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Original Article

Silviculture

# Benchmark: Biomass Production in Eucalyptus Plantations as a Consequence of Fertilization

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## ABSTRACT

The objective of this work was to evaluate the effects of fertilization, spatial arrangement and age on the biomass production in eucalyptus. The experiment was set up in a randomized block design with four replicates. Overall, 15 fertilizations adopted by forest companies in plots were evaluated, and two arrangements, 3.0 x 3.0 m and 6.0 x 1.5 m, were tested in subplots. Diameter at 1.30 m and total height were measured at 12, 24, 36, 48 and 60 months after planting to estimate trunk biomass. Dependence between commercial fertilization and arrangement were observed for trunk biomass. The biomass production rate in treatments where higher amounts of nutrients were applied decreased from the second year. The 3.0 x 3.0 m arrangement proved to be the most attractive option at 60 months using treatment with 2000 kg of agrosilicon, 400 kg of reactive phosphate, 130 kg of 04:26:16 + 0.5% Cu + 0.5% Zn and 150 kg of KCl + 1% B.

**Keywords:** space arrangement, forest fertilization, forestry.

# 1. INTRODUCTION

Rapid technological development and increasing changes in market profiles compel organizations to constantly seek out and develop new solutions in order to know their position and to not stop pursuing excellence (Macedo-Soares & Ratton, 1999). In the context in which forestry companies are inserted, the concern with maintaining or increasing the quality of silvicultural processes is fundamental. Thus, well-structured information base is required to assist decision-making. For this, it is important to develop processes for performance measurement that, according to Macedo-Soares & Ratton (1999), should be aligned with the organization's strategic objectives. The benchmark process, as a tool for performance measurement, is an instrument that can contribute to improve the performance of the productive chain.

The main eucalyptus producing companies for bioenergy and pulp in the state of Minas Gerais adopt similar silvicultural technologies from planting to harvesting, such as integrated pest management, soil tillage, competing vegetation control and harvesting. Fertilization of stands is the main silvicultural practice that differs among companies. Companies generally have an experimental network that is evaluated over several years and used to calibrate fertilization recommendations specific to the edaphoclimatic conditions of stands. The nutritional management of eucalyptus stands in Brazil has provided significant gains and has ensured the sustainability of forest sites (Gonçalves et al., 2008; Stape et al., 2010).

Different fertilization recommendations under similar soil and climatic conditions are not uncommon, although productivity gains are not always obtained where higher amounts of nutrients are applied (Stape et al., 2008, 2010). The response magnitude when applying fertilizers varies according to the type and time of soil preparation, competition with undesirable plants, history of area use, fertilizer and corrective doses, spatial arrangement, water availability and soil and climatic conditions (Smethurst et al., 2003; Whitehead & Beadle, 2004; Santana et al., 2008; Tarouco et al., 2009; Stape et al., 2010; Silva et al., 2013; Pulito et al., 2015).

In terms of forestry, one of the main decision making elements is the analysis of the optimal spatial arrangement through growth studies of individuals under different space conditions. This will not only influence the individual growth of plants, but also the final production by area (Magalhães et al., 2006). The choice of spacing arrangement gives each tree enough space to achieve maximum growth with better quality and lower cost (Magalhães et al., 2006; Martins et al., 2009). The production of wood, cellulosic pulp or raw material for bioenergy production can be maximized with different planting arrangements, since final products have different specificities that can be influenced by the type of forest management adopted.

This work is aligned with recent efforts and initiatives of forestry companies to develop more effective systems. In the specific case of this study, it is based on evaluating the effect of commercial fertilizations used by companies operating in the state of Minas Gerais on eucalyptus production in order to not only provide support, but also decisively contribute to the effective implementation and consolidation of organizational improvement strategies.

Given the importance of nutrition in the wood production process, the aim of this work was to use the benchmark to evaluate the effects of fertilization, spacing arrangement and age on the production of eucalyptus trunk biomass.

# 2. MATERIAL AND METHODS

This study was developed in an area belonging to the Gerdau group, in the municipality of Três Marias - MG (latitude 18º15'37" south and longitude 45º04'57" west). The predominant climate in the region is Aw according to the Köppen classification (hot and rainy summers and mild and dry winters), with average annual temperature of 23ºC, mean annual rainfall of 1,242 mm (Meneses et al., 2015) and in a homogeneous area characterized by alic and dystrophic Red-Yellow Latosol (Table 1).

In order to carry out the benchmark, commercial fertilization was operationally adopted by 15 large forest companies located in the state of Minas Gerais, which use wood for the production of charcoal or cellulose. A randomized block design implementing a strip scheme was adopted, with dimensions of 36 x 84 m. Four blocks were installed using plot treatments of the 15 operational fertilizations (Table 2), and two spacing arrangements (3.0 x 3.0 m and 6.0 x 1.5 m) were tested in subplots (36 x 42) using GG100 clone (*E. urophylla* × *E. grandis*). Ant control was carried out

**Table 1.** Chemical and physical characterization of the soil of the study area.

| depth (cm) | pH | P | K | Ca | Mg | Al | H+Al | O.M. | Sa | S | C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $mg.dm^{-3}$ | | $cmolc.dm^{-3}$ | | | | $dag.kg^{-1}$ | | | |
| 0-20 | 4.7 | 0.87 | 16.2 | 0.18 | 0.09 | 0.50 | 3.30 | 1.5 | 78 | 10 | 12 |
| 20-40 | 4.6 | 0.53 | 11.2 | 0.09 | 0.05 | 0.47 | 3.14 | 1.2 | 80 | 4 | 16 |

O.M.: Organic Matter; Sa: Sand; S: Silt; C: Clay. Extractors: M.O.: Oxi-Red.; pH in water – Relationship 1:2.5; P, K: Mehlich I; Al, Ca, Mg: KCl; H+Al: Buffered SMP

**Table 2.** Commercial fertilization by treatment, application time (TA) and amount of products used.

| Treatment | Product (TA - $kg.ha^{-1}$) |
|---|---|
| 1 | Agrosilicon (TA1 - 2000); Reative Phosphate (TA2 - 400); 04:26:16+0.5%Cu+0.5%Zn (TA3 - 130); KCl+1%B (TA4 - 150) |
| 2 | Limestone Agrimag (TA1 - 1500); Plaster (TA1 - 1500); Simple Superphosphate +0.5%B+0.5%Cu+0.5%Zn (TA2 - 300); 06:30:06+0.5%B+0.5%Zn (TA3 - 150); 20:05:20 (TA4 - 150); 20:05:20 (TA5 - 150); Boron (liquid form) (TA6 - 2) |
| 3 | Limestone Agrimag (TA1 - 1500); Reative Phosphate (TA2 - 300); 06:30:12 (TA3 - 175); 08:00:32+0.7%B (TA4 - 130); KCl (TA5 - 150) |
| 4 | Agrosilicon (TA1 - 1500); Reative Phosphate (TA2 - 400); 06:30:06+0.5%B+0.5%Zn+0.5%Cu (TA3 - 110); KCl+1.2%B+1%Zn+0.5%Cu (TA4 - 150); KCl+1.2%B+1%Zn+0.5%Cu (TA5 - 150); Borax (TA6 - 25) |
| 5 | Limestone Rima (TA1 - 1000); Reative Phosphate (TA2 - 450); 06:30:06+0.5%B+0.5%Zn (TA3 - 100); KCl+1%B (TA4 - 150); KCl+1%B (TA5 - 150) |
| 6 | Limestone Rima (TA1 - 1000); Basifós (TA2 - 300); KCl+1%B (TA4 - 150); KCl+1%B (TA5 - 150) |
| 7 | Limestone Rima (TA1 - 1000); Phosphate of the Araxá (TA2 - 650); 06:30:06+0.5%B+0.5%Zn (TA3 - 100); KCl+1%B (TA4 - 150); KCl+1%B (TA5 - 150) |
| 8 | Limestone Rima (TA1 - 1000); 03:19/30:01+0.3%B+0.25%Zn+0.25%Cu+6.6%S (TA2 - 300); KCl+1%B (TA4 - 150); KCl+1%B (TA5 - 150) |
| 9 | Pre-lime (TA1 - 1000); 03:19/30:00+0.3%B+0.25%Zn+0.25%Cu+6.6%S+1%Mg (TA2 - 300); 00:00:38+16%Mg+0.7%B (TA4 - 230); 00:00:38+16%Mg+0.7%B (TA5 - 230) |
| 10 | Pre-lime (TA1 - 420); Balloon powder (TA1 - 20000); 06:30:06+0.5%B+0.5%Zn (TA3 - 100); KCl+1%B (TA4 - 175); Copper and Borogran (TA6 - 8 e 24) |
| 11 | Limestone Agrimag (TA1 - 2000); 04:18/30:04+0.2%Zn+0.25%B+0.2%Cu (TA2 - 390); 15:00:30 (TA4 - 170); KCl+1%B (TA5 - 220) |
| 12 | Limestone Agrimag (TA1 - 500); Reative Phosphate (TA2 - 400); 06:30:06+1%B+1%Zn+1%Cu (TA3 - 140); KCl (TA4 - 150); KCl (TA5 - 150); Borogran (TA6 - 20) |
| 13 | Limestone Rima (TA1 - 1500); Triple Superphosphate (TA2 - 170); 04:28:10 (TA3 - 100); 15:00:15+0.5%B (TA4 - 120); Borogran (TA6 - 25) |
| 14 | Limestone Agrimag (TA1 - 2000); Plaster (TA1 - 500); Simple Superphosphate (TA2 - 300); 6:30:06+0.2%B+1%Zn+1%Cu (TA3 - 150); 20:05:20 (TA4 - 120); 18:00:18 (TA5 - 350); 15:00:30 (TA6 - 400) |
| 15 | Limestone Agrimag (TA1 - 1500); Reative Phosphate (TA2 - 610); 10:28:06+1%B (TA3 - 150); 20:00:20+2%B (TA4 - 150); Borogran (TA6 - 30) |

Application times (TA) were the following: TA1: 15 days before planting, in a 1 m strip on the planting line, without incorporation; TA2: 7 days before planting applied with subsoiler 40 cm deep; TA3: planting, side furrows 20 cm from the plant and 10 cm deep; TA4: 120 days after planting in cup projection, without incorporation; TA5: 480 days after planting in cup projection, without incorporation; and TA6: 840 days after planting in cup projection, without incorporation.

using granulated formicide bait following a systematic method throughout the area and specifically located whenever necessary. Control of competing vegetation was carried out with herbicide before installing the experiment and whenever necessary after planting.

In each experimental unit, diameter was measured at 1.30 m of soil height (*Dap,* cm), the total height (*Ht,* m) and trunk biomass was estimated ($B_{trunk}$, $Mg.tree^{-1}$) for 80 central plants at 12, 24, 36, 48 and 60 months, using the clone-specific Equation 1.

$$Biomass_{trunk} = 0.000002 * Dap^{1.994157} * Ht^{1.692833}, with r = 0.98 \quad (1)$$

Data were submitted to analysis of variance by the F test, and means were compared by the Scott-Knott's test at 5% using the Sisvar statistical software (Ferreira, 2011).

In order to evaluate the relative performance of treatments, operational fertilizations of all treatments were converted into amounts of nutrients applied per treatment, regardless of time of application. The amounts applied per nutrient were subsequently and empirically grouped into five categories: *very high, high, intermediate, low and not applied*. Each category was characterized by a distinct symbol. Fertilizations of each treatment have been operationally used by large companies and were calibrated by field experiments over the years. Therefore, the denomination of adopted categories does not mean that there was a nutrient limitation or excess for biomass production. Ranks were created to allow a comparison of the performance in relation to the fertilization used.

## 3. RESULTS

The growth in trunk biomass varied according the commercial fertilizations adopted in all evaluated months, and only at 48 months among arrangements (P≤0.05) (Table 3). A significant effect for the interaction of commercial fertilization x arrangement (P≤0.05) was verified at 12, 24, 36, 48 and 60 months (Table 3), evidencing that fertilization and arrangement factors are dependent on trunk biomass production, which means that the behavior of the fertilization adopted depends on the arrangement variation. At 60 months in arrangements of 3.0 x 3.0 m and 6.0 x 1.5 m, trunk biomass production presented average values of 82.2 and 81.7 $Mg.ha^{-1}$, respectively.

Arrangements 3.0 x 3.0 m and 6.0 x 1.5 m provided different biomass values among treatments at all ages measured; thus, trunk biomass changed as a function of treatment. Experiments of commercial fertilization x arrangement for trunk biomass resulted in significant effect on arrangements (3.0 x 3.0 m and 6.0 x 1.5 m) at 12, 24, 36, 48 and 60 months, within treatments (P≤0.05) (Table 4).

T14 in the 6.0 x 1.5 m arrangement had the highest trunk biomass (3.4 $Mg.ha^{-1}$) at 12 months. T1 (3.0 x 3.0 m) provided the largest trunk biomass with 22.4; 53.3; 84.4 and 104.6 $Mg.ha^{-1}$, respectively, at 24, 36, 48 and 60 months. Treatments with the lowest mean biomass value for these ages were 7, 15, 13, 10 and 13, respectively, with averages of 1.5; 14.7; 34.8; 52.9 and 72.2 $Mg.ha^{-1}$, in arrangements of 6.0 x 1.5 m; 3.0 x 3.0 m; 6.0 x 1.5 m; 3.0 x 3.0 m and 3.0 x 3.0 m.

In general, it was observed that arrangement in the square format (3.0 x 3.0 m) stood out in relation to the rectangular format (6.0 x 1.5 m) when evaluating trunk biomass production over time.

When considering trunk biomass production at 60 months, T1 was approximately 1.45 times higher than T13 (the least productive) for the same arrangement. The second (T14) most productive biomass was approximately 14% lower than T1 in the same arrangement (3.0 x 3.0 m). In treatment with the highest amount of nutrients (T14), biomass production in the 3.0 x 3.0 m and 6.0 x 1.5 m treatments was 90.3 $Mg.ha^{-1}$ for both, being the second and third in trunk production, respectively. As can be seen, the effect of fertilization becomes less pronounced in relation to trunk production as forest development occurs.

For N, Mg, S and Zn, the corresponding *less* symbol scale predominates for most treatments (Table 5). It is also observed that most companies use amounts

**Table 3.** Summary of the analysis of variance for variable trunk biomass ($Mg.ha^{-1}$) at 12, 24, 36, 48 and 60 months.

| Source of variation | DF | Middle Square | | | | |
|---|---|---|---|---|---|---|
| | | 12 | 24 | 36 | 48 | 60 |
| Blocks | 3 | $0.03^{ns}$ | $0.52^{ns}$ | $4.28^{ns}$ | $13.36^{ns}$ | $36.05^{ns}$ |
| Treatment | 14 | 1.14* | 24.39* | 119.40* | 314.03* | 501.79* |
| Error 1 | 42 | 0.02 | 0.69 | 3.77 | 9.51 | 16.90 |
| Spacing | 1 | $0.26^{ns}$ | $3.69^{ns}$ | $22.38^{ns}$ | 174.82* | $9.98^{ns}$ |
| Error 2 | 3 | 0.11 | 2.52 | 3.73 | 7.65 | 7.94 |
| Treatment x Spacing | 14 | 0.26* | 3.84* | 14.73* | 88.12* | 30.62* |
| Error 3 | 42 | 0.03 | 0.82 | 3.95 | 8.48 | 15.22 |
| Total | 119 | | | | | |
| CV | | 19.03 | 10.71 | 10.63 | 11.68 | 10.58 |

DF = degrees of freedom; $^{ns}$ = not significant; * = significant at 5% and CV = experimental variation coefficient (%).

**Table 4.** Trunk biomass ($Mg.ha^{-1}$) in two spatial arrangements at 12, 24, 36, 48 and 60 months, by treatment (T).

| T | 12 months | | 24 months | | 36 months | |
|---|---|---|---|---|---|---|
| | 3.0 x 3.0 m | 6.0 x 1.5 m | 3.0 x 3.0 m | 6.0 x 1.5 m | 3.0 x 3.0 m | 6.0 x 1.5 m |
| 1 | 2.4 c A | 2.2 c A | 22.4 a A | 20.8 a A | 53.3 a A | 45.9 a B |
| 2 | 2.1 d A | 2.5 b A | 21.3 a A | 21.0 a A | 46.9 b A | 46.0 a A |
| 3 | 3.0 b A | 2.4 b A | 20.5 b A | 18.3 c A | 45.2 b A | 41.2 b B |
| 4 | 2.5 c A | 2.2 c A | 19.9 b A | 18.8 b A | 45.1 b A | 42.5 b A |
| 5 | 1.7 e A | 1.8 d A | 16.8 c A | 17.1 d A | 40.7 c A | 39.1 c A |
| 6 | 2.2 d A | 2.4 b A | 18.0 c A | 19.8 a A | 40.7 c A | 40.2 c A |
| 7 | 1.8 e A | 1.5 e A | 17.1 c A | 16.4 d A | 35.9 d A | 37.4 c A |
| 8 | 1.9 e A | 2.5 b A | 17.7 c A | 20.3 a A | 37.7 d B | 41.4 b A |
| 9 | 1.9 e A | 2.6 b A | 19.4 b A | 20.6 a A | 43.0 b A | 43.3 b A |
| 10 | 2.1 e A | 2.0 c A | 17.3 c A | 18.0 c A | 40.3 c A | 38.5 c A |
| 11 | 2.0 e A | 2.4 b A | 17.1 c A | 18.1 c A | 40.0 c A | 38.2 c A |
| 12 | 2.3 d A | 2.4 b A | 17.9 c A | 19.1 b A | 37.7 d A | 37.6 c A |
| 13 | 2.3 d A | 2.2 c A | 16.1 d A | 16.2 d A | 36.4 d A | 34.8 c A |
| 14 | 3.3 a A | 3.4 a A | 20.3 b A | 20.0 a A | 41.4 c A | 42.4 b A |
| 15 | 2.1 d A | 2.5 b A | 14.7 e A | 16.9 d A | 35.4 d A | 38.1 c A |

| T | 48 months | | 60 months | |
|---|---|---|---|---|
| | 3.0 x 3.0 m | 6.0 x 1.5 m | 3.0 x 3.0 m | 6.0 x 1.5 m |
| 1 | 84.4 a A | 69.7 a B | 104.6 a A | 97.4 a B |
| 2 | 75.9 b A | 70.9 a B | 87.2 b B | 93.6 a A |
| 3 | 73.4 c A | 64.2 b B | 85.2 c A | 85.6 b A |
| 4 | 71.8 c A | 64.7 b B | 89.5 b A | 84.0 c A |
| 5 | 69.7 d A | 58.8 c B | 79.9 d A | 78.1 d A |
| 6 | 67.4 d A | 63.0 b B | 86.9 c A | 82.9 c A |
| 7 | 67.2 d A | 59.7 c B | 76.8 d A | 78.8 d A |
| 8 | 53.9 f B | 59.9 c A | 75.9 d A | 81.2 c A |
| 9 | 60.7 e A | 63.8 b A | 85.2 c A | 80.8 c A |
| 10 | 52.9 f B | 58.1 c A | 73.6 d A | 74.2 d A |
| 11 | 62.4 e A | 59.9 c A | 80.3 c A | 76.0 d A |
| 12 | 54.7 f A | 57.9 c A | 73.5 d A | 74.9 d A |
| 13 | 58.3 e A | 59.3 c A | 72.2 d A | 73.5 d A |
| 14 | 66.8 d A | 66.8 b A | 90.3 a A | 90.3 b A |
| 15 | 56.3 f B | 62.9 b A | 72.6 d A | 74.4 d A |

Same lowercase letters in each column indicate equality between means estimated for each treatment, within each age assessed, by the Scott Knott test (P> 0.05). Same capital letters in each row indicate equality between the means estimated for each arrangement within each age evaluated by the Scott Knott test (P> 0.05).

**Table 5.** Total amount of nutrients applied per treatment (T) empirically grouped by similar symbols in the column, depending on the amount of fertilizer applied.

| T | N | P | K | Ca | Mg | S | B | Cu | Zn |
|---|---|---|---|---|---|---|---|---|---|
| | $kg.ha^{-1}$ | | | | | | | | |
| T1 | $5.2^{\circ}$ | $34.1^{+}$ | $87.7^{+}$ | $703.3^{*}$ | $144.7^{*}$ | $6.7^{\circ}$ | $1.5^{\circ}$ | $0.7^{+}$ | $0.7^{\circ}$ |
| T2 | $69.0^{\#}$ | $44.0^{\#}$ | $57.3^{\circ}$ | $643.2^{*}$ | $126.7^{\#}$ | $223.1^{*}$ | $4.3^{\#}$ | $1.5^{\#}$ | $2.3^{+}$ |
| T3 | $20.9^{+}$ | $34.7^{+}$ | $126.7^{+}$ | $463.1^{+}$ | $126.7^{\#}$ | $3.2^{\circ}$ | $0.9^{\circ}$ | $0.0^{-}$ | $0.0^{-}$ |
| T4 | $6.6^{\circ}$ | $32.9^{+}$ | $116.9^{+}$ | $553.2^{\#}$ | $108.6^{+}$ | $6.1^{\circ}$ | $6.9^{*}$ | $2.1^{*}$ | $3.6^{\#}$ |
| T5 | $6.0^{\circ}$ | $30.8^{\circ}$ | $139.5^{\#}$ | $473.1^{+}$ | $54.3^{\circ}$ | $4.8^{\circ}$ | $3.5^{+}$ | $0.0^{-}$ | $0.5^{\circ}$ |
| T6 | $9.0^{\circ}$ | $23.6^{\circ}$ | $144.4^{\#}$ | $405.3^{\circ}$ | $54.3^{\circ}$ | $3.0^{\circ}$ | $3.9^{\#}$ | $0.6^{+}$ | $0.6^{\circ}$ |
| T7 | $6.0^{\circ}$ | $35.8^{+}$ | $139.5^{\#}$ | $524.6^{\#}$ | $54.3^{\circ}$ | $0.0^{-}$ | $3.5^{+}$ | $0.0^{-}$ | $0.5^{\circ}$ |
| T8 | $9.0^{\circ}$ | $64.2^{*}$ | $137.0^{\#}$ | $386.6^{\circ}$ | $55.6^{\circ}$ | $19.8^{+}$ | $3.9^{\#}$ | $0.8^{+}$ | $0.8^{\circ}$ |
| T9 | $9.0^{\circ}$ | $64.2^{*}$ | $145.1^{\#}$ | $458.0^{+}$ | $44.4^{\circ}$ | $19.8^{+}$ | $4.1^{\#}$ | $0.8^{+}$ | $0.8^{\circ}$ |
| T10 | $6.0^{\circ}$ | $34.0^{+}$ | $169.8^{*}$ | $393.1^{\circ}$ | $126.4^{\#}$ | $240^{*}$ | $4.7^{\#}$ | $0.8^{+}$ | $18.5^{*}$ |
| T11 | $41.1^{\#}$ | $81.7^{*}$ | $153.9^{*}$ | $514.6^{\#}$ | $168.9^{*}$ | $0.0^{-}$ | $3.2^{+}$ | $0.8^{+}$ | $0.8^{\circ}$ |
| T12 | $8.4^{\circ}$ | $34.0^{+}$ | $156.4^{*}$ | $231.6^{\circ}$ | $42.2^{\circ}$ | $4.2^{\circ}$ | $3.4^{+}$ | $1.4^{\#}$ | $1.4^{+}$ |
| T13 | $22.0^{+}$ | $39.7^{\#}$ | $23.2^{\circ}$ | $551.8^{\#}$ | $81.4^{+}$ | $0.0^{-}$ | $3.1^{+}$ | $0.0^{-}$ | $0.0^{-}$ |
| T14 | $156.0^{*}$ | $43.2^{\#}$ | $179.3^{*}$ | $626.8^{*}$ | $168.9^{*}$ | $65.0^{\#}$ | $0.8^{\circ}$ | $0.0^{-}$ | $0.8^{\circ}$ |
| T15 | $45.0^{\#}$ | $42.3^{\#}$ | $32.4^{\circ}$ | $542.9^{\#}$ | $126.7^{\#}$ | $6.4^{\circ}$ | $7.5^{*}$ | $0.0^{-}$ | $0.0^{-}$ |

$^{*}$= Very high; $^{\#}$= High; $^{+}$= Intermediate; $^{\circ}$= Low; $^{-}$= Not applied.

between the *high* and *intermediate* scale for P, K and Ca, and three or more companies adopting *very high* values. Moreover, most companies adopt amounts between *high* and *intermediate* scale for B and Cu, although Cu is not applied in some recommendations (T3, T5, T7, T13, T14 and T15). T1 presented *very high* amounts of Ca and Mg, however without presenting higher trunk biomass production over time.

## 4. DISCUSSION

The main feature of Benchmark is the relative performance evaluation among treatments of interest. This work evaluated the effects of commercial fertilizations used by large companies operating in the state of Minas Gerais on eucalyptus production. The analysis was based on the joint effect of fertilization on production. This comparison is important because there is not a single fertilization recommendation for eucalyptus adopted by producing companies.

Since all companies generally adopt the nutritional balance method to define fertilization, there should be no major discrepancies in recommendations. In literature, it is common to observe different fertilization recommendations in similar areas, although there are no compatible economic gains with the highest amounts of applied nutrients. This study showed large discrepancies in productive terms (Table 4), and the results observed by Stape et al. (2008, 2010) and Oliveira et al. (2010) corroborate such affirmation.

From the second year, T1 stood out as the most productive (Table 4). This received only 3.3% of the amount of N and 48.9% with respect to K, which were applied in T14 (Table 5). For the region under study, it is evident that there is no need to apply high amounts of N, a fact that is observed in different Brazilian regions (Stape et al., 2008, 2010; Oliveira et al., 2010). In addition to not promoting greater productivity gains, this nutrient significantly impacts the fertilization cost and is environmentally undesirable, as it produces nitrous oxide ($N_2O$) and contribute to the emission of greenhouse gases (Bichel et al., 2016).

T1 produced about 1.45 times more aerial biomass than T13 (the least productive) (Table 4), evidencing the high productive capacity of this fertilization for the region. The mean biomass of T1 (Table 4) at 60 months was similar to that found by Meneses et al. (2015) (107.4 $Mg.ha^{-1}$) at the same site, and higher than the average production found by Stape et al. (2010) (100.0 $Mg.ha^{-1}$) in the northern region of Minas Gerais at that same age, indicating the potential of this fertilization for the region. The higher growth in trunk biomass in response to T1 confirms the importance of fertilization to reach high productivity of forests planted in Savana soils. The direct and positive relationship between productivity and forest nutrition is widely demonstrated in literature (Santana et al., 1999; Stape et al., 2010; Pulito et al., 2015), until water becomes a factor limiting productivity.

T14 presented higher trunk biomass at 12 months in both arrangements in relation to the other treatments. However, the growth rate decreased from the second year. A possibility of this occurrence may have been the fact that this treatment received large amounts of nutrients, mainly N and K (Table 5). In addition to the fact that these two nutrients are among the most expensive, they are mainly responsible for the initial growth of plants (Santana et al., 2002; Pulito et al., 2015). In a study conducted in the state of São Paulo, eucalyptus positively responded to increased fertilizer doses, resulting in increased productivity; however, the effects of higher doses decreased from the second year of planting (Silva et al., 2013). Similar results were also observed by Pulito et al. (2015) and Stape et al. (2010). In studying the fertilization response in eucalyptus production in savanna soils, Barros et al. (1981) found that fertilization is essential to obtain good yields, and that the growth rate in the first two years is differentiated according to fertilization, but tends to equalize over time.

It is emphasized that the amount of each nutrient should be applied according to the plant assimilability to maintain nutrient concentrations in plant tissues at appropriate levels. In addition to the amount of nutrients applied, the proportion of nutrients should also be considered. The results show that the growth rate of eucalyptus in treatments with the highest amount of nutrients reduced from the second year. This occurred after the canopy phase, which means that plants occupied the total area and intraspecific competition for water and light became more growth restrictive. The results observed by Stape et al. (2008, 2010) and Silva et al. (2013) corroborate those observed in this study. Barros et al. (2005) pointed out that the higher proportion of nutrients required by fast-growing forest species such as eucalyptus should be provided up to a maximum of three years. After this age, biochemical and biogeochemical cycling processes are able to meet the nutrient demand until the end of the rotation.

Regarding arrangements, the square arrangement in most treatments produced higher trunk biomass compared to the rectangular arrangement. This occurred from 36 months, because there was no difference between arrangements for all treatments until this age (Table 4), which means that competition for resources was lower or even non-existent until this age. From 36 months, competition for resources in the rectangular arrangement was higher, a fact that was probably related to the competition of trees in the planting line, where it restricted and increased competition for light, nutrients and water. However, a factor that must be taken into consideration in relation to arrangements is tree harvesting. In rectangular spacing, the harvesting cost is lower in relation to square arrangements (Martins et al., 2009; Leite et al., 2014), significantly increasing the final production cost of square arrangements.

## 5. CONCLUSION

Benchmark has been shown to be an adequate strategy to resolve uncertainties about the effect of different fertilizations and spatial arrangements on eucalyptus wood production.

Biological response expressed in higher biomass production, occurred in association with higher amounts of fertilizer applied in the first years of cultivation. This effect reduced after two years and became less expressive at the end of the cutting cycle.

Fertilization of 2000kg of agrosilicon, 400kg of reactive phosphate, 130kg of 04:26:16+0.5%Cu+0.5%Zn and 150kg of KCl+1%B per hectare in the 3.0 x 3.0 m arrangement proved to be the most attractive option according to trunk production at 60 months.

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