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*Artigo Científico*

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# Fertilization during the establishment of a *Eucalyptus camaldulensis* plantation in the northern Brazilian Amazon[1]

## *Adubação no estabelecimento de um plantio de* ***Eucalyptus camaldulensis*** *na Amazônia setentrional brasileira*

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**Abstract -** Forestry plantations should be regarded as an alternative sustainable land-use system in degraded savannah areas. They contribute to the maintenance of productive processes in degraded soils that are of economic importance for local inhabitants; in addition, in the ecological sense, timber and non-timber products from planted forests reduce the exploitation pressure on native forests. Eucalyptus plantations on degraded savannahs in the northern Brazilian Amazon may help to reduce exploitation pressure on native forests. However, there is no information regarding the nutrients rates that would allow faster eucalyptus growth in that region. A trial was installed in an Yellow Latosol (Oxisol) soil type adopting a one-half-type fractional factorial design with four rates of N, P, and K. Functions were adjusted for the dependent variables height, diameter at breast height (DBH), leaf tissue nutrient content, and soil-chemical attributes. Interaction N versus K was observed on tree height with a maximum of 7.8 m recorded at 200 kg ha$^{-1}$ of N and 50 kg ha$^{-1}$ of K. Phosphorus fertilization promoted greater DBH growth with maximum value at 120 kg ha$^{-1}$ of P; however, the highest gain was obtained at 30 kg ha$^{-1}$ of P. The NPK rates that maximized Eucalyptus camaldulensis growth were 200, 30, and 50 kg ha$^{-1}$, respectively.

**Key words -** Forest plantation. Land rehabilitation. Macronutrient input. Savannah degraded soils.

**Resumo -** Plantações de eucalipto, em áreas de lavrado degradadas na Amazônia Setentrional brasileira, devem contribuir para diminuir a pressão de exploração em florestas nativas. Porém, não há informações sobre as doses de nutrientes que permitem o rápido crescimento do eucalipto nesta região. Um experimento para avaliar a resposta à adubação do *Eucalyptus camaldulensis* foi instalado em Latossolo Amarelo, adotando o delineamento fatorial fracionário com quatro doses de nitrogênio (N), fósforo (P) e potássio (K). Funções foram ajustadas para as seguintes variáveis dependentes: altura, diâmetro à altura do peito (DAP), conteúdo de nutrientes nas folhas e atributos químicos do solo. Foi observada interação NxK para a altura, com um máximo de 7,8 metros registrados com a dose de 200 kg ha$^{-1}$ de N e 50 kg ha$^{-1}$ de K. A adubação fosfatada promoveu o maior crescimento do DAP com o valor máximo obtido com a dose de 120 kg ha$^{-1}$ de P; O maior ganho, entretanto, foi obtido com a dose de 30 kg ha$^{-1}$ de P. As doses de NPK que maximizaram o crescimento do *Eucalyptus camaldulensis* foram 200, 30 e 50 kg ha$^{-1}$, respectivamente.

**Palavras-chave -** Adição de macronutrientes. Plantio florestal. Reabilitação de áreas degradadas. Solos degradados da Savana.

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# Introduction

The Amazonian state of Roraima is located in the northern part of the Brazilian territory. Tropical forest ecosystems are found in the southern portion of Roraima, while significant areas of savannah occur in the northeastern part (BARBOSA; FEARNSIDE, 2005). Extensive areas of savannah ecosystems in Roraima are still not under anthropic influence, but others have been used for grazing and annual cropping. Savannah soils can be seriously damaged under inappropriate land-use systems, and degradation in pastures occurs mainly due to overgrazing and invasion of weeds (FEARNSIDE; BARBOSA, 1998). Poor pasture management has been assumed to be the main cause of soil fertility reduction along with soil compaction, decreases in water supply, soil erosion and acceleration of nutrient losses (CERRI *et al*. 2004). Furthermore, overgrazing and poor pasture management are causes of soil carbon losses (ELMORE; ASNER, 2006; SOUZA *et al.* 2010) and may compromise greenhouse gases mitigation.

Forestry plantations should be regarded as an alternative sustainable land-use system in degraded savannah areas. They contribute to maintaining productive processes in degraded soils that are of economical importance for local inhabitants; in addition, in the ecological sense, timber and non-timber products from planted forests reduce the exploitation pressure on native forests. Regardless of whether soil properties (such as bulk density) are ameliorated once degraded pastures are converted into forest plantations, soil-chemical attributes might improve (BOLEY *et al*., 2009). Additionally, the adoption of adequate silvicultural practices can ensure rapid soil covering and probably soil protection and rehabilitation. Because they can influence soil erosion positively or negatively, eucalyptus plantations have been discussed in the context of both soil protection and ecosystem rehabilitation (ZHOU *et al.,* 2002) depending on plantation characteristics and management practices. Soil-chemical properties of degraded lands can also be modified by eucalyptus plantations depending on fertilisation management strategies. The most favourable conditions for achieving land rehabilitation using Eucalyptus plantations are based on the guarantees of fast canopy cover, litter formation (ZHENG *et al.,* 2008), soil organic matter accumulation, and nutrient cycling.

Nitrogen, phosphorus, and potassium are essential macronutrients which play an important role in plant development (ZHANG *et al.,* 2010). The effects of fertilisation with these nutrients on both plant growth and chemical contents of leaves have been extensively studied in Eucalyptus forests (HUNTER, 2000; GRACIANO et *al*., 2005; FENN *et al.,* 2006). Many Eucalyptus fertilisation studies have been conducted in Latosols and Ferralsols at central, southern, and northeast Brazilian regions (FERNANDEZ *et al*. 2000, STAPE *et al*. 2008, LACLAU *et al*. 2008; STAPE *et al*., 2010). The Latosols in Amazon region are more acid and present higher amounts of exchangeable aluminium than Latosols found at Brazilian central region (DEMATTÊ; DEMATTÊ, 1993). It is not well known if *E. camaldulensis* growth response to NPK fertilisation in Latosols at northern Brazilian Amazon will be similar to the responses observed in other regions. Recent studies have emphasized that potassium application has been neglected in many developing countries and this has resulted in soil K depletion, dificulting the increase in crop yields even though other nutrients are supplied (ZHANG *et al*., 2010).

Understanding the effects of fertilisation management practices on vegetation and soil properties is important with regard to forest growth and land rehabilitation. However, there is no information regarding the nutrient rates that would allow faster eucalyptus growth in soils at northern Brazilian Amazon. The objectives of this study were to evaluate soil-chemical attributes, as well as growth parameters and mineral nutrition status of *Eucalyptus camaldulensis* trees, in response to different doses of nitrogen (N), phosphorus (P) and potassium (K) applied to degraded savannah soils at northern Brazilian Amazon.

# Materials and methods

The experiment was established in June 2007 at the Empresa Brasileira de Pesquisa Agropecuaria (Embrapa) Roraima experimental field station, which is located in the Boa Vista County (60°43’51”W; 2°45’26”N) in the Brazilian state of Roraima. The climate of this region is Awi under the Köppen Classification with 1100–1700 mm of annual rainfall (BARBOSA, 1997). The driest months are among December and March (with approximately 10% of the annual precipitation), and the peak of the rainy season is from May to August (with nearly 60% of the annual precipitation) (BARBOSA; FEARNSIDE, 2005). The experimental site was selected according to the following factors: representativeness of degraded soil conditions in savannah ecosystems, and past management.

The soil was classified as Yellow Latosol (Oxisol) with a sandy clay loam texture; soil characteristics are presented in Table 1. Before *Eucalyptus camaldulensis* seedlings were planted, lime was applied to the soil in an amount that was calculated to raise soil calcium and magnesium content according to Eucalyptus requirements (GONÇALVES *et al.,* 1997). Micronutrients were added via fritted trace elements (FTE) that were applied to the soil to increase boron and zinc contents to supply Eucalyptus needs (GONÇALVES *et al*., 1997).

**Table 1** - Soil characteristics at the experimental site

| Depth | pH[a] | M.O.[b] | P [c] | K[d] | Ca[d] | Mg[d] | CEC[d] | V[e] | Sand | Silt | Clay |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (m) | $H_2O$ | g kg$^{-1}$ | mg kg$^{-1}$ | | cmol$_c$ kg$^{-1}$ | | | % | | g kg$^{-1}$ | |
| 0.0 - 0.2 | 4.8 | 16.1 | 0.20 | 0.01 | 0.25 | 0.65 | 3.6 | 25.6 | 75 | 1 | 24 |
| 0.2 - 0.4 | 5.1 | 13.6 | 0.10 | 0.01 | 0.25 | 0.60 | 3.4 | 25.1 | 73 | 7 | 20 |

[a]1:2.5 soil:water; [b]Walkley & Black; [c]Mehlich extract; [d] Sum of bases (1N $NH_4$-acetate at pH 7) + exch. H and Al (1N Ca-acetate pH 7); [e] Bases saturation

The experiment was arranged in a fractional factorial design of one-half type (4 x 4 x 4) as proposed by Colwell (1978) and adapted by Andrade and Noleto (1986) to allow calculations of all first order interactions. Confounding of unlike treatment effects was used to reduce the size of the trial, which consisted of only a fraction of the complete factorial combinations; the trial comprised a total of 32 treatments without replication and divided into two blocks (Table 2).

Experimental plots were composed of 40 trees in five rows with a spacing of two meters within and three meters between rows. The middle of 18 trees of each plot were used for sampling. Treatments consisted of four N, P, and K rates (kg ha$^{-1}$): N (0, 50, 100, and 200; supplied as urea), P (0, 30, 60, and 120; supplied as triple superphosphate), and K (0, 50, 100, and 200; supplied as potassium chloride). The fertiliser with phosphorus was applied during seedling planting, while the application of nitrogen and potassium mixed fertilisers was divided into four periods, namely July 2007, April 2008, May 2008 and July 2008.

The evaluations of tree growth and the collection of both leaves and soil samples were conducted 16 months after planting. The growth of *E. camaldulensis* was evaluated by the measurement of tree height and diameter at breast height (DBH). Tree height was measured using an ultrasonic hypsometer (Vertex), while DBH was measured using a tape that was wrapped around the trees at 1.3 meters height. Leaf sampling was conducted by collecting only mature leaves that were located in the primary branches of the trees. Leaf samples were oven-dried for 24 h at 65 °C, ground finely in a stainless steel sail grinder and sieved to

**Table 2** - Treatment descriptions and total nutrient rates applied in the experiment

| Treatment | Bloco I | | | Treatment | Bloco II | | |
|---|---|---|---|---|---|---|---|
| | N | P | K | | N | P | K |
| | | kg ha$^{-1}$ | | | | kg ha$^{-1}$ | |
| 111 | 0 | 0 | 0 | 114 | 0 | 0 | 200 |
| 122 | 0 | 30 | 50 | 123 | 0 | 30 | 100 |
| 133 | 0 | 60 | 100 | 132 | 0 | 60 | 50 |
| 144 | 0 | 120 | 200 | 141 | 0 | 120 | 0 |
| 212 | 50 | 0 | 50 | 213 | 50 | 0 | 100 |
| 221 | 50 | 30 | 0 | 224 | 50 | 30 | 200 |
| 234 | 50 | 60 | 200 | 231 | 50 | 60 | 0 |
| 243 | 50 | 120 | 100 | 242 | 50 | 120 | 50 |
| 313 | 100 | 0 | 100 | 312 | 100 | 0 | 50 |
| 324 | 100 | 30 | 200 | 321 | 100 | 30 | 0 |
| 331 | 100 | 60 | 0 | 334 | 100 | 60 | 200 |
| 342 | 100 | 120 | 50 | 343 | 100 | 120 | 100 |
| 414 | 200 | 0 | 200 | 411 | 200 | 0 | 0 |
| 423 | 200 | 30 | 100 | 422 | 200 | 30 | 50 |
| 432 | 200 | 60 | 50 | 433 | 200 | 60 | 100 |
| 441 | 200 | 120 | 0 | 444 | 200 | 120 | 200 |

analyse the total contents of N, P, K, Ca, Mg, B, Cu, Fe, Mn, Zn. Analysis methods were as follows: N by the semi-micro Kjeldahl method after wet digestion with $H_2SO_4$ plus catalyser salts; P by the vanadomolybdophosphoric yellow method; K by flame emission spectrometry; and Ca, Mg, B, Cu, Fe, Mn, and Zn by atomic absorption spectrometry after wet digestion with $HNO_3/HClO_4$.

Soil samples were taken from the 0.0-0.2 m depth layer within the tree canopy projection. The chemical attributes determined were pH (1:2.5 water concentration) available P and K (Mehlich-1 extract; determination by the spectrophotometry method for P and flame emission spectrometry for K), Ca and Mg (1.0 M potassium chloride; determination by atomic absorption spectrometry).

Data were tested for significant differences among treatments in a randomised incomplete block. A response function of the type $Y=b_0 + b_1N + b_2N^2 + b_3P + b_4P^2 + b_5K + b_6K^2 + b_7NP + b_8NK + b_9PK$ was calculated using the GLM procedures of the SAS system (SAS 2003). In the response function, Y is the dependent variable, $b_0$ to $b_9$ are the regression coefficients, and N, P, and K are the total rates of nutrients applied in the experiment. Significance of $b_0 \ldots b_9$ coefficient was tested and new response functions were adjusted including only significant effects ($p<0.05$). Dependent variables were (1) tree height, (2) DBH, (3) mineral nutrient status, and (4) soil-chemical attributes. Linear regression analysis was used to estimate correlations between soil-chemical attributes, mineral nutrient status of *E. camaldulensis*, and tree growth.

## Results and discussion

Nutrient rates contributed to improving *E. camaldulensis* growth in the studied soil. It was observed nitrogen and potassium interaction ($p < 0.05$) on plant height (Table 3), and a maximum of 7.8 m was recorded at N = 200 kg $ha^{-1}$ and K = 50 kg $ha^{-1}$ (Figure 1). This positive effect of fertilisers on tree growth appears to be a trend for some species for which fertilisation management has been studied. Specifically, it has been observed for *E. camaldulensis* that, at least in the first year after fertiliser application, trees present strong and significant responses to applied nutrients; however, differences due to treatments began to fade around the third year after planting (GURUMURTHY, 1994). On the other hand, compared to sites without fertilisation, previous studies have shown Eucalyptus responses to fertilisation from the time of plantation establishment through the end of the cycle (FERNANDEZ *et al.*, 2000; STAPE *et al.*, 2010); these results emphasise the importance of nutrient inputs from the time of stand establishment.

In the present study, nitrogen associated with potassium application rates promoted a gain of 4 m height in *E. camaldulensis* (trees reached 7.8 m height 16 months after planting). Some examples of nitrogen versus potassium interaction were discussed by Zhang *et al.,* (2010), emphasizing that yield response to K uptake depends on N nutritional status and the interaction is usually positive when nitrogen is supplied. A previous study showed that Eucalyptus tree height was significantly enhanced by N application in the first 24 months after planting (tree height reached approximately 10 m). However, the authors noted that this response was no longer significant after trees reached the age of 24 months (LACLAU *et al.,* 2008). The same authors found that potassium fertilisation led to an increment in tree height at age 36 months. The improvement of nitrogen availability during the early growth of Eucalyptus trees led to advance in the stage of stand development, but do not change the inherent site productivity. Canopy closure is able to occur earlier in the plots with nitrogen fertilisation and, in this

**Table 3** - Coefficient of response function models for *E. camaldulensis* growth, mineral nutrient status, and soil-chemical attributes

| | Model coefficient† | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $b_0$ | N | $N^2$ | P | $P^2$ | K | $K^2$ | NP | NK | PK | CV(%) | $R^2$ |
| TREE GROWTH PARAMETERS | | | | | | | | | | | | |
| Height | 2.888021 | .021040 | -.000014 | .046748 | -.000290 | .017752 | -.000064 | -.000051 | -.000071* | .000091 | 14.7 | 0.76 |
| DBH | 5.696586 | .044586* | -.000109 | .207208** | -.001263 | .063035** | -.000216 | .000059 | -.000052 | .000046 | 14.4 | 0.87 |
| MINERAL NUTRIENT STATUS | | | | | | | | | | | | |
| N | 13.22275 | .028151 | -.000114 | -.067007 | .000280 | -.016105 | .000053 | .000330** | .000054 | .6430 | 12.2 | 0.73 |
| P | 0.253423 | .000752 | -.000002 | .009102** | -.000048 | -.001531 | .000004 | .000007 | .000001 | .000010 | 14.7 | 0.88 |
| K | 3.676994 | -.012417 | .000055 | -.015652 | .000024 | .068856** | -.00018 | -.000038 | .000013 | .000123 | 15.9 | 0.88 |
| SOIL CHEMICAL ATTRIBUTES | | | | | | | | | | | | |
| P | 0.513833 | .003263 | -.000006 | .000196 | .000257 | .000300 | .000037 | .000107 | -.000038 | -.00017* | 58.23 | 0.64 |
| K | 0.011588 | -.000019 | .0000007 | -.000889 | .000005 | .001015 | -.0000005 | .000002 | -.000001 | -.000005** | 37.71 | 0.86 |

†$Y = b_0 + b_1N + b_2N^2 + b_3P + b_4P^2 + b_5K + b_6K^2 + b_7NP + b_8NK + b_9PK$. *, ** Significant at $\alpha = 0.05$ and 0.01, respectively.

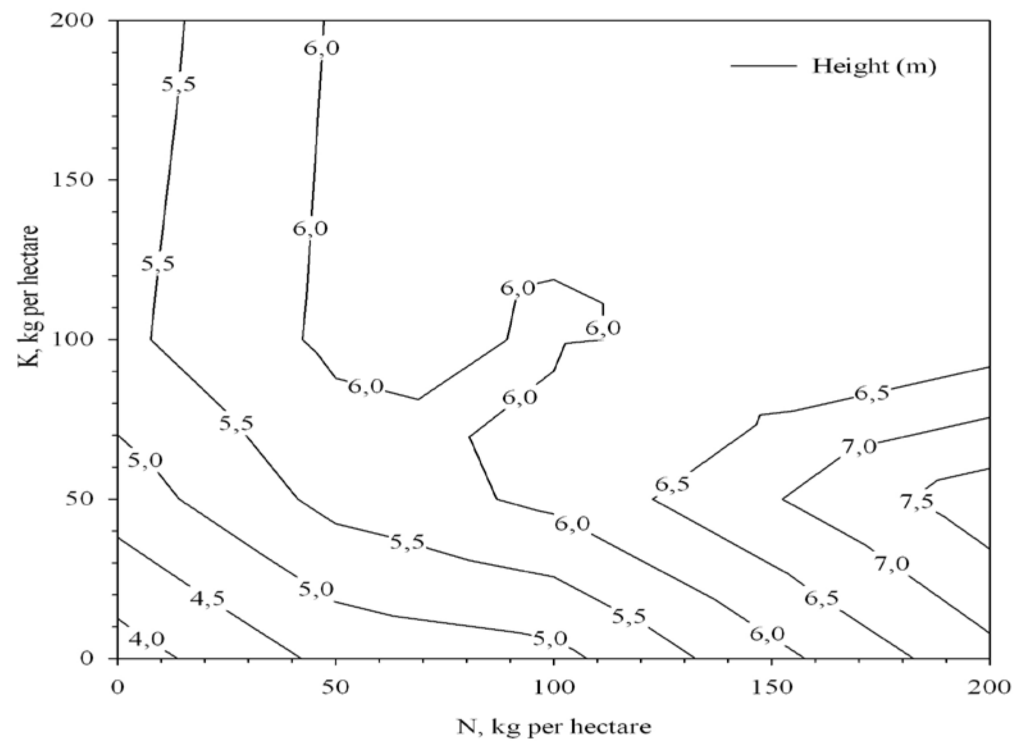


**Figure 1** - Response surface contour plot of *Eucalyptus camaldulensis* height.

situation, soil exposition to erosion agents can be reduced earlier than in the – N treatment.

Regarding the growth parameter DBH, the linear responses ($p < 0.05$) to nitrogen, phosphorus, and potassium indicate that growth would be further increased by even greater additions of nutrients than those tested. ; while height increased from 3.8 to 7,8 m (Figure 1), DBH increased from 3.7 to 5.2 cm (Figure 2a) with nitrogen doses from 0 to 200 kg $ha^{-1}$. The $R^2$ values of the fitted response curves equalled 0.76 and 0.87 for height and DBH, respectively (Table 3 and Figure 1a). Therefore we found that the total gains in growth parameters of E. camaldulensis due to N versus K and N applications were 4 m for height and 1.5 cm for DBH. However, greater additions could not be of interest and, for practical purposes, the greatest single DBH response was at the lowest level of phosphorus fertilisation (30 kg $ha^{-1}$). Phosphorus demand is high in the first year of eucalyptus growth, and this nutrient is recognised as the one that frequently limits forest growth (FERNANDEZ *et al.,* 2000; FISHER; BINKLEY, 2000).

Phosphorus fertilisation promoted greater DBH growth of *E. camaldulensis* trees in comparison with application of N and K. Linear DBH response ($p < 0.01$) was observed for phosphorus application (Table 3), and the $R^2$ value of the fitted curve was 0.62 (Figure 2b). The growth parameter DBH responded to P application with maximum value amounting to 5.6 cm at a P application rate of 120 kg $ha^{-1}$ (Figure 2b) and the DBH increase observed with P application represented a total gain of 3.1 cm in tree diameter.

Positive responses of Eucalyptus trees to P fertilisation are common because plantings are done in soils with low natural P availability (LACLAU *et al.,* 2008). According to Brazilian criteria for interpretation of soil phosphorus content, the natural P available in the studied Latosol was classified as very low (0.2 and 0.1 mg $kg^{-1}$ in soil depths of 0-0.20 and 0.20-0.40 m, respectively), explaining the positive effect of P fertilisation. A previous study showed greater increase in *E. grandis* growth in response to phosphorus than to nitrogen application; this was explained by the changes in dry-mass partitioning, as plants fertilised with phosphorus allocated more carbon to shoot than to root growth (GRACIANO *et al.,* 2005).

The increase in tree growth parameters was more evident for N versus K and for P application rates, but potassium application also enhanced DBH by 1.4 cm. The greatest single DBH response within potassium rates was at the lowest level (50 kg $ha^{-1}$). Laclau *et al.,* (2008) observed a large response of Eucalyptus to K fertilisation, with potassium addition leading to a height increase of 3.7 m at age 36 months. While some authors

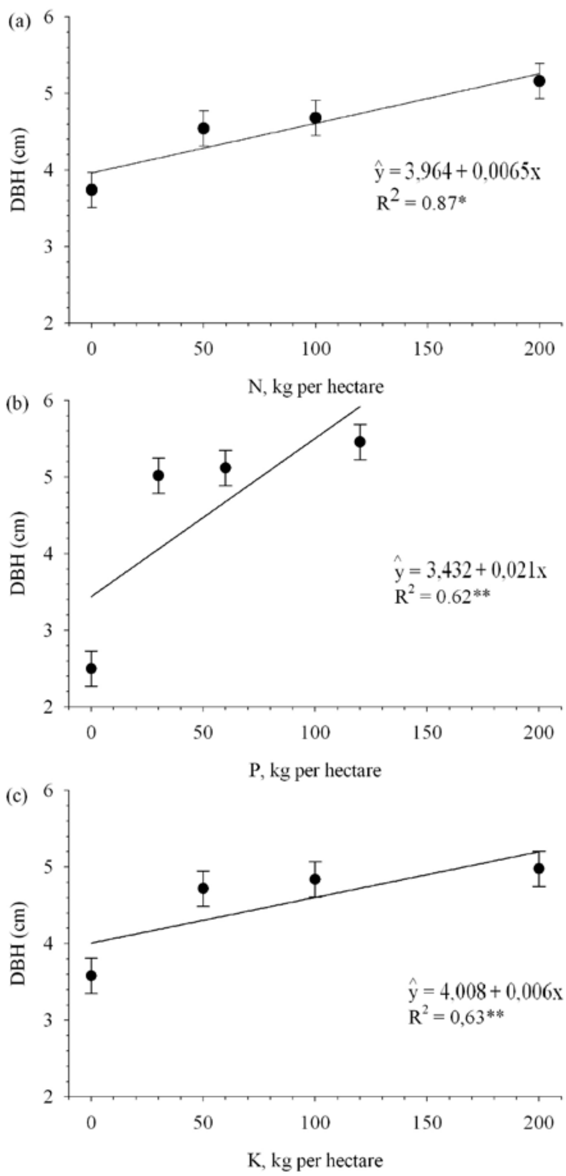


**Figure 2** - *Eucalyptus camaldulensis* DBH responses to (a) nitrogen (N), (b) phosphorus (P), and (c) potassium (K) application rates. *, ** Significant at $\alpha = 0.05$ and 0.01, respectively.

have showed a lack of response of Eucalyptus trees to potassium application (BOUILLET *et al.,* 2004), others have affirmed that K fertilisation significantly increased tree growth in height and basal area over the first 4 years (ALMEIDA *et al.,* 2010). A response of Eucalyptus trees to K application is common in Brazil (GONÇALVES *et al.,* 2008), and it is likely related to the low amount of exchangeable K present in highly weathered soils due to a lack of primary minerals bearing K and the losses of this ion due to leaching.

A significant response for N concentration in leaves was observed only for nitrogen versus phosphorus rates application, which increased N concentration from 10.08 to 20.62 g $kg^{-1}$ (Figure 3). This observation indicates the important role of phosphorus for nitrogen uptake, and consequently for trees growth, of *E. camaldulensis*. Other studies have shown both Eucalyptus growth and mineral nutrient responses to N application dependent of soil P availability (GRACIANO *et al.,* 2005). Graciano *et al.* (2006) suggested that fertilisation with P increases N uptake by enhanced growth through a mechanism unrelated to increased N demand. The nitrogen status in *E. camaldulensis* leaves (10.08 to 20.62 g $kg^{-1}$) was similar to the average concentration of 15 g $kg^{-1}$ reported in other research for different Eucalyptus species of comparable age (MISRA *et al*., 1998). This was also similar to the average value of 14 g $kg^{-1}$ related in another study in which N contents in *E. camaldulensis* leaves were evaluated 36 months after planting (HUNTER, 2001). The nitrogen application rates of 50 and 100 kg $ha^{-1}$ resulted in N levels (14.4 and 16.0 g $kg^{-1}$, respectively) that were assumed to be adequate for Eucalyptus under conditions in Brazil (MALAVOLTA *et al*., 1997).

A linear response to foliar P ($R^2$=0.87) was observed for P fertilisation with maximum values amounting to 1.0 g $kg^{-1}$ of P at a P application rate of 120 kg $ha^{-1}$ (Figure 4). The increase in P concentration of *E. camaldulensis* leaves (0.4 to 1.0 g $kg^{-1}$) indicated that the highest evaluated phosphorus application rate (120 kg $ha^{-1}$) promoted nutrient concentrations close to the lower end of the range (1.0 to 1.2 g $kg^{-1}$) that is assumed to be adequate for Eucalyptus under conditions in Brazil (MALAVOLTA *et al.,* 1997). The highest P application rate in the studied Latosol also promoted nutrient concentrations in *E. camaldulensis* leaves that were close to concentrations found for the same species in a deep lateritic soil in India (GURUMURTHY, 1994; HUNTER, 2001). The P increase in Eucalyptus leaves due to fertilisation with phosphorus has been reported by other researchers (GRACIANO *et al.,* 2006).

In this study, fertilisation increased K in leaves from 4.3 to 12.0 g $kg^{-1}$ (Figure 5). The highest potassium application rate (200 kg $ha^{-1}$) resulted in nutrient concentrations close to the upper end of the range (10 to 12 g $kg^{-1}$) that is assumed to be adequate for Eucalyptus under conditions in Brazil (MALAVOLTA *et al.,* 1997). However, potassium concentrations in leaves of Eucalyptus growing in plots with a zero potassium application rate were close to the average obtained for *E. saligna* 38 months after planting in response to potassium fertilisation (4.4 g $kg^{-1}$). Studies have showed that leaf K concentration is lower in the –K treatments than in +K treatments even in earlier growth (LACLAU *et al.,* 2008).

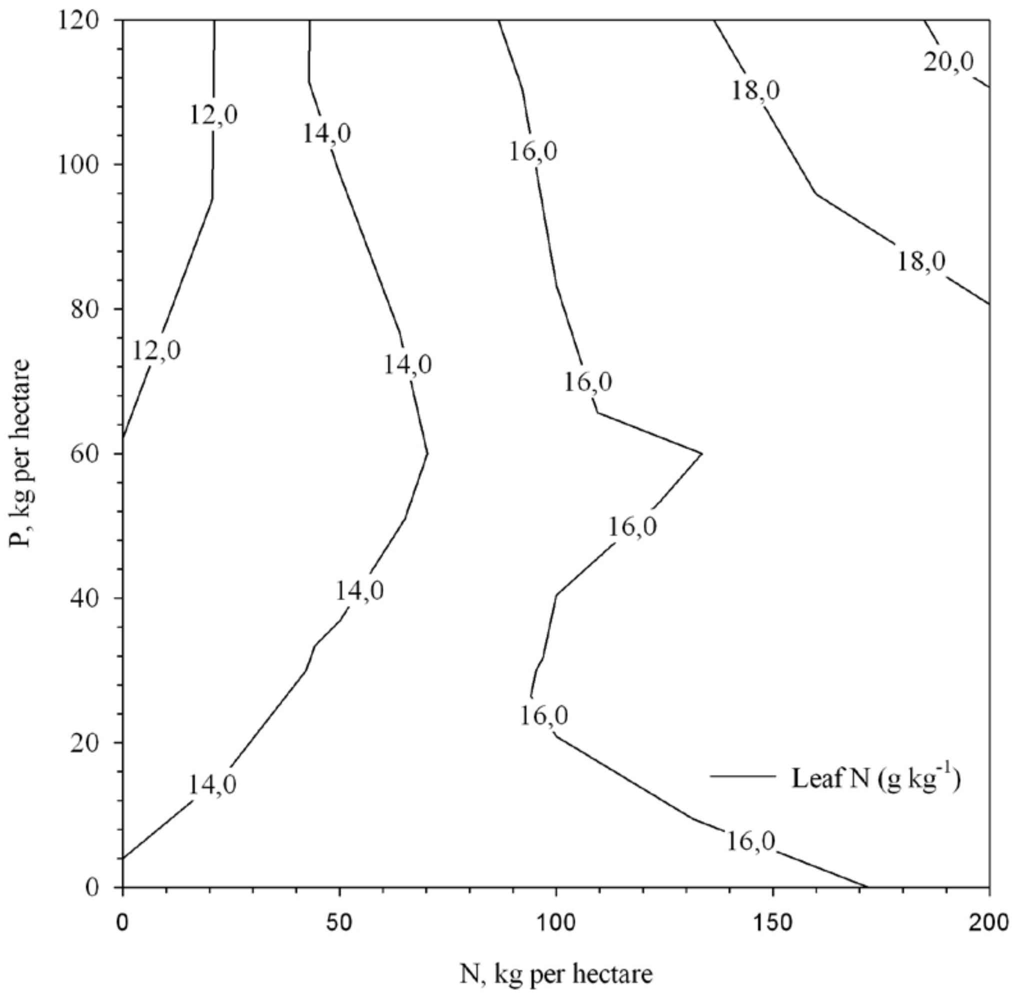


**Figure 3** - Response surface contour plot of leaf N in *Eucalyptus camaldulensis* trees.

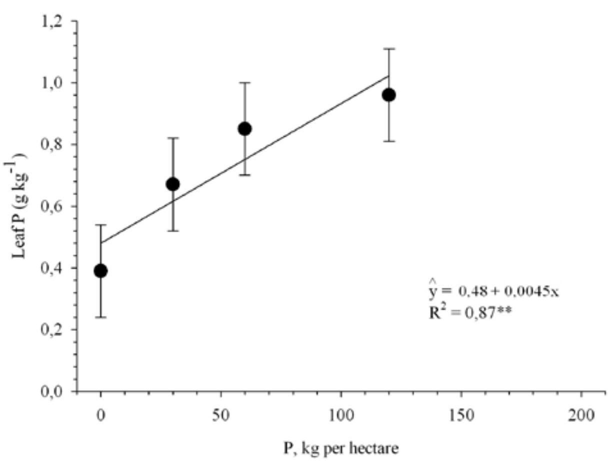


**Figure 4** - Leaf phosphorus (P) responses to phosphorus application rates. *, ** Significant at $\alpha$ = 0.05 and 0.01, respectively.

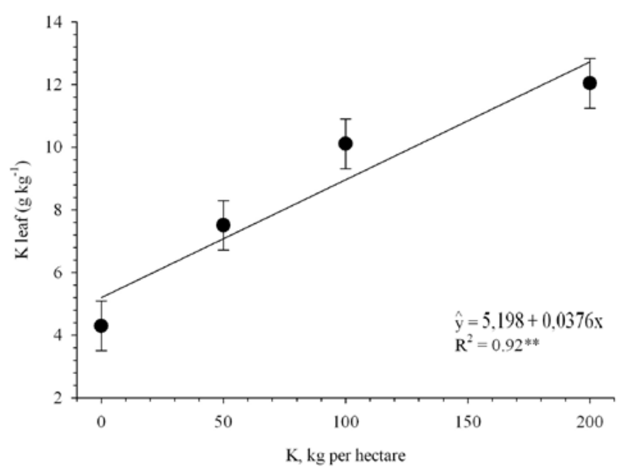


**Figure 5** - Leaf potassium (K) responses to potassium application rates. *, ** Significant at $\alpha$ = 0.05 and 0.01, respectively.

Regarding the improvement of soil-chemical attributes as a result of NPK fertilisation, significance was observed for soil P availability ($P < 0.05$) with phosphorus versus potassium application. A maximum of 6.7 mg $kg^{-1}$ of P was recorded at P=120 kg $ha^{-1}$ and K=0 kg $ha^{-1}$ (Figure 6a). The interaction phosphorus versus potassium also was observed to soil K content ($P < 0.01$). The $R^2$ value of the fitted response curve amounted to 0.86 (Table 3), with the maximum K content in soil (0.18 $cmol_c$ $kg^{-1}$) occurring at a K application rate of 200 kg $ha^{-1}$ and at a P application rate of 0 kg $ha^{-1}$ (Figure 6b). Potassium content observed in the soil samples collected two years after fertiliser application (Figure 6b) were 2 to 12 times higher than that observed in the samples analysed for soil characterisation (Table 1).

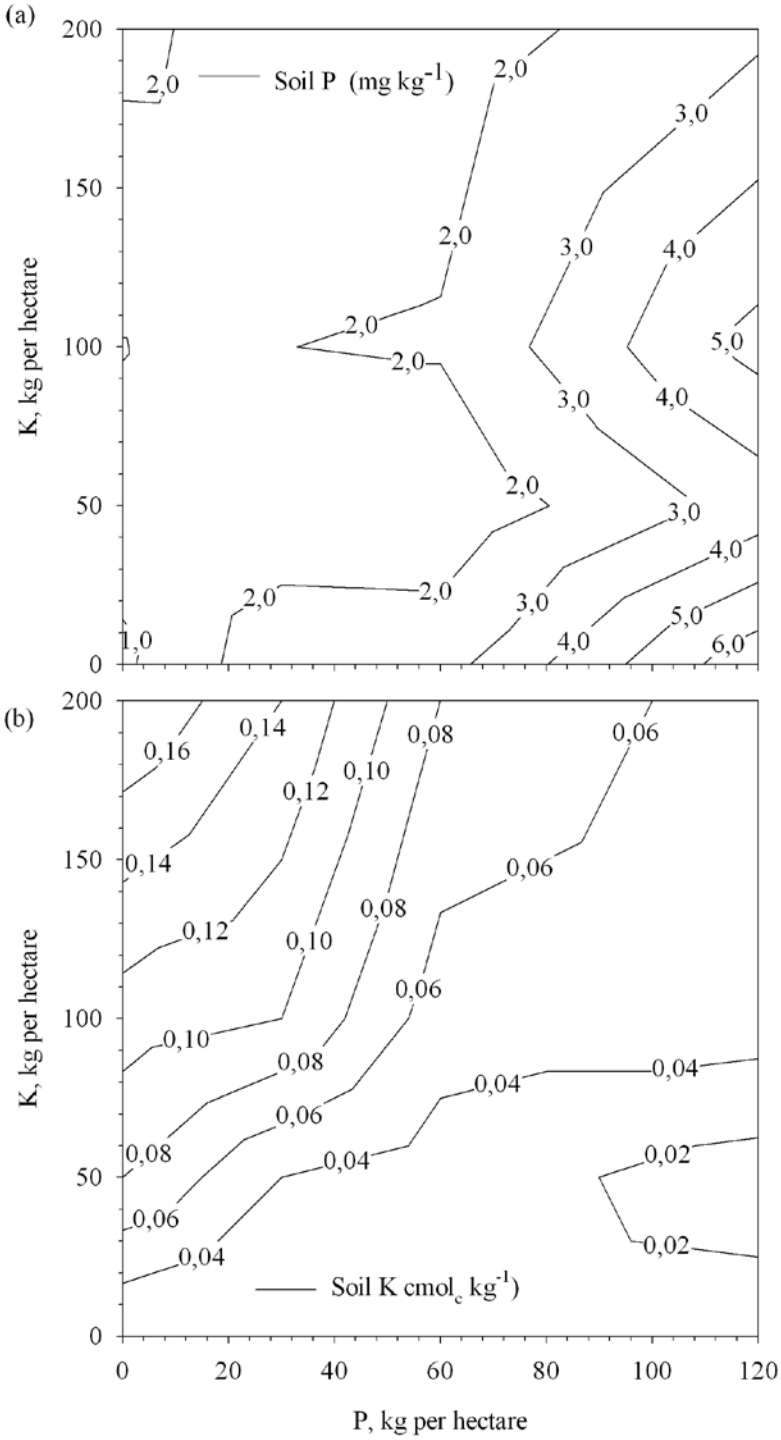


**Figure 6** - Response surface contour plot of (a) soil phosphorus (P) and (b) soil potassium (K).

The study observed that even after P fertilisation, soil phosphorus content was within the range assumed to be “very low” (0 to 5 mg $dm^{-3}$) by the criteria for interpretation of phosphorus in Brazilian savannah soils (SOUSA; LOBATO, 2004). In this situation, the P application rate recommended for Eucalyptus by Andrade (2004) is around 100 kg $ha^{-1}$ of $P_2O_5$, which is close to the highest P rate evaluated in this study. Based on its linear response, the maximum *E. camaldulensis* DBH growth was obtained with an application rate of 120 kg $ha^{-1}$ of P; however, as already mentioned in this paper, the greatest single growth response (DBH) in the present research was at 30 kg $ha^{-1}$ of P.

Phosphorus versus potassium interaction ($p < 0.05$) was observed to soil P content, contributing to increase potassium content in the very weathered and leached savannah Latosol. Analysis of samples collected for soil characterisation, and in the plots with zero potassium, revealed low K exchangeable content according to criteria described by Vilela *et al.,* (2004) for Brazilian savannah soils. Following these same criteria, potassium application rates of 50, 100, and 200 kg $ha^{-1}$ shifted exchangeable soil potassium to the interpretation classes of medium, adequate, and high, respectively. Therefore, potassium application rates improved K content in soil, and consequently, in the leaf tissue of *E. camaldulensis*. The response to potassium fertilisation seems to led to long-term change in site properties (LACLAU *et al*., 2008). However, it is important to take in account the low Latosol CEC (less than 4 $cmol_c$ $kg^{-1}$), which is a characteristic very representative of savannah soils in the northern Brazilian Amazon. According to Wild (1971), exchangeable K is low in savannah soils; however, quantity-intensity (Q/I) measurements to assess $K^+$ availability indicated relatively high intensity. On the other hand, the quantity factor, determined as exchangeable $K^+$ (ammonium acetate extractable K) or determined by linear extrapolation of the Q/I relationship, is low.

This characteristic also explains the satisfactory potassium content in *E. camaldulensis* leaves even when fertiliser was not applied. On the other hand, intense pluvial events in the northern Brazilian Amazon might facilitate potassium leaching in forest systems in which plant growth and nutrient uptake are not as rapid as they are in annual crop systems. In this sense, split potassium fertiliser application may be an important tool to avoid nutrient losses.

# Conclusions

The initial growth of *E. camaldulensis* plantation on savannah Latosols (Oxisol) of northern Brazilian Amazon can be increase by addition of the following rates 200 kg N $ha^{-1}$, 30 kg P $ha^{-1}$, and 50 kg K $ha^{-1}$. Interpretation of leaf nutrient concentrations shows adequate levels for the highest rates of N, P, and K. The improvement of phosphorus and potassium availability in savannah Latosol is promoted by the highest rates of phosphorus and potassium.

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