EFFECT OF AGE AND SPACING ON BIOMASS PRODUCTION IN FOREST PLANTATIONS[1]

Elder Eloy[2*], Dimas Agostinho da Silva[3], Braulio Otomar Caron[2], Elvis Felipe Elli[4] and Felipe Schwerz[5]

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[2] Universidade Federal de Santa Maria, Departamento de Engenharia Florestal, Frederico Westphalen, RS-Brasil. E-mail: <eloyelder@yahoo.com.br> and <otomarcaron@yahoo.com.br>.

[3] Universidade Federal do Paraná, Departamento de Engenharia e Tecnologia Florestal, Curitiba, PR-Brasil. E-mail: <dimas.agostinho.silva@gmail.com>.

[4] Universidade de São Paulo, Programa de Pós-Graduação em Engenharia de Sistemas Agrícolas, SP-Brasil. E-mail: <elvisfelipeelli@yahoo.com>.

[5] Universidade de São Paulo, Programa de Pós-Graduação em Fitotecnia, SP-Brasil. E-mail: <felipe_schwerz@hotmail.com>.

*Corresponding author.

ABSTRACT – The aim of this study was to determine the effect of age and plant spacing on biomass production of four forestry tree species: *Acacia mearnsii* De Wild, *Eucalyptus grandis* W. Hill ex Maiden, *Mimosa scabrella* Benth, and *Ateleia glazioviana* Baill. The following spacings of plants at the ages of 1, 3, and 5 years after planting were considered: 2.0 × 1.0 m, 2.0 × 1.5 m, 3.0 × 1.0 m, and 3.0 × 1.5 m. The study was installed in randomized complete block design. Biomass was determined by weighing different components of the trees after harvesting. Plant spacing affected biomass production of forestry trees at different ages after planting. Dense spacings produced larger quantities of biomass than less dense spacing. The tree species differed in biomass production: *Eucalyptus grandis* produced the largest quantity (325.1 t ha^{-1}), followed by *Acacia mearnsii* (239.3 t ha^{-1}), *Mimosa scabrella* (53.4 t ha^{-1}), and *Ateleia glazioviana* (32.1 t ha^{-1}). Wood biomass represented the biomass component with the largest production over time, which showed an increasing proportion throughout the age groups, followed branch, leaf, and bark biomass.

Keywords: Forest species; Planting density; Short rotation plantations.

EFEITO DA IDADE E DO ESPAÇAMENTO NA PRODUÇÃO DE BIOMASSA DE PLANTIOS FLORESTAIS

RESUMO – Esse trabalho teve como objetivo determinar o efeito da idade e do espaçamento de plantio na produção de biomassa das espécies florestais: ***Acacia mearnsii*** *De Wild,* ***Eucalyptus grandis*** *W. Hill ex Maiden,* ***Mimosa scabrella*** *Benth e* ***Ateleia glazioviana*** *Baill. Foram considerados plantios com diferentes espaçamentos: 2,0x1,0 m, 2,0x1,5 m, 3,0x1,0 m e 3,0x1,5 m, nas idades de 1, 3 e 5 anos após o plantio. O trabalho foi instalado em delineamento experimental de blocos completos casualizados. A determinação da biomassa aérea consistiu na colheita e pesagem das diferentes partes das árvores. Os espaçamentos de plantio influenciam na produção de biomassa das partes das espécies florestais, nas diferentes idades após o plantio. Os espaçamentos mais adensados proporcionam maiores quantidades de biomassa que os menos adensados. As espécies florestais diferenciam-se em relação à produção de biomassa. O* ***Eucalyptus grandis*** *(325,1 t ha^{-1}) apresenta a maior produção, seguido da* ***Acacia mearnsii*** *(239,3 t ha^{-1}),* ***Mimosa scabrella*** *(53,4 t ha^{-1}) e* ***Ateleia glazioviana*** *(32,1 t ha^{-1}). A madeira apresenta a maior participação na biomassa total ao longo do tempo, sendo constatada a crescente proporção percentual ao longo das classes etárias, seguido do galho, folha e casca.*

Palavras-Chave: Espécies florestais; Densidade de plantio; Plantios de curta rotação.

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1. INTRODUCTION

Over the last decades, the demand for energy has mostly been met by non-renewable sources, which results in a variety of difficulties regarding energy supply and the maintenance of the balance between economy and environment. Therefore, many countries are looking for alternatives that may potentially mitigate these problems, particularly by intensification in the production of renewable sources, including forest biomass (Carneiro et al., 2014).

Forest biomass here is referred to as the quantity of total plant mass occurring in a forest, and it can be determined by two different approaches, destructive and non-destructive. Destructive methods (also referred to as 'direct' methods) use measurements on the plant material directly in the forest, upon harvesting. Non-destructive methods ('indirect') employ models that relate the variable 'biomass' with other variables commonly measured, e.g. during forest inventories (Sanquetta et al., 2014a). According to Schikowiski et al. (2013) the direct method of weighing all materials is, however, the most accurate approach.

Studies on forest biomass have several purposes; among them is the assessment of forest growth to investigate energy production potential. Climate change-related issues caused by increased concentrations of greenhouse gases, particular

ly carbon dioxide (CO_2), have also attracted interest owing to biological carbon sequestration and CO_2 fixation by forest plants (Sanquetta et al., 2014b).

Currently, 8.2% of the energy produced originates from wood and charcoal, according to official sources of energy connecting area (Brasil, 2016). Biomass as a source of energy is typically used by developed countries, which employ advanced and highly efficient technologies with low emissions. In contrast, underdeveloped countries primarily rely on non-renewable energy sources, and are thus responsible for a substantial amount of pollution, which is also because of the inefficiency of their energy generation methods.

The advances achieved in Brazilian silviculture regarding the use of forest biomass for energy generation are promoted by the beneficial edaphoclimatic conditions. In this context, the role of short-rotation plantations as a means of producing biomass should be emphasized, taking economic, social, and environmental dynamics into account.

Decisions on silvicultural treatments and forest management aiming at the production of biomass for energy depend on the final wood processing method, the choice of suitable genetic material, planting density, and the rotation period. One of the most important aspects to be considered in the formation of forest stands for energy generation purposes is the spacing of individual plants.

Plant spacing is a complex aspect from a silvicultural, technological, and economic point of view, as it affects growth rates, cutting age, wood quality, silvicultural practices, and, consequently, production costs (Caron et al., 2015). Therefore, defining the spacing for forest planting is very important, considering its influence on the growth rate and the amount and quality of raw material, and thus on production costs. Optimal spacing is therefore defined by the capability of producing the highest product amount in the desired size, shape, and quality; however, optimal spacing depends on the plant species, site characteristics, and genetic potential of the reproductive material used (Eloy et al., 2015).

When targeting timber production for energy purposes, typically, dense spacing is recommended to produce the largest quantity of biomass per unit area in the shortest amount of time possible (Eloy et al., 2017a). Therefore, forestry management strives to identify species with sufficient environmental plasticity, high productivity, and superior energy-generation properties.

In this context, the objective of this work was to determine the effect of age and plant spacing on biomass production capacity in four forest species, distributed in four spacings, at three different ages after planting.

2. MATERIAL AND METHODS

2.1 Study area

This study work was carried out in an area belonging to the Federal University of Santa Maria (UFSM/FW; 27°22' S; 53°25' W), at 480 m altitude, in the city of Frederico Westphalen, Rio Grande do Sul.

The climate in this region is rated as 'Cfa,' according to the Köppen climate classification system: a humid subtropical climate with an average annual temperature of 19.1 °C (ranging from 0 °C to 38 °C) and an average annual rainfall of 1606 mm. The experimental area is approximately 30 km from the city of Iraí, to which this climate data refers to. Iraí has an average annual temperature of 18.8 °C, and average temperature of 13.3 °C in the coldest month (Maluf, 2000).

The experiment was set up in a randomized complete block design, arranged in a 4 × 4 × 3 factorial experiment, i.e., four forest species (*Acacia mearnsii* De Wild, *Eucalyptus grandis* W. Hill ex Maiden, *Mimosa scabrella* Benth, and *Ateleia glazioviana* Baill), four spacings (2.0 × 1.0 m, 2.0 × 1.5 m, 3.0 × 1.0 m and 3.0 × 1.5 m), and three periods after planting (1st, 3rd, and 5th year). The experiment were performed in three replicates in subdivided plots, where each plot was represented by the spacing and the species, and the subplot by the age of the plants. The block contained 16 experimental units, with 45 plants distributed in 5 rows in each unit. The experimental units were divided into three sections, with one being evaluated at each age.

The soil of the area (located within the mapping unit of Passo Fundo) is classified as typical dystrophic red latosol, with a well-drained clayey texture (Embrapa, 2006). The experimental area was in a lowland region with good soil deposition. In preparation for planting, subsoiling and harrowing operations were carried out. Planting was done manually in September 2008, and each seedling was fertilized with 150 g of nitrogen, phosphorus, and potassium, in formulation 8-24-12.

2.2 Sampling

The destructive evaluations were carried out in the 1st year (2009), 3rd year (2011), and 5th year (2013) after planting. A total of 144 trees was selected in each year of evaluation, corresponding to 36 trees per spacing. From these trees, six discs with approximately 2 cm thickness were sampled at the following positions along the stem: 0% (base), 1.30 m (diameter at breast height - DBH), 25%, 50%, 75%, and 100% of the total height of the tree. The discs were numbered according to their relative trunk position and experimental location. After this, they were packed in plastic bags and transported to the Laboratory of Agroclimatology of UFSM/FW, where they were marked, the bark and wood were separated, and two opposite symmetric wedges of each disc were cut.

Branch and leaf samples were collected in a stratified way, i.e., in the lower, middle, and upper stratum of the tree canopy, in order to obtain homogeneous samples representing the whole extension of the crown. The samples were labeled and dried in greenhouses under circulating air exchange to produce dry matter. Samples of wood, bark, leaves, and branches were dried at 103 ± 2 °C to constant mass.

Advanced leaf senescence during the evaluation periods (i.e., September) did not permit leaf sampling of *Ateleia glazioviana*.

2.3. Determination of biomass

For determination of the different biomass components, viz., wood biomass, bark biomass, branch biomass, and leaf biomass of different forest tree species distributed in the different spacings at different age classes, a direct method was employed, which consisted of harvesting and weighing of the different components (Sanquetta, 2002). The total fresh mass of each sampled tree was determined in the field, and moisture of each component was measured in the laboratory.

The dry biomass of the aerial part, in t ha^{-1}, was calculated considering the population density of each spacing, with a survival rate of 100% in the 1st and 3rd year, and 94% in the 5th year after planting, as confirmed by the experimental conditions.

2.4 Data analysis

Statistical analyses were performed using the Statistical Analysis System (SAS, 2003) software. We performed an analysis of variance, and an F-test; the assumption of normal distribution was tested by Shapiro-Wilk's test, heteroskedasticity was tested using Bartlet test; a regression analysis and Tukey's test were performed, all at 5% error probability.

3. RESULTS

In the analysis of variance, we observed a significant difference in the biomass production by wood, bark, branch, leaf, and total biomass, depending on the three analyzed factors: year, species, and spacing. In the same way, this characteristic was confirmed for all tested interactions, including species × spacing; year × species; year × spacing; and year × species × spacing, for all variables. Taking into account the simple effect analysis and evaluating the influence between the three factors, a significant difference was found in all observations, except from bark biomass in the first year (Table 1).

Table 1 – Analysis of variance of wood, bark, branch, leaf, and total biomass, of the four forest species, distributed in the four spacings, in the 1st, 3rd, and 5th year after planting.
Tabela 1 – *Análise de variância para a biomassa da madeira, casca, galho, folha e total, das quatro espécies florestais, distribuídas nos quatro espaçamentos, no primeiro, terceiro e quinto ano após o plantio.*

Main effect							
Factor of study		DF	Mean Square				
			Wood	Bark	Branch	Leaf	Total
Species		3	150928.0*	923.8*	3995.3*	1988.2*	246092.1*
Spacing		3	14592.5*	150.9*	718.6*	294.9*	30310.4*
Species × spacing		9	2368.2*	37.6*	368.0*	75.3*	5780.3*
* Significant to the probability of type A error							
Year		2	205369.7*	1282.0*	7557.1*	1763.1*	344151.4*
Year × species		6	76511.6*	270.0*	1158.1*	398.8*	97449.0*
Year × spacing		6	4027.5*	65.6*	174.7*	78.4*	7444.3*
Year × species × spacing		18	1032.6*	16.6*	205.1*	66.7*	2500.5*
Block		2	121.4	0.1	16.5	3.0	328.2
* Significant to the probability of type B error							
Coefficient of determination			0.98	0.98	0.97	0.98	0.98
Coefficient of variation (%)			21.9	20.2	21.6	14.6	19.2
Simple effect							
Year × spacing × species							
Year	1	15	5.0*	0.2^{ns}	3.8*	11.5*	62.6*
	3	15	4849.2*	297.5*	472.7*	346.4*	13882.0*
	5	15	52728.0*	92.2*	1266.9*	340.8*	74920.0*
Spacing(m)	2.0 × 1.0	11	43933.0*	297.6*	2023.9*	524.3*	72874.0*
	2.0 × 1.5	11	29123.0*	194.8*	522.1*	286.4*	41976.0*
	3.0 × 1.0	11	25555.0*	156.1*	790.2*	376.8*	40474.0*
	3.0 × 1.5	11	17752.0*	73.0*	289.0*	123.5*	26638.0*
Species	*A. mearnsii*	11	11281.0*	166.2*	2216.7*	326.9*	31548.0*
	M. scabrella	11	1377.6*	16.0*	67.2*	3.9*	2482.0*
	E. grandis	11	77115.0*	337.4*	510.0*	371.5*	103629.0*
	A. glazioviana	11	529.8*	4.6*	108.6*	-	1096.3*

Where: (*) Indicate statistical significance, and (^{ns}) indicates non-significance at a 5% probability level of error, according to Fisher's distribution, (-) indicates no evaluation was performed.

Eucalyptus grandis produced a larger quantity of leaf and total biomass in all spacings in the first year, compared with that in the other species. Also, this species produced larger quantities of biomass in terms of wood, bark, and branch; however, this was not statistically different from those produced by *Acacia mearnsii* and *Mimosa scabrella*, except for in the 2.0 × 1.0 m spacing of *Mimosa scabrella* (Figure 1).

In the 3rd year after planting, *Acacia mearnsii* produced the largest quantity of branch biomass in all spacings. Furthermore, *Eucalyptus grandis* produced the largest quantity of biomass in terms of wood (91.0 t ha^{-1}), bark (16.3 t ha^{-1}), leaf (17.4 t ha^{-1}), and total (142.9 t ha^{-1}) in the densest spacing (2.0 × 1.0 m), compared with those in the other species. The species *Ateleia glazioviana* showed the lowest values regarding wood, bark, and total biomass for all spacings, which was not significantly different from *Mimosa scabrella* in the 3.0 × 1.0 m and 3.0 × 1.5 m spacings. Branch biomass, however, was superior to *Mimosa scabrella* in all spacings (Figure 2).

In the 5th year after planting, *Eucalyptus grandis* produced the largest quantity of total biomass (325.1 t ha^{-1}, 286.6 t ha^{-1}, 280.2 t ha^{-1}, and 234.0 t ha^{-1}), which was in line with the results of the 1st and 3rd year, and was followed by *Acacia mearnsii* (239.3 t ha^{-1}, 119.5 t ha^{-1}, 93.1 t ha^{-1}, and 79.8 t ha^{-1}), *Mimosa scabrella* (53.4 t ha^{-1}, 49.9 t ha^{-1}, 29.2 t ha^{-1}, and 29.8 t ha^{-1}), and *Ateleia glazioviana* (32.1 t ha^{-1}; 23.9 t ha^{-1}; 30.4 t ha^{-1}, and 19.9 t ha^{-1}) for the four spacings: 2.0 × 1.0 m; 2.0 × 1.5 m; 3.0 × 1.0 m, and 3.0 × 1.5 m, respectively (Figure 3).

Where: Means followed by the same lowercase letters do not differ between spacings, in the respective species; Means followed by upper case letters do not differ between species, in the respective spacings, at 5% of error probability according to Tukey's test.

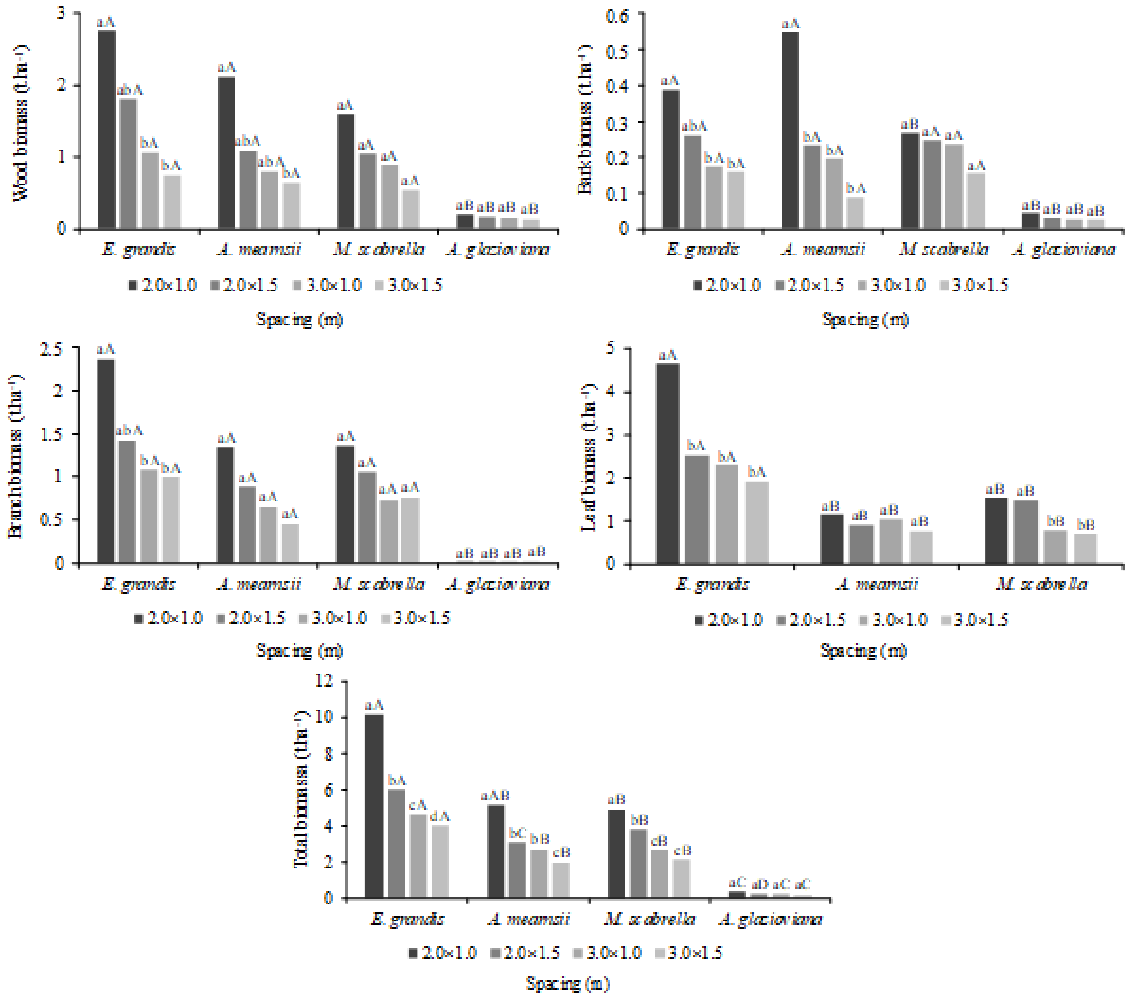

Figure 1 – Mean values of wood, bark, branch, leaf, and total biomass (t ha^{-1}) of forest species distributed in different spacings, one year after planting.

***Figura 1 –** Valores médios de biomassa da madeira, casca, galho, folha e total (t ha^{-1}), das espécies florestais distribuídas nos diferentes espaçamentos, um ano após o plantio.*

A direct relationship of planting density and biomass distribution in the different components was found in the analyses of the means of total aerial biomass of the 1st year (Figure 1), 3rd year (Figure 2), and 5th year (Figure 3) after planting: higher density treatments showed the highest values of biomass, compared with that in the low density treatments.

The significant models for biomass production of the four forest species along the three evaluated periods and biomass proportion in relation to tree age is presented in figure 4. In general, an increasing trend of biomass production over the years was found, mainly in terms of wood and total biomass.

Eucalyptus grandis showed the greatest development of wood biomass, compared with that in other species and other biomass components, varying from 25.8% to 83.7% from the 1st to 5th year, respectively. In contrast, leaf ratio decreased with stem growth, from 46.3% to 5.6%, respectively, over the study period (Figure 4a).

Where: Means followed by the same lowercase letters do not differ between spacings, in the respective species; Means followed by upper case letters do not differ between species, in the respective spacings, at 5% of error probability according to Tukey's test.

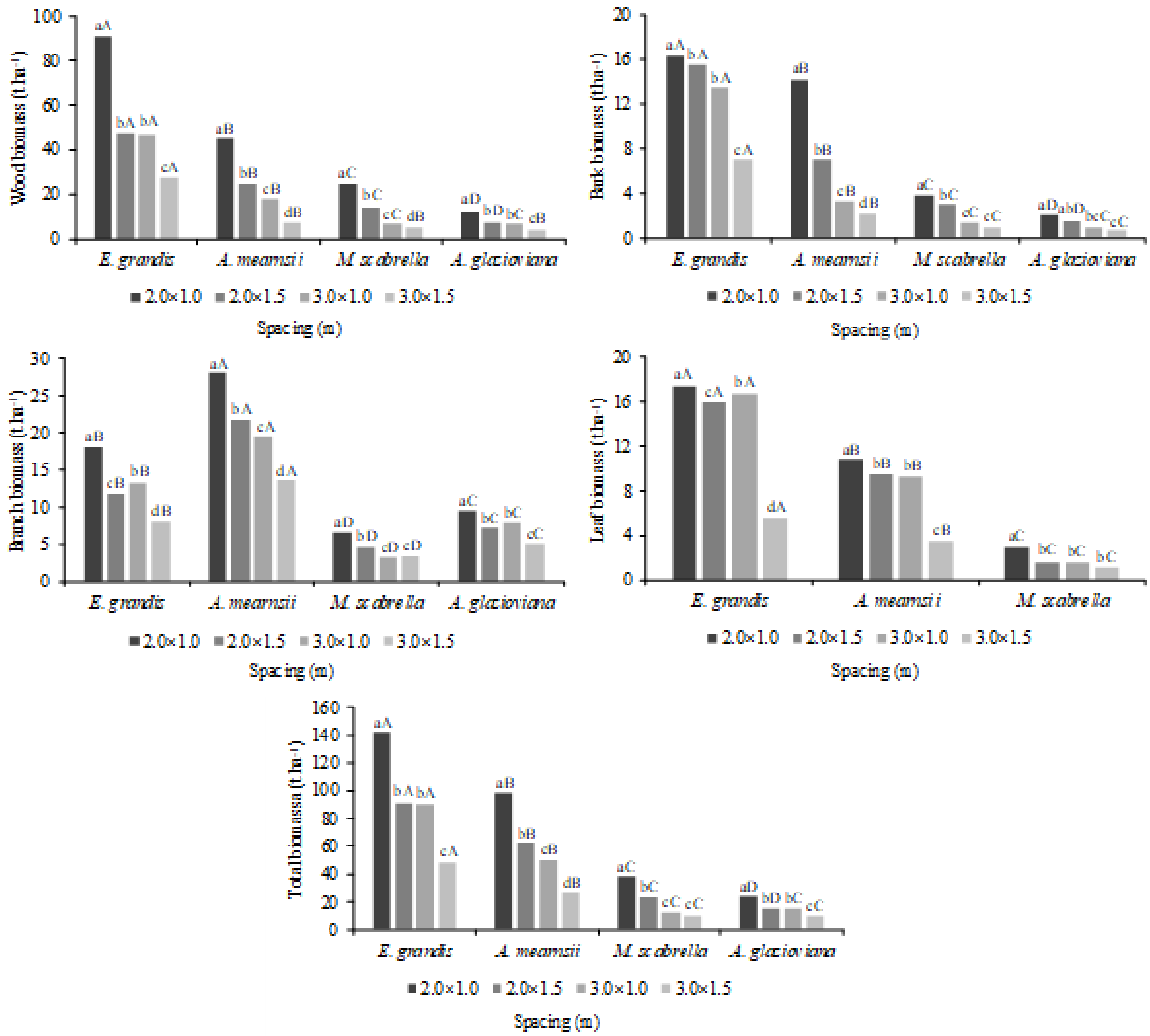

Figure 2 – Mean values of wood, bark, branch, leaf, and total biomass (t ha^{-1}) of forest species distributed in different spacings, three years after planting.

Figura 2 – *Valores médios de biomassa da madeira, casca, galho, folha e total (t ha^{-1}), das espécies florestais distribuídas nos diferentes espaçamentos, três anos após o plantio.*

Acacia mearnsii (Figure 4b) and *Mimosa scabrella* (Figure 4d) showed similar characteristics of proportions over time; however, the differences were less pronounced than that in *Eucalyptus grandis*. Regarding wood production, a variation of 35.9% to 61.1%, and 30.4% to 69.6%, respectively, was found from the 1st to 5th year. In contrast, *Ateleia glazioviana* (Figure 4c) showed a decrease in the proportion of wood biomass over time, which was low until the 3rd year, with a variation from 79.9% to 46.8%, and increased until the 5th year (71.1%).

4.DISCUSSION

It was observed that the spacings tested affected biomass yields of the aerial parts of forest trees. Our results are corroborated by the findings of various

Where: Means followed by the same lowercase letters do not differ between spacings, in the respective species; Means followed by upper case letters do not differ between species, in the respective spacings, at 5% of error probability according to Tukey's test.

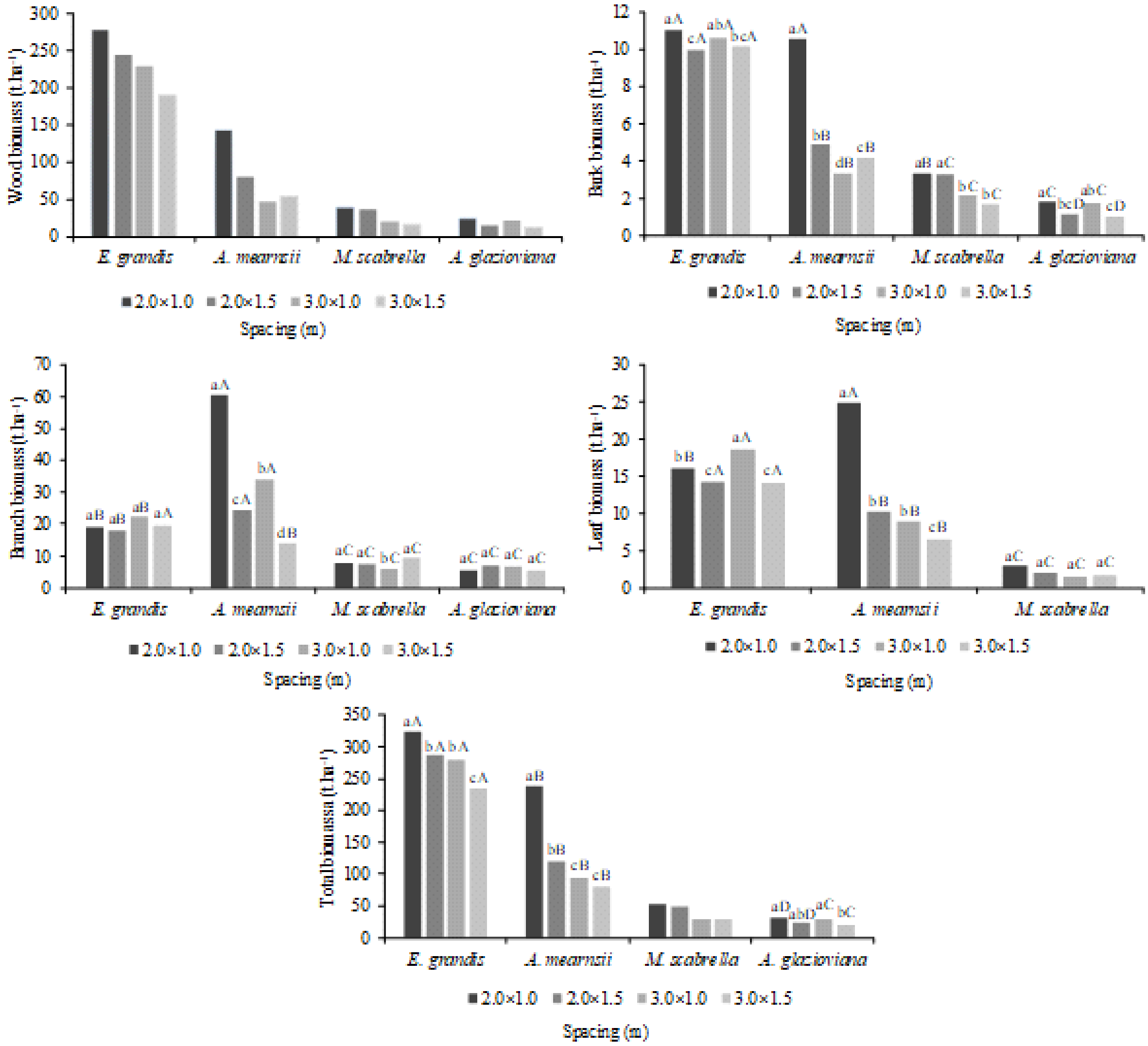

Figure 3 – Mean values of wood, bark, branch, leaf, and total biomass (t ha^{-1}) of forest species distributed in different spacings, five years after planting.

Figura 3 – *Valores médios de biomassa da madeira, casca, galho, folha e total (t ha^{-1}), das espécies florestais distribuídas nos diferentes espaçamentos, cinco anos após o plantio.*

previous studies that demonstrated the influence of density and planting age on the production of forest stands. Among these are the studies of Schneider et al. (2001), Leles et al. (2001), and Müller et al. (2005). Other authors such as Leite et al. (1997), Assis et al. (1999), Santana et al. (1999), Ladeira et al. (2001), Rondon (2002), Vieira et al. (2012), and Schikowski et al. (2013) found an effect of plant spacing, population age, and site quality on biomass distribution between and within species.

The average values of biomass produced in this work were lower than those reported in previous studies from the stands of younger ages. Lima et al. (2011) found an average biomass yield of the *Eucalyptus*

Where: x = year after planting; R² = Coefficient of determination; CV = Coefficient of variation.

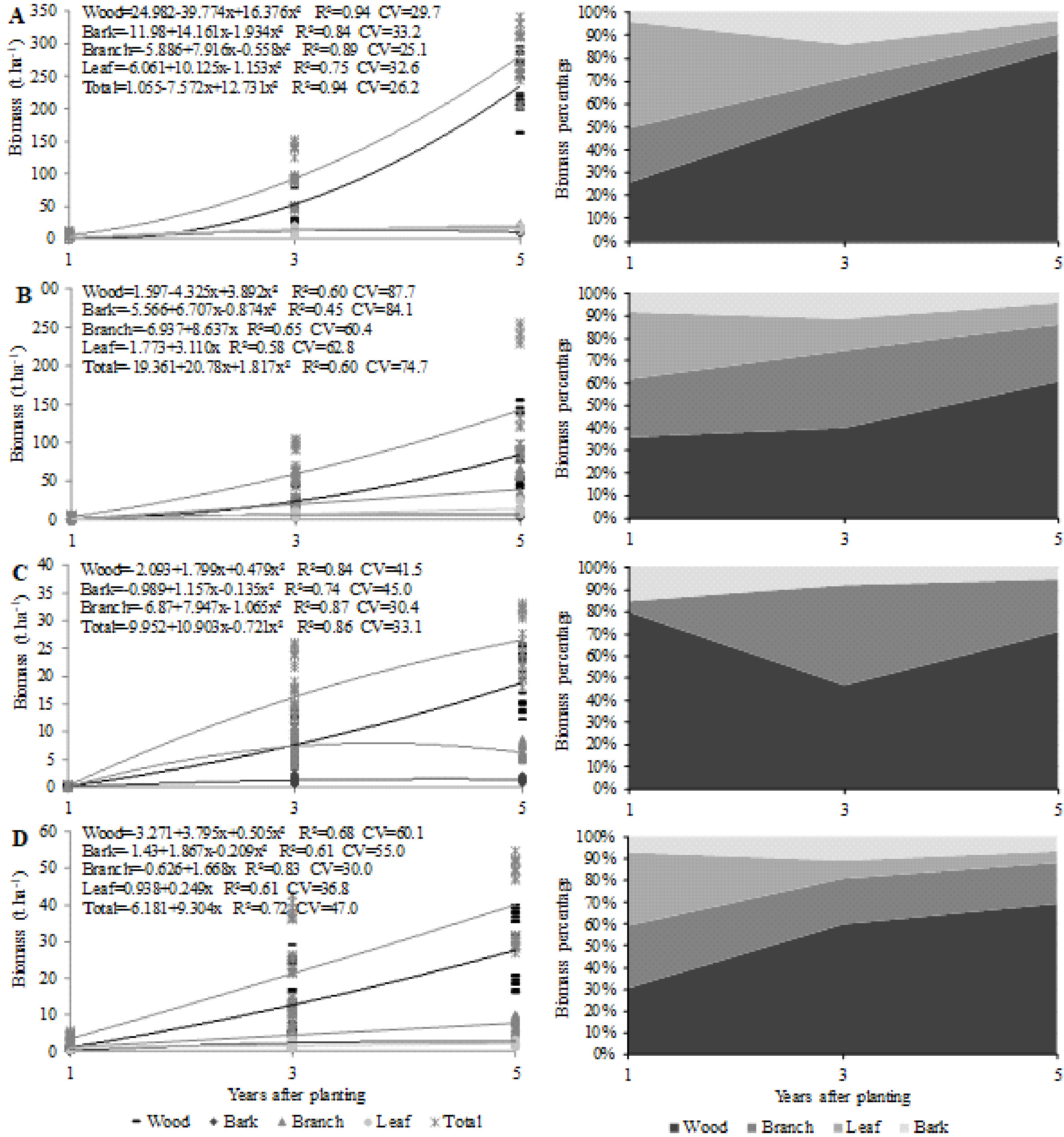

Figure 4 – Regression equations (left) of wood, bark, branch, leaf, and total biomass (ton ha^{-1}) and percentage of biomass (right) of the four forest species: *Eucalyptus grandis* (A), *Acacia mearnsii* (B), *Ateleia glazioviana* (C), and *Mimosa scabrella* (D), in different years after planting.

Figura 4 – *Equações de regressão (à esquerda) da biomassa da madeira, casca, galho, folha e total (ton ha^{-1}) e porcentagem da biomassa (à direita) das quatro espécies florestais: Eucalyptus grandis (A), Acacia mearnsii (B), Ateleia glazioviana (C) e Mimosa scabrella (D), em diferentes anos após o plantio.*

benthamii stem of 416 t ha^{-1}, at 6 years of age. Also, Brito et al. (1983) found biomass productions of 405.6 t ha^{-1} *Eucalyptus Salina*, and 518.2 t ha^{-1} for *Eucalyptus grandis*, at 10 years of age.

The lower initial biomass production of *Ateleia glazioviana* than that in the other species, both in terms of period and spacing (Figures 1 and 2), is because of its growth, which is considered to be slow or delayed, according to Carvalho (2003). However, due to its characteristic bifurcations and large canopy, this species produced a considerable amount of branch biomass (Figure 2). This variation is influenced mainly by the greater area available to the canopy in less dense plantings.

The highest values of biomass observed in treatments with higher planting densities confirm the results of Botelho (1998) and Oliveira Neto et al. (2003): relating planting density with the distribution of biomass in the components of the different species, we found higher biomass production per unit area in the smaller planting spacing, which was mainly owing to the greater number of individual plants.

Thus, decreasing trends of biomass production can be observed in the different parts of the plants as a function of increasing available area for plant growth. However, Müller et al. (2005) reported that over time the amount of wood in trees planted in different spacings tends to equalize, owing to growth stagnation in the denser plantations at younger ages and wider-spaced plantings at more advanced ages.

Wood biomass represented the largest proportion of biomass production. The increase of this proportion was observed throughout all age groups, except for in *Ateleia glazioviana*, which showed an irregular growth pattern than the other species. In relation to branch, leaf, and bark, an oscillation in the participation of these biomass components was observed throughout the age classes; however, there seemed to be no evidence of uniformity, although a trend of their respective proportions to decrease with stem growth was observed (Figure 4).

The more pronounced development of wood in *Eucalyptus grandis* compared with that in other components and species is in line with the results of Vieira et al. (2012). Their study described an increase of growth in these components, reaching more than 85% of the total aerial biomass at 6 years of age. Correspondingly, Rondon (2002) observed that the majority of the aerial biomass of trees is within the trunk portion.

Poggiani et al. (1983) and Pereira et al. (1984) found that on average 85% of the aerial biomass of *Eucalyptus saligna* at 8 and 9 years of age comprised of wood and bark, whereas the rest was accounted for by the canopy. Moreover, Santana et al. (1999) found an even more pronounced bias than those in the earlier studies, with 88% to 92% of the biomass concentrated in the stems of *Eucalyptus saligna* and *Eucalyptus grandis* at five sites with trees above 6.5 years of age. Similar results were found in *Eucalyptus* spp. by Leles (1995) and Barichello et al. (2005), who confirmed the relative contributions to total biomass by the different components in the following order: wood > branch > leaf > bark.

Schumacher (1992) argues that during the initial development phase of a forest, much of the total carbohydrates is used for the production of biomass of the canopy, but over time, when individual canopies begin to compete with each other for space, biomass production in the trunk increases and that of the leaves and branches decreases gradually. However, Schikowiski et al. (2013) and Eloy et al. (2017b) emphasize the importance of the other components besides the stem in order to assess the total biomass of a tree and its variation, and to identify the potentially influencing factors.

5. CONCLUSIONS

Biomass production of different forest tree species is influenced by plant spacing and depends on the age after planting.

The increase in planting density is directly related to biomass production per unit area, i.e., denser spacings yield larger quantities of biomass than the less-dense plantings.

Forest species differ regarding biomass production. *Eucalyptus grandis* produced the largest quantity, followed by *Acacia mearnsii*, *Mimosa scabrella*, and *Ateleia glazioviana*.

Age affects the production and proportion of the biomass components.

Wood biomass represents the largest proportion of biomass production over time, with increasing percentage proportions throughout all age groups, followed by those of the branch, leaf, and bark.

For a greater production of aerial biomass within a shorter duration, it is, thus, recommended to plant *Eucalyptus grandis* in spacings of 2.0 × 1.0 m.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Assis RL, Ferreira MM, Morais EJ. A produção de biomassa de *Eucalyptus urophylla* S. T. Blake sob diferentes espaçamentos na região de cerrado de Minas Gerais. Revista Árvore, 1999; 23, (2):151-6.

Barichello LR, Schumacher MV, Vogel HLM. Quantificação de biomassa de um povoamento de *Acacia mearnsii* De Wild. na Região Sul do Brasil. Ciência Florestal. 2005;15(2):129-35.

Botelho SA. Espaçamento. In: Scolforo JRS. Manejo florestal. Lavras: UFLA/FAEPE; 1998. p.381-405.

Brito JO, Barrichelo LEG, Seixas F, Migliorini AJ, Muramoto MC. Análise da produção energética e de carvão vegetal de espécies de eucalipto. IPEF. 1983(23):53-6.

Carneiro ACO, Castro AFNM, Castro RVO, Santos RC, Ferreira LP, Damásio RAP, et al. Potencial energético da madeira de *Eucalyptus* sp. em função da idade e de diferentes materiais genéticos. Revista Árvore. 2014;38(2):375-81.

Caron BO, Eloy E, Souza VQ, Schmidt D, Balbinot R, Behling A, et al. Quantificação da biomassa florestal em plantios de curta rotação com diferentes espaçamentos. Comunicata Scientiae. 2015; 6(1): 106-12.

Carvalho PER. Espécies arbóreas brasileiras. Colombo: Embrapa Florestas; 2003. 1039p.

Eloy E, Caron BO, Silva DA, Souza VQ, Trevisan R, Behling A, et al. Produtividade energética de espécies florestais em plantios de curta rotação. Ciência Rural. 2015;45(8):1424-31.

Eloy E, Silva DA, Caron BO, Elli EE, Schwerz F. Age and tree spacing and their effects on energy properties of *Ateleia glazioviana*. Ciência Rural. 2017a; 47(9):378-87.

Eloy E, Silva DA, Caron BO, Trevisan R, Balbinot R. Effect of age and plant spacing on the energy properties of black wattle. Comunicata Scientiae.2017b;8(3):469-76.

Empresa Brasileira de Pesquisa Agropecuária - Embrapa. Sistema Brasileiro de Classificação de Solos. 2ª.ed. Rio de Janeiro: Embrapa-SPI; 2006.

Ladeira BC, Reis GG, Reis MGF, Barros NF. Produção de biomassa de eucalipto sob três espaçamentos em uma seqüência de idade. Revista Árvore. 2001;25(1):69-78.

Leite FP, Barros NF, Novaes NF. Crescimento de *Eucalyptus grandis* em diferentes densidades populacionais. Revista Árvore. 1997;21(3):313-21.

Leles PSS, Reis GG, Reis MGF, Moraes EJ. Crescimento, produção e alocação de matéria seca *E. camaldulensis* e *E. pellita* sob diferentes espaçamentos na região do cerrado, MG. Scientia Forestalis. 2001(59):77-87.

Leles PSS. Crescimento alocação de biomassa e distribuição de nutrientes e uso de água em *E. camaldulensis* e *E. pellita* sob diferentes espaçamentos [dissertação] Viçosa, MG: Universidade Federal de Viçosa; 1995.

Lima EA, Silva HD, Lavoranti OJ. Caracterização dendroenergética de árvores de *Eucalyptus benthamii*. Pesquisa Florestal Brasileira. 2011;31(65):9-17.

Maluf JRT. Nova classificação climática do Estado do Rio Grande do Sul. Revista Brasileira de Agrometeorologia. 2000;8(1):141-50.

Brasil. Ministério das Minas e Energia. Balanço Energético Nacional - Ano base 2015. Empresa de Pesquisa Energética. Rio de Janeiro: 2016. 62p.

Müller MD, Couto L, Leite HG, Brito JO. Avaliação de um clone de eucalipto estabelecido em diferentes densidades de plantio para produção de biomassa e energia. Biomassa & Energia. 2005;2(3):177-86.

Oliveira Neto SN, Reis GG, Reis MGF, Neves JCL. Produção e distribuição de biomassa em *Eucalyptus camaldulensis* Dehn. em resposta à adubação e ao espaçamento. Revista Árvore. 2003;27(1):15-23.

Rondon EV. Produção de biomassa e crescimento de árvores de *Schizolobium amazonicum* sob diferentes espaçamentos na região da mata. Revista Árvore. 2002;26(5):573-6.

Pereira AP, Andrade DC, Leal PGL, Teixeira NCS. Produção de biomassa e remoção de nutrientes em povoamentos de *Eucalyptus citriodora* e *Eucalyptus saligna* cultivados na região de cerrado de Minas Gerais. Floresta. 1984;15(1):18-26.

Poggiani F, Couto HTZ, Corradini L, Fazzuo ECM. Exploração de biomassa e nutrientes através da exportação dos troncos e das copas de um povoamento de *Eucalyptus saligna*. IPEF. 1983(25):37-9.

Sanquetta CR. Métodos de determinação de biomassa florestal. In: Sanquetta CR, editor. As florestas e o carbono. Curitiba: 2002. p.119-40.

Sanquetta CR, Behling A, Dalla Corte AP, Simon A, Pscheidt H, Ruza MS, Mochiutti S. Estoques de biomassa e carbono em povoamentos de acácia-negra em diferentes idades no Rio Grande do Sul. Scientia Forestalis. 2014b;42(103):361-70

Sanquetta CR, Dalla Corte AP, Mognon F, Maas GCB, Rodrigues AL. Estimativa de carbono individual para *Araucaria angustifolia*. Pesquisa Agropecuária Tropical. 2014a;44(1):1-8.

Santana RC, Barros NF, Neves JCL. Biomassa e conteúdo de nutrientes de procedências de *Eucalyptus grandis* e *Eucalyptus saligna* em alguns sítios florestais do estado de São Paulo. IPEF. 1999(56):155-69.

SAS Learning Edition. Getting started with the SAS Learning Edition. Cary: 2003. 200p.

Schikowiski AB, Dalla Corte AP, Sanquetta CR. Modelagem do crescimento e de biomassa individual de Pinus. Pesquisa Florestal Brasileira. 2013;33(75)269-78.

Schneider PR, Fleig FD, Finger CAG, Spathelf P. Produção de madeira e casca verde por índice de sítio e espaçamento inicial de Acácia-negra (*Acacia mearnsii* De Wild). Ciência Florestal. 2001;11:151-65.

Schumacher MV. Aspectos da ciclagem de nutrientes e do microclima em talhões de *Eucalyptus camaldulensis* Dehnh, *Eucalyptus grandis* Hill ex Maiden e *Eucalyptus torelliana* F. Messel [dissertação] Piracicaba: Escola Superior de Agricultura "Luiz de Queiroz", Universidade de São Paulo; 1992.

Vieira M, Bonacina DM, Schumacher MV, Calil FN, Caldeira MVW, Watzlawick LF. Biomassa e nutrientes em povoamento de *Eucalyptus urograndis* na Serra do Sudeste-RS. Semina: Ciências Agrárias. 2012;33(1):2481-90.