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Efeito do espaçamento sobre o crescimento e produção de eucalipto de rápida rotação aos 24 meses de idade

Spacing effect on growth and yeld of fast rotation Eucalyptus at 24 months of age

Efecto del espaciado sobre el crecimiento y la producción de eucalipto de rotación rápida a los 24 meses de edad

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Resumo

Este estudo teve como objetivo avaliar o crescimento em altura, diâmetro e a produção volumétrica de um clone de eucalipto aos 24 meses de idade, plantado em diferentes espaçamentos. Foram coletados os valores de circunferência a altura do solo, circunferência a altura do peito e a altura de todas as plantas das parcelas, aos 6, 12, 18 e 24 meses após o plantio. A partir dos dados coletados foram obtidos os valores de diâmetro a altura do solo e do peito e a altura média em cada idade. Aos 24 meses após o plantio foi realizada a cubagem rigorosa da árvore média de cada parcela para a obtenção do volume de madeira por árvore e por hectare. O espaçamento não apresentou um padrão claro de influência sobre a altura total das plantas. A altura final não foi afetada pelo espaçamento. O efeito do espaçamento de plantio sobre o crescimento em diâmetro a altura do solo se intensificou a partir do primeiro ano após o plantio. O diâmetro médio das árvores aumentou com o espaçamento de plantio, assim como o volume de madeira por árvore. O volume de madeira por hectare foi maior nos espaçamentos mais adensados.

Palavras-chave: Adensamento; Florestas energéticas; Produção florestal.

Abstract

The objective of this study was to evaluate the growth in height, diameter and volume production of a eucalyptus clone at 24 months of age planted at different spacing. Values of circumference at soil height, circumference at chest height and the heights of all plants in the plots were collected at 6, 12, 18 and 24 months after planting. Using the collected data, the diameter values at ground and chest height and the mean height at each age were calculated. Rigorous cubing of the average tree in each plot was performed 24 months after planting to obtain the wood volume per tree and per hectare. The spacing did not present a clear pattern of influence on the total height of the plants. The final height was not affected by spacing. The effect of planting spacing on growth in diameter at soil height intensified from the first year after planting. Tree mean diameter increased with planting spacing, as well as the wood volume per tree. Wood volume per hectare was higher in the denser spacing.

Keywords: Densification; Energy forests; Forest production.

Resumen

Este estudio tuvo como objetivo evaluar el crecimiento en altura, diámetro y la producción volumétrica de un clon de eucalipto a los 24 meses de edad, plantado en diferentes espacios. Los valores de circunferencia a la altura del suelo, circunferencia a la altura del pecho y la altura de todas las plantas en las parcelas se recolectaron a los 6, 12, 18 y 24 meses después de la siembra. A partir de los datos recopilados, se obtuvieron los valores de diámetro al suelo y altura del pecho y la estatura media en cada edad. A los 24 meses después de la siembra, el árbol promedio de cada parcela se cubrió rigurosamente para obtener el volumen de madera por árbol y por hectárea. El espacio no mostró un patrón claro de influencia en la altura total de las plantas. La altura final no se vio afectada por el espaciado. El efecto del espaciamiento de la siembra sobre el crecimiento en diámetro y altura del suelo se intensificó desde el primer año después de la siembra. El diámetro promedio de los árboles aumentó con el espacio de siembra, así como el volumen de madera por árbol. El volumen de madera por hectárea fue mayor en el espacio más denso.

Palabras clave: Densificación; Bosques energéticos; Producción forestal.

1. Introduction

Species of the *Eucalyptus* genus are widely planted in Brazil not only for its wood quality (which is suitable for various purposes), but also for its good ecological adaptation which provides rapid growth. However, growth responses may vary due to the site quality and the implemented spacing (Oliveira Neto et al., 2010; Beltrame et al., 2012).

The formation of clonal eucalyptus forests represented a major advance in Brazilian silviculture, enabling greater production, improved stand quality and homogenization of the raw material used by the forest-based industry. In spite of this, this advance does not exempt adopting implantation techniques such as spacing and management in order to obtain regular and productive stands that economically fulfill the implantation and harvest conditions, especially when it comes to obtaining plantations for industrial purposes (Berger et al., 2002).

The growing global demand for fuels and the high consumption of fossil fuels such as oil and coal, have raised global concern with environmental issues because they are non-renewable energy sources and highly harmful to the environment. Therefore, studies on the potential of generating energy from forest biomass have been performed in Brazil and around the world, reporting the potential of biomass for generating clean energy (Eloy et al., 2015).

The use of fast-growing and short-rotation energy forests for energy production has been increasing as a renewable and safer energy matrix since they are non-polluting, in contrast to fossil energy sources (Longue Júnior and Colodette, 2013), and is an activity that has been continuously growing in Brazil over the last decade (Eloy et al., 2014).

To this end, forest stands can be managed using a larger number of trees per unit area, reducing the conventional 2 to 3 meters between plants in the line to smaller spacings such as 0.5 to 1.5 meters between plants in the line, or even using double lines. Although the use of densely planted plantations for energy production is not yet a common practice among forest companies due to a lack of efficiency in management, this can generate changes in the physical-chemical characteristics of the wood, modify the economic viability of a stand, and better arrange the forest, thus obtaining a higher incremental value per area and maximum productivity in the final product, in addition to better exploiting the sites (Machado, 2014).

According to Magalhães et al. (2006), adequate planning is necessary in order to choose the appropriate spacing, considering variables such as the pattern of plant growth, site quality, end product, silvicultural treatments and the exploitation method. In studying the influence of spacing on wood production, several authors have stated that there is greater growth in diameter and a larger individual volume in larger spacings. On the other hand, plantations conducted in reduced spacing are highlighted by the high volumetric production per hectare, which is a very important factor when the objective is energy production from the wood (Leite et al., 1997; Berger et al., 2002; Reiner et al., 2011; Lima et al., 2013). However, each genetic material behaves differently throughout its growth depending on the site and its space for growth.

Thus, the objective of this work was to evaluate the growth in height, diameter and volume production of a *Eucalyptus urophylla* x *E. grandis* hybrid I 144 clone at 24 months of age in six different plant spacing arrangements.

2. Methodology

A field experiment was evaluated over an interval of 24 months, with data collected on site, using sampling techniques for plant height, stem diameter and volumetric measurements. The experiment was of a qualitative and quantitative nature and applied statistical methods for the evaluation of the collected data (Pereira et al., 2018).

The experiment was installed in the northeastern region of Mato Grosso do Sul State, being part of the Cassilândia geographic microregion, at 790 m altitude and at the geographic coordinates: Latitude - 18° 41’ 33” South and Longitude - 52° 40’ 45” West of Greenwich. The original vegetation cover of the site is cerrado with clear fields and the predominant soil class is Dystrophic Red Latosol. The climate is humid tropical (Aw) according to the Köppen classification, with rainy season in the summer and dry in the winter with average annual precipitation of 1,850 mm. The average annual temperature varies from 13°C to 28°C (Cunha et al., 2013).

That experiment was performed in a randomized block with six spacings (2.0 x 0.5 m, 2.0 x 1.0 m, 2.5 x 0.5 m, 2.5 x 1.0 m, 0 x 0.5 m, 3.0 x 1.0 m) and three replicates. The I 144 clone (*Eucalyptus urophylla* x *E. grandis*) was used. Each experimental plot consisted of 4 lines with 12 plants each, with the plot area being 10 plants in each of the two central lines.

The evaluations occurred in four seasons (6, 12, 18 and 24 months after planting), where diameter at soil height (DSH) and total height (TH) data were collected from the 20 plants in the useful area of each plot. Diameter at breast height (DBH) was measured at 24 months. A randomized complete block design in a factorial scheme with plots subdivided by time was used for these parameters. Spacing was considered in the plot and time in the subplot.

For determining the solid wood volume, an average tree of each plot was felled at 24 months and cubed using the Smalian method with sections every 2.0 m from the DBH. The following formula was used in order to carry out the calculations:

$$V_t = Vp + \sum \left[\left(\frac{Gi + Gi_{+1}}{2} \right) Li \right] \quad (1)$$

In which: V_t is the total volume of the tree (m³), V_p is the tip volume (m³), G_i is the basal area at the beginning end of the section (m²), G_{i+1} is the basal area at the end of the section (m²) and L_i is the length of the section (m).

The tip volume was determined by the calculation formula for cone volume:

$$V_p = \frac{1}{3} \times G_p \times L_p \quad (2)$$

In which: G_p is the basal area of the tip (m²) and L_p is the tip length (m).

Basal area calculations were done using the conventional mathematical method.

$$G_1 = \frac{\pi \times d_i^2}{40000} \quad (3)$$

In which: d_i is the diameter of the section (cm).

An adjustment of the volumetric Spurr model was performed after cubing the trees ($Vol = \beta_0 + \beta_1 \times DBH^2 \times TH \pm e$) to estimate the volume of the trees measured in the plots. The volumetric model used data for total height (TH) and diameter at 1.30 m from soil height (DBH) to estimate the volumes. The adjusted R^2 was 0.9586 and Syx% was 5.7300. All coefficients were significant at 5% probability.

$$Vol = 0.002411 + 0.000034 \times DBH^2 \times TH + \varepsilon \quad (4)$$

The data obtained at 24 months of age (TH, DBH, individual volume and volume per hectare) were submitted to analysis of variance. The Tukey test was applied for the qualitative variable (spacing) at 5% probability, and regression analysis was performed for the quantitative variable (time).

3. Results and Discussion

3.1 Periodic increment

At 12 months of age, no significant difference was observed in periodic total height increment between the spacings (Table 1). This is probably due to the absence of competition between the trees, and the same began to be noticed from 18 months of age. According to Chies (2005), in the initial stage of growth the plant mainly needs moisture and heat; if these elements are available in adequate quantities, any site is able to support the initial growth of a stand, even at high densities.

Table 1. Periodic increment in total height of eucalyptus I 144 clone under different spacings in three periods from the age of six months.

Spacing	Periodic increment in total height (m)		
	6-12 months	12-18 months	18-24 month
2.0 x 0.5 (m)	1.12 a C	3.61 b B	5.31 a A
2.5 x 0.5 (m)	1.47 a B	4.28 ab A	4.52 b A
3.0 x 0.5 (m)	1.07 a C	4.53 a B	5.62 a A
2.0 x 1.0 (m)	1.54 a C	4.15 ab B	5.08 ab A
2.5 x 1.0 (m)	1.26 a B	4.46 a B	5.51 a A
3.0 x 1.0 (m)	1.28 a C	3.65 b B	4.41 b A

Means followed by the same lowercase letter in the column and upper case in the row do not differ by Tukey test at the 5% probability level.
Source: prepared by the authors

In Table 1, it is possible to observe that the periodic increment in total height does not differ between the spacing at the beginning of the growth of the eucalyptus plants, but it is well characterized with the advancing age of the plants.

From 12 months of age, there was a difference between the spacing, however, the increment in height did not present a defined pattern. At 18 months of age, both the largest spacing and the lowest spacing resulted in similar incremental values. However, at 24 months the spacing with lower population density (3.0 x 1.0 m) resulted in a lower mean periodic increment (4.41 m), and not statistically differing from the 2.0 x 1.0 and 2.5 x 0.5 m spacings.

After 18 months of age there was a growth spurt in height in all the studied arrangements (Table 1). In the period between 18 and 24 months after planting, the plants responded with the largest increments for most of the spacings, except for 2.5 x 0.5 m.

Until the first year after planting, the influence of the spacing on the periodic increment in DSH was also not observed (Table 2).

Table 2. Periodic increment in diameter at soil height (DSH) of eucalyptus I 144 clone under different spacings in three periods from the age of six months.

Spacing	Periodic increment in DSH (cm)		
	6-12 months	12-18 months	18-24 months
2.0 x 0.5 (m)	2.02 a B	2.59 c AB	2.96 ab A
2.5 x 0.5 (m)	2.43 a A	2.85 c A	2.29 b A
3.0 x 0.5 (m)	2.20 a B	3.07 c B	2.97 ab AB
2.0 x 1.0 (m)	1.87 a B	3.56 bc A	3.52 a A
2.5 x 1.0 (m)	2.00 a C	4.25 ab A	3.13 ab B
3.0 x 1.0 (m)	1.73 a C	5.05 a A	3.67 a B

Means followed by the same lowercase letter in the column and upper case in the row do not differ by Tukey test at the 5% probability level.
Source: prepared by the authors

It is observed in Table 2 that the behavior of periodic increment in diameter was similar to that observed for increase in height, between the spacing. Larger spacing provided a greater increase in diameter, but decreased between 18-24 months of age.

At 18 months of age, plants growing in the denser spacings, which were 0.5 meters apart between plants in the line, presented a lower increase (mean of 2.84 cm) to those in which this spacing was higher (mean of 4.29 cm), i.e. the spacing of 1.0 m in the planting line provided a 51% greater increase in diameter than the more densified spacing. In the 3.0 x 1.0 m spacing an increase of 5.05 cm of DSH was observed, while this value was 3.07 cm for plants growing in 3.0 x 0.5 m, resulting in a difference of 65%. Leite et al. (1997) also found that mean incremental values in CBH increased with spacing from 32 months of age.

At 24 months of age, only the plants established in the 2.5 x 0.5 m spacing were smaller than those of the treatments 3.0 x 1.0 m and 2.0 x 1.0 m, with a periodic increase of

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2.29 cm; in addition, it was not influenced by the plantation age, and it grew satisfactorily in all periods compared to the other spacings (Table 2).

The two larger spacings (2.5 x 1.0 m and 3.0 x 1.0 m) had a greater increase in DSH between 12 and 18 months, and they significantly reduced their growth in the last evaluated period (Table 2). Also, the denser spacings increased or maintained their periodic increase values.

3.2 Growth over time

At six months of age, the total height of the plants did not differ significantly between the spacings (Table 3) due to the lack of competition among the plants, as verified in the periodic increment analysis in height.

Table 3. Growth in overall height of the I 144 clone in different spacings at four ages.

Spacing	Height (m)			
	6 months	12 months	18 months	24 months
2.0 x 0.5 (m)	1.07 a	2.19 ab	5.80 c	11.11 bc
2.5 x 0.5 (m)	1.23 a	2.70 a	6.98 a	11.50 b
3.0 x 0.5 (m)	0.71 a	1.79 b	6.32 abc	11.94 ab
2.0 x 1.0 (m)	1.02 a	2.56 ab	6.71 ab	11.30 bc
2.5 x 1.0 (m)	1.30 a	2.56 ab	7.02 a	12.53 a
3.0 x 1.0 (m)	1.10 a	2.38 ab	6.03 bc	10.44 c

Means followed by the same lowercase letter in the column do not differ by Tukey test at the 5% probability level.
Source: prepared by the authors

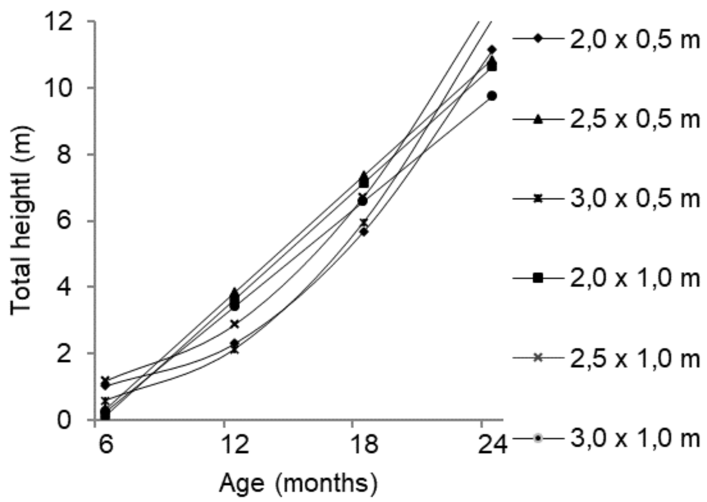
For the total height of the eucalyptus clone I 144 (Table 3), it is observed that at 12, 18 and 24 months of age, the spacing interfered in the height of the plants, and at 24 months of age, the largest spacing resulted in plants lower.

From 12 months age, height began to differentiate between spacings; however, there was no clear pattern of the influence of the useful area per plant in relation to height growth. In working with different forest species, Nascimento et al. (2012) also did not observe a clear growth pattern by the different species in the spacings tested at 18 months.

At 18 and 24 months of age, the lowest plant height values were verified for the largest spacing (Table 3). Studies have shown contradictory results regarding the influence of spacing in relation to the growth of forest plants in height. Pacheco et al. (2015) found that the initial planting density of *Pinus taeda* L. does little to interfere with the average height growth of the forest, but evidenced a higher growth in height in the last years in more open spaces and a smaller growth for more closed spaces. In evaluating the response of *E. dunnii* in different planting spacings, Reiner et al. (2011) did not detect significant differences in height and diameter until the second year after planting. In studying the growth of *E. saligna* over time, Berger et al. (2002) verified that the growth in average height practically did not differ between the treatments studied. Oliveira et al. (2009) studied the silvicultural and productive performance of eucalyptus under different spatial arrangements in an agrosilvipastoral system, and Inoue et al. (2011) evaluated the influence of growth space on the height and diameter of *Pinus taeda* L., observing an increase in tree height in larger useful areas per plant. This is in contrast to what was verified by Leles et al. (2011), who found the highest tree heights of native species at wider spacings.

It was observed that the 3.0 x 0.5 m spacing was inferior to the other spacings from 7.5 months to 13 months of age, so that after that age it had a growth spurt, and at 24 months it was presented as second best, while the best spacing was 2.5 x 1.0 m which presented a more pronounced growth after 12 months (Figure 1).

Figure 1. Height Growth for the I 144 clone in different studied row spacings in relation to age.



Y=1.847402-0.310729 I+0.029096 I²
R^2= 99.95%

Y=-3.163627+0.584645 I
R^2= 95.89%

Y=1.324957- 0.311030 I+0.031594 I²
R^2= 99.64%

Y=-3.348235+0.583228 I
R^2= 95.98%

Y=1.624629-0.248993 I+0.029500 I²
R^2= 99.70%

Y=-2.931822+0.527965 I
R^2= 95.10%

Source: prepared by the authors

In general, it is possible to observe in Figure 1 that there is no stagnation in the growth of plants, and there may be an alternation for growth between the spacing, according to the age of evaluation. From 21 months on, the spacing 3.0 x 1.0 m stood out with trees of lower heights, followed by 2.0 x 1.0 m spacing.

Spacing influenced tree growth in DSH at all evaluated ages, but at six months there was no clear pattern in the influence of spacing as occurred for the height variable in the first months after planting; this could have occurred due to the late replanting that was done in this experiment (Table 4).

Table 4. Growth in diameter at soil height (DSH) of the I 144 clone in different spacings at four ages.

Spacing	DSH (cm)			
	6 months	12 months	18 months	24 months
2.0 x 0.5 (m)	1.67 ab	3.69 b	6.28 c	9.24 c
2.5 x 0.5 (m)	2.10 a	4.54 a	7.38 b	9.68 c
3.0 x 0.5 (m)	1.17 b	3.37 b	6.44 c	9.40 c
2.0 x 1.0 (m)	1.91 ab	3.78 b	7.34 b	10.86 b
2.5 x 1.0 (m)	2.06 a	4.07 ab	8.32 a	11.15 b
3.0 x 1.0 (m)	2.02 a	3.75 b	8.80 a	12.47 a

Means followed by the same lowercase letter in the column do not differ by Tukey test at the 5% probability level.
Source: prepared by the authors

Table 4 shows that trees at more advanced ages have a larger growth in diameter when they are in larger spacing.

Pacheco et al. (2015) did not observe differences in diameter at breast height growth or in height up to the 5th and 9th year after planting, respectively.

The plants had the highest DSH averages at the age of 12 months in the spacings that were 2.5 m between rows. However, starting from 18 months when the competition between trees began to intensify, the spacings with the highest useful area per plant (2.5 x 1.0 and 3.0 x 1.0 m) resulted in higher average DSH values compared to the spacings with the lowest useful area per plant (Table 4). This pattern was repeated at 24 months of age, and the higher the useful area per plant the higher the DSH. Nascimento et al. (2012) evaluated several forest species at 18 months of age and also observed that the species generally had larger mean diameter at soil height values in the larger spacings.

At 12 months of age the spacing began to exert more influence on the DSH, clearly observing that spacings with greater useful area per plant result in higher DSH values. The 2.5

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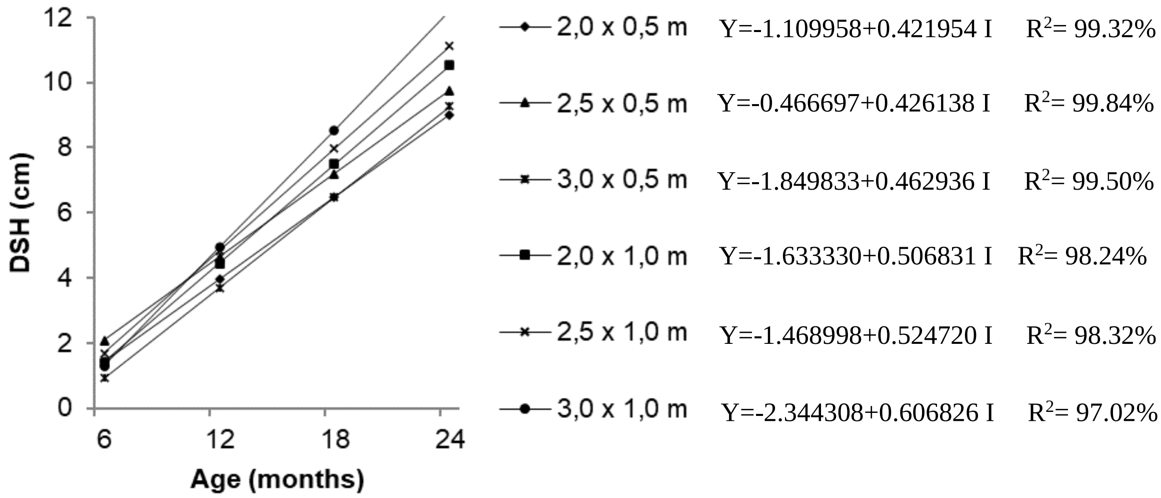
x 0.5 m and 2.0 x 0.5 m spacings had the greatest decrease in the growth rate from 13 months of age (Figure 2).

Figure 2. Growth in diameter at soil height (DSH) for the I 144 clone in different studied row spacings in relation to age.



Source: prepared by the authors

For all spacings, it can be seen (Figure 2) that the growth of the diameter of the trees is continuous with the age of evaluation, resulting in higher values for the wider spacings.

Growth and volumetric production at 24 months of age

As already observed in all periods of growth evaluated, the growth in total height did not allow for observing a clear growth pattern, since larger and smaller useful areas did not differ statistically among them, being that the greater spacing (3.0 x 1.0 m) produced smaller trees (10.44 m), and did not statistically differ from the denser spacings (Table 5).

Table 5. Total height, diameter (DBH) and individual volumetric production and per hectare of the I 144 clone in different spacings at 24 months of age.

Spacing	HT (m)	DBH (cm)	Individual volume (m^3 $plant^{-1}$)	Volume by area (m^3 ha^{-1})
2.0 x 0.5 (m)	11.11 ab	7.61 b	0.0242 c	242.36 a
2.5 x 0.5 (m)	11.50 ab	7.94 b	0.0270 c	216.12 ab
3.0 x 0.5 (m)	11.94 a	8.09 b	0.0290 bc	193.34 bc
2.0 x 1.0 (m)	11.30 ab	9.08 a	0.0339 b	169.72 c
2.5 x 1.0 (m)	12.53 a	9.71 a	0.0425 a	170.00 c
3.0 x 1.0 (m)	10.44 b	9.33 a	0.0333 b	110.88 d

Means followed by the same lowercase letter in the column do not differ by Tukey test at the 5% probability level.
Source: prepared by the authors

Table 5 shows that the largest usable plant area results in less height, but in the wider spacing, there is a larger diameter of the trees, culminating in a larger individual volume of the plants, but that does not result in larger volume by area.

The same was observed by Ferreira et al. (2014) in studying the *E. urophylla* x *E. grandis* clone in different spacings.

Oliveira Neto et al. (2010) and Leles et al. (2011) report that the height may respond in different ways in relation to the plant spacing, not being influenced much by it, and may increase as the area per plant increases or decreases. Nascimento et al. (2012) also did not observe a clear growth pattern in height for the different forest species studied as a function of the tested spacings.

For diameter, it was observed that the diameter was smaller in the lower useful area per plant, more specifically where the distance between plants in the planting line was 0.5 m, with averages between 7.61 and 8.09 cm. In larger spacings this average increased to values between 9.08 and 9.71 cm, as was observed for growth in DSH. Similar results were found by Ferreira et al. (2014), who reported that growth in DBH of the plants in the spacings 3.0 x 2.5 and 3.0 x 2.0 m from four years of age tended to be higher than in 3.0 x 1.5 m and 3.0 x 1.0 m spacings. Leite et al. (1997), Berger et al. (2002), Magalhães et al. (2006), Oliveira et al. (2009), Oliveira Neto et al. (2010), Inoue et al. (2011), Reiner et al. (2011) and Pacheco et al. (2015), also observed that larger diameter values occur in larger spacings, and smaller in denser spacings, indicating a higher response of this variable with the increase in spacing.

Trees planted in more narrow spacings resulted in smaller individual volumes, lower than those located where plant spacing was 1.0 m (Table 5). The same was observed for Berger et al. (2002), Magalhães et al. (2006), Oliveira et al. (2009), Reiner et al. (2011), Ferreira et al. (2014) and Sereghetti et al. (2015), who observed greater individual volume of the trees in wider spacings. However, although the 2.5 x 1.0 m spacing had a smaller working area than the 3.0 x 1.0 m spacing, it presented the best result, with an average of 0.0425 m^3 $plant^{-1}$; this occurred due to the fact that it presents a higher mean DBH and height between the studied spacings, as the height directly influences the individual volume.

Unlike the result found for individual volume and as expected for volume per hectare, the highest values occurred in the denser spaces due to the higher number of trees per hectare in smaller spaces, as observed by Oliveira et al. (2009) and Reiner et al. (2011) who obtained similar results. Magalhães et al. (2006) also observed a decrease in the volume per hectare with the increase in spacing. This is also similar to Berger et al. (2002), who was able to achieve lower commercial volume yield without bark per hectare for the treatments that constituted the largest living space (12 m^2); and Lima et al. (2013) who worked with *Pinus taeda* in different spacings, and observed a production of more twisting and smaller trunks with smaller diameters in high planting densities in relation to the lower densities, but they presented larger annual increases in volume per unit area.

The results found indicate that the use of the denser planting of eucalyptus can be important in obtaining greater energy yields, since the volume of wood obtained per hectare is much higher in reduced spacing, considering the rapid rotation. However, energy assessments should be sought in the denser spacing, to verify whether the caloric power of the largest volume of wood is advantageous in energy production.

4. Conclusions

Spacing did not present a clear influence pattern on the total height of the plants up to the studied age.

The influence of planting spacing on growth in diameter at soil height intensified from the first year after planting.

The increase in plant spacing provided higher diametric growth, as well as higher volumetric yields per tree, while the volume per area was higher in denser spacings.

As a suggestion in this line of research for future work, it is indicated to evaluate productivity, caloric power and the dynamics of nutrients with the soil at different ages.

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