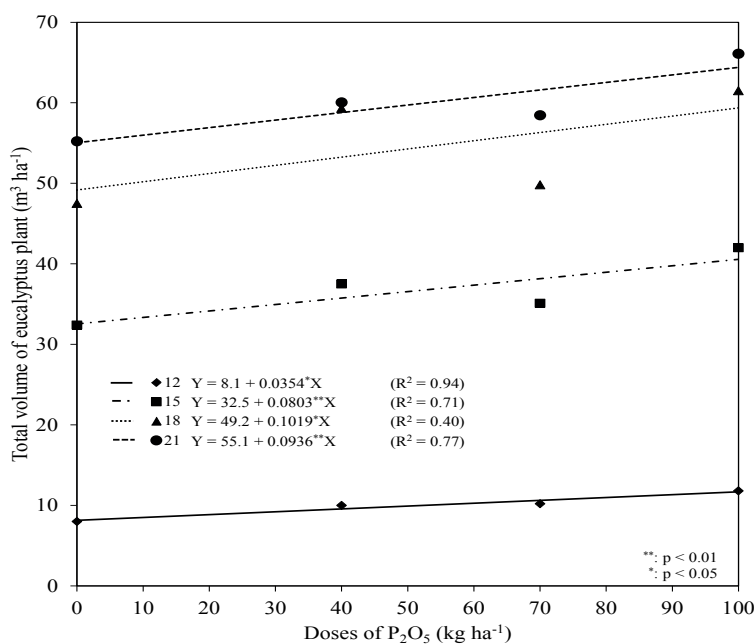
Figure 5. Diameter at breast height (DBH) (A) and mean height (B) of eucalyptus at 12, 15, 18 and 21 months of age as a function of doses of phosphorous (P₂O₅). Três Lagoas, Mato Grosso do Sul, Brazil, 2012/13.



The growth in the diameter and height of the plant as a function of P doses caused an increase in timber volume on the order of 30.6, 19.8, 17.2 and 14.5% at 12, 15, 18 and 21 months, respectively, with the highest dose applied relative to the omission of this nutrient (Figure 6). These results indicate the possibility of even greater growth with doses higher than those tested. However, the

rates of increase of the characteristics evaluated decreased in the period from 12 to 21 months after planting between the largest dose and the control. Such a result reinforces the assertion that this element is in more demand in the initial phase of growth because in this period, the critical level of P in the soil is greater. Stahl (2009) reports that eucalyptus species are considered nutrient-demanding, especially for P in the initial phase.

Figure 6. Total volume of eucalyptus timber with bark at 12, 15, 18, and 21 months of age as a function of doses of phosphorous (P_2O_5). Três Lagoas, Mato Grosso do Sul, Brazil, 2012/13.



The values of the critical levels of P in the soil in the crop maintenance phase (adult) are less than those at implantation (initial phase), after which the requirement for this nutrient decreases with increasing age (NOVAIS et al., 1982, 1986). In their study with NPK fertilization for eucalyptus production in Cerrado soils, Barros et al. (1981) reported that P was the main limiting factor to growth and that as eucalyptus develops, its capacity to absorb this nutrient increases due to the development of its root system, which can encompass a greater volume of soil.

The positive responses to phosphate fertilization are due to the extremely low availability of P in the soil ($P_{\text{resin}} = 1 \text{ mg dm}^{-3}$). Paula and Lopes (2003) evaluated the growth of 6-month-old eucalyptus under doses and sources of P in areas of minimum cultivation where the mean levels of P in the soil varied from low to medium and estimated that the dose to obtain maximum growth in height would be 155 kg ha^{-1} of P_2O_5 . Cipriani et al. (2012) found that for eucalyptus growth, regardless of the clone, and phosphate fertilization, there was a strong positive correlation between doses of P_2O_5 and the height of

plants, with the best dose estimated between 108 and 128 kg ha⁻¹ of P₂O₅.

The concentrations of macronutrients in the eucalyptus leaves were within the ranges considered adequate by Dell et al. (2001) for the initial growth phase, with the exception of N, which was slightly below the adequate range

(Table 3). The low concentration of N observed in this study is justifiable because the nutritional evaluation was performed in the dry season (July). Assis et al. (2006) found that the concentrations of nutrients in the leaves of *Eucalyptus urophylla* plants vary with the season sampled, with the lowest concentrations of the nutrients N, K and P found in the dry season.

Table 3. Concentrations of macronutrients (nitrogen - N, phosphorous - P, potassium - K, calcium - Ca, magnesium - Mg and sulfur - S) in eucalyptus at 18 months of age as a function of doses of phosphorous (P₂O₅). Três Lagoas, Mato Grosso do Sul, Brazil, 2013.

Doses of P ₂ O ₅ (kg ha ⁻¹)	N	P	K	Ca	Mg	S
	g kg ⁻¹					
0	17.5 ^{ns}	1.2 ^{ns}	7.3 ^{ns}	6.2 ^{ns}	2.2 ^{ns}	1.5 ^{ns}
40	15.5	1.1	6.6	6.5	1.9	1.4
70	16.2	1.1	7.3	5.6	2.1	1.4
100	17.5	1.3	7.3	6.8	2.1	1.5
C.V. (%)	7.25	7.76	13.95	11,72	9.92	6.61

ns - not significant.

Potassium fertilization

At 12 and 18 months, K doses had an effect on DBH. In the first evaluation, the values increased linearly, with the maximum DBH obtained with the application of 114 kg ha⁻¹ of K₂O. At 18 months, the values fit a quadratic function, with the maximum DBH of 9.0 cm obtained with the application of 86 kg ha⁻¹ of K₂O (Figure 7). It should be noted that by the time of the first evaluation, the second application of K had been made (at 9 months), with a cumulative total of applied K of 0, 60, 87 and 114 kg ha⁻¹ of K₂O, and at 14 months, the third application of K was made, with a cumulative total of applied K of 0, 90, 135 and 180 kg ha⁻¹ of K₂O. Costa and Tonini (2011) evaluated the application of doses of K in *Eucalyptus camaldulensis* in soil with low K content and, at 16 months after planting, found a linear response for DBH, reaching the maximum value with a dose of 200 kg ha⁻¹ of K (240 kg ha⁻¹ of K₂O). Under conditions of low K content, Almeida

(2009) also found that *Eucalyptus grandis* plants at 12 months became 54% thicker with the application of 140 kg ha⁻¹ of K₂O compared with the control.

K fertilization also affected height, with a linear fit observed at 12 months as a function of doses of K, with a maximum growth of 11.8% obtained with the application of the largest dose of 114 kg ha⁻¹ of K₂O compared with the control. In subsequent evaluations, the results fit a quadratic function, with the maximum height obtained with the application of 129, 104 and 128 kg ha⁻¹ of K₂O (15, 18 and 21 months, respectively) (Figure 7). Almeida (2009) found that for *Eucalyptus grandis* at 12 months, the application of 140 kg ha⁻¹ of K₂O resulted in plants that were 38% taller than the control plants.

Growth in diameter and height, as a function of doses of K, were reflected as an increase in the volume of timber with bark. At 12 months, there was linear growth with an increase of 30.0% with the 114 kg ha⁻¹ dose of K₂O compared to the control.

At 18 and 21 months, there was a quadratic fit, with the maximum volume yield obtained with the application of 94 and 125 kg ha⁻¹ of K₂O, generating 55.0 and 62.4 m³ ha⁻¹, respectively (Figure 8). The response obtained at 21 months with the highest dose

compared to the previous evaluation is associated with the greatest requirement for this nutrient during the crop cycle. According to Barros et al. (1990), the critical level of K in the soil increases with the age of the crop.

Figure 7. Diameter at breast height (DBH) (A) and mean height (B) of eucalyptus at 12, 15, 18 and 21 months of age as a function of doses of potassium (K₂O). Três Lagoas, Mato Grosso do Sul, Brazil, 2012/13.

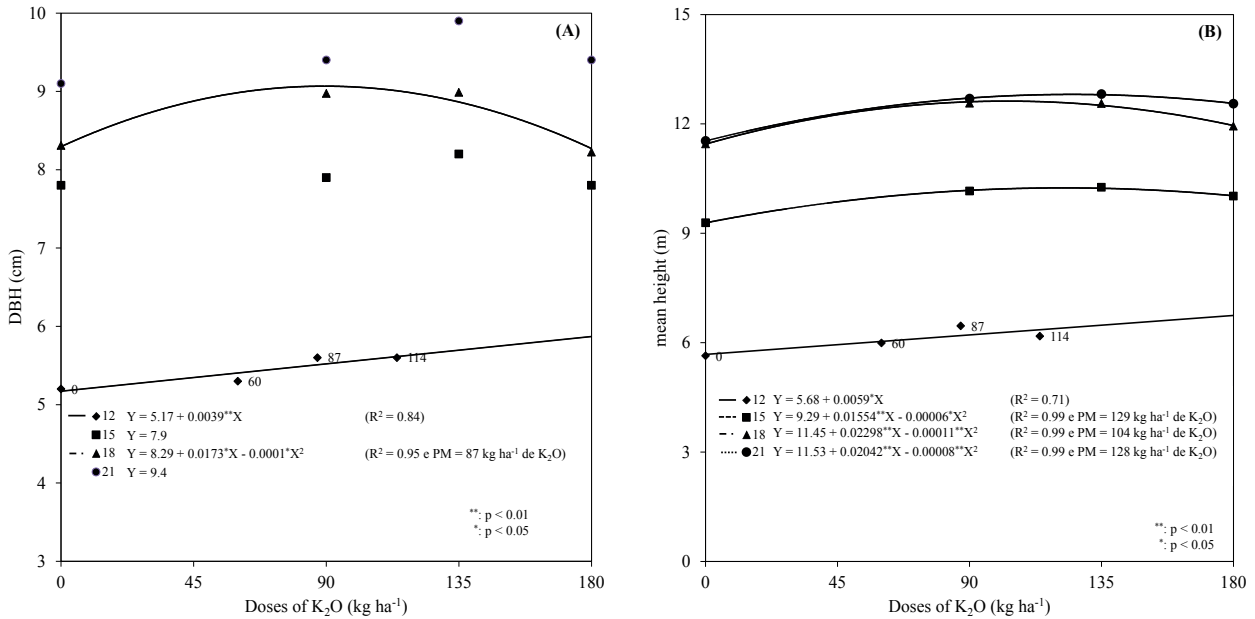
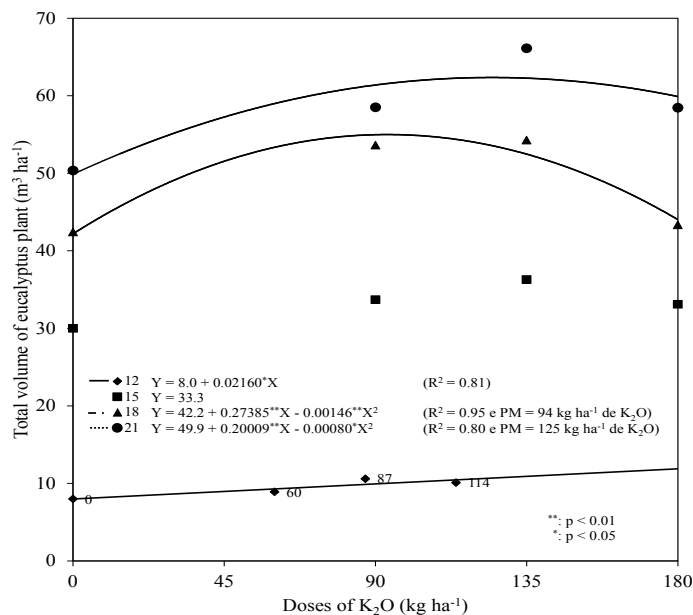


Figure 8. Total volume of eucalyptus timber with bark at 12, 15, 18, and 21 months of age as a function of doses of potassium (K₂O). Três Lagoas, Mato Grosso do Sul, Brazil, 2012/13.



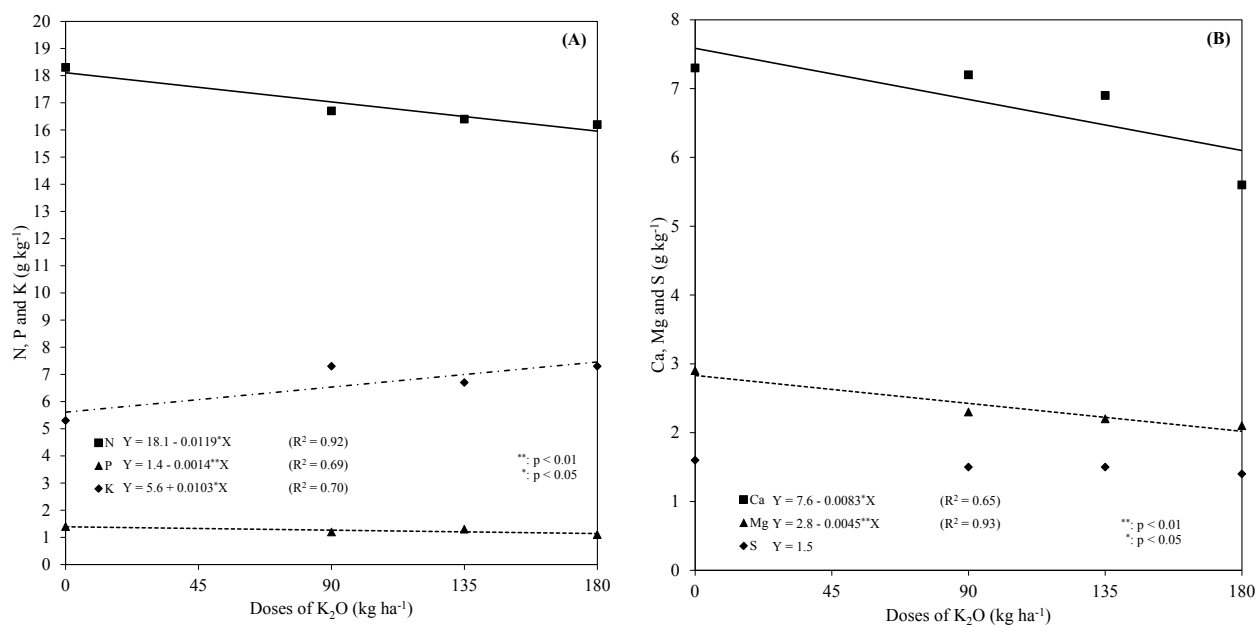
The response of the crop to K fertilization was expected, as the soil displayed a very low level of K. In conditions of higher levels of K in the soil, the responses of *Eucalyptus* to the application of this nutrient have not been very consistent, with responses observed only in soils in which K levels did not surpass $1.0 \text{ mmol}_c \text{ dm}^{-3}$ (SILVEIRA; MALAVOLTA, 2000). Based on the recommendation of these authors, the amount of K to be applied depends on the level of exchangeable K in the soil and should be between 120 and 150 kg ha^{-1} of K_2O . Another recommendation for the same K soil-level condition and sandy texture suggests the application of 50 kg ha^{-1} of K_2O (GONÇALVES et al., 1997).

In a study conducted in Cerrado soil, Almeida (2009) concluded that *Eucalyptus grandis* responds dramatically to K fertilization in its leaf area index,

DBH and height and can double timber volume yield at 36 months post-planting. Almeida (2009) also reported that supplying 100 kg ha^{-1} of K_2O was sufficient to reach 90% of the maximum yield at this age. Galo (1993) found a response to K fertilizer for *Eucalyptus grandis* at 6.5 years of age in Cerrado soils in which the original level of K was also very low ($0.59 \text{ mmol}_c \text{ dm}^{-3}$). To obtain 90% of the maximum timber production, it was necessary to apply 108 kg ha^{-1} of K_2O .

In general, the concentrations of macronutrients in eucalyptus leaves remained close or within the ranges considered adequate by Dell et al. (2001) for the initial growth phase (Figure 9). The concentrations of P, Ca, Mg and S were within the proposed range, N was slightly below, and K was low only with the omission of the application of this nutrient (5.3 g kg^{-1} of K).

Figure 9. Concentrations of nitrogen (N), phosphorous (P) and potassium (K) (A) and of calcium (Ca), magnesium (Mg) and sulfur (S) (B) in eucalyptus leaves at 18 months of age as a function of doses of potassium (K_2O). Três Lagoas, Mato Grosso do Sul, Brazil, 2013.



The increase in doses of K affected the concentrations of all the macronutrients with the exception of S. For K, there was an increase in

leaf concentration as a function of its application to the soil in increasing doses, differing from the concentrations of N, P, Ca and Mg, which

decreased (Figure 9).

The likely cause of decreased concentrations of N and P is the “dilution effect” of these nutrients in the leaf because with increasing doses of K, there was greater plant growth in DBH, height, and volume (Figures 7 and 8), resulting in lower concentrations of these nutrients. According to Valeri et al. (2001), the application of K favored tree development, which led to a decrease in N content in timber and branches. Silva et al. (2008) found that the lowest leaf concentration of P in their study, observed in a treatment with mineral fertilizer, may be attributed to the rapid fixation of mineral P added to the soil via fertilizer, also associated with the dilution effect of P in the greater amount of biomass produced in this treatment.

A decrease in leaf concentrations of Ca and Mg as a function of increased doses of K was also found by Silveira (2000), who evaluated the effect of K on growth, nutrient concentrations and characteristics of juvenile timber of *Eucalyptus grandis* progeny grown in a nutrient solution. The author reported that in all of the progeny, the concentration of Ca and Mg in plant tissues, especially in the leaves, was negatively affected by increased doses of K.

This decrease is related to external factors that influence ionic absorption between K, Ca and Mg in the soil; in this case, a high concentration of one of the nutrients in the soil results in less absorption of the other, demonstrating competitive inhibition. A traditional example of competitive inhibition is observed when high concentrations of K inhibit the absorption of Ca and Mg (MALAVOLTA, 1980). This type of inhibition may be overcome when the external concentration of the element is increased, creating a higher probability of occupying the binding sites and displacing the competing ion (MALAVOLTA, 2006).

Marschner (1995) reports that K can cross the plasma membrane with greater speed, delaying the absorption of slower cations, such as Ca and Mg. This

preferential absorption of K is associated with its monovalence (K^+), with a lower degree of hydration compared to the bivalent cations (Ca^{2+} and Mg^{2+}) (PRADO, 2008). However, the lower absorption of these nutrients did not result in damaged eucalyptus because leaf concentrations were adequate.

Conclusions

N fertilization caused a low-magnitude increase in DBH and in timber volume in soil with low OM content, with the growth in volume determined by the increase in diameter. The maximum productivity of timber at 21 months was obtained with the application of 71 kg ha⁻¹ of N.

P fertilization affected growth in DBH, height and volume of eucalyptus, and the increases observed with the highest dose in relation to the control decreased with the age of the crop. The maximum timber yield at 21 months was obtained with the application of 100 kg ha⁻¹ of P₂O₅.

K fertilization had a greater effect on growth in DBH, height and volume of eucalyptus compared to that of N and P fertilization. The maximum timber yield at 21 months was obtained with the application of 125 kg ha⁻¹ of K₂O.

Acknowledgements

To FAPESP for the translation funding of the article (process number 2013/17935-2), to Cargill Agrícola S/A for research funding, to CAPES and IPEF by master scholarship.

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