INFLUENCE OF INITIAL DENSITY ON BIOMASS PRODUCTION IN A *Pinus taeda* L. PLANTATION IN THE CENTRAL-SOUTH REGION OF PARANÁ, BRAZIL

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Resumo

Influência da densidade inicial na produção de biomassa em plantação de Pinus taeda L. na região Centro-Sul do Paraná. A avaliação do potencial produtivo de um plantio florestal, por meio da produção de biomassa, é fundamental para o manejo e o planejamento das indústrias de base florestal, sendo o espaçamento um dos fatores de maior relevância na produção de biomassa. O presente estudo teve como objetivo avaliar a produção de biomassa acima do solo em povoamentos de *Pinus taeda* L. em função do espaçamento, onde foram avaliados três diferentes talhões (2,0 m x 2,0 m (menor); 3,0 m x 2,0 m (médio) e 4,0 m x 2,0 m (maior)), implantados no município de Irati, Paraná. Foram amostradas pelo método direto, 47, 43 e 46 árvores, totalizando 136 árvores, respectivamente. Cada árvore foi segmentada em: fuste, galhos vivos, galhos mortos e acículas. O teste F (ANOVA) e o teste de médias de Tukey foram aplicados. Para todos os componentes individuais analisados, o espaçamento "maior" acumulou mais biomassa do que os espaçamentos "menor" e "médio", sendo 34,5 e 14,9% maior para a biomassa total individual, respectivamente. Já para a produção por hectare, o espaçamento "menor" produziu 36,0 e 20,2% mais biomassa do que os espaçamentos "maior" e "médio", respectivamente, configurando-se como o mais apropriado para a produção de biomassa total. O componente "fuste" representou de 83,7 a 88,5% da biomassa produzida, seguido pelos "galhos mortos", "galhos vivos" e "acículas". Somente a biomassa para galhos mortos e acículas sofreram influência significativa do espaçamento.
Palavras-chave: Espaçamento de plantio; estoque de biomassa; biomassa aérea; avaliação de biomassa florestal.

Abstract

The evaluation of the productive potential of a forest plantation through biomass production is fundamental for managing and planning forest-based industries, with the spacing one of the factors that has influence on biomass production. This study aimed to evaluate the production of aboveground biomass in *Pinus taeda* L. stands as a function of the spacing, in which three different stands (2.0 m x 2.0 m (smallest), 3.0 m x 2.0 m (medium) and 4.0 m x 2.0 m (larger)), implanted in the municipality of Irati, Paraná state, Brazil, were evaluated. Thus, 47, 43 and 46 trees (from the 3 different spacings) were sampled by the direct method, respectively, totaling 136 trees. Each tree was segmented into: stem, live branches, dead branches and needles. The F-test (ANOVA) and Tukey's test was applied. For all individual components analyzed, the "larger" spacing accumulated more biomass than the "smallest" and "medium" spacings, being 34.5 and 14.9% higher for the individual total biomass, respectively. As for the production per hectare, the "smallest" spacing produced 36.0 and 20.2% more biomass than the "larger" and "medium" spacings, respectively, configuring itself as the most appropriate for the total biomass production. The "stem" component represented from 83.7 to 88.5% of the produced biomass, followed by "dead branches", "live branches" and "needles". Only the biomass for dead branches and needles were significantly influenced by spacing.
Keywords: Plantation spacing; biomass stock; aboveground forest biomass; forest biomass assessment.

INTRODUCTION

The planted forest sector in Brazil is primarily responsible for supplying forest-based industries, being an important indicator of economic, social and environmental development, providing the population with job opportunities and income generation, in addition to contributing with the mitigation of climate change and the provision of ecosystem services. Of the total planted forest areas in the country, 1.64 million hectares (18%) are of the *Pinus* genus, with the state of Paraná being the largest producer, representing 44% of total production (IBÁ, 2019).

Evaluating the productive potential of a forest plantation through biomass production is fundamental for managing and planning of forest-based industries, especially when the biomass distribution in the tree components is known. Sanquetta *et al.* (2015) considered that the term forest biomass can mean the entire plant mass existing in the forest or just the arboreal fraction thereof, and the term forest phytomass or arboreal phytomass can also be used.

Quantifying forest biomass is of fundamental economic importance. For example, raw material in the energy industry is acquired according to the amount of weight that the forest represents, as volume estimates often do not represent the real energy potential that the forest has produced. In addition to the use of raw materials for energy, forests have received increasing attention regarding their potential to contribute to reduce the “greenhouse effect” through their ability to store carbon during the natural process of biomass production (CHAVE *et al.*, 2014; KUSMANA *et al*., 2018).

However, directly determining the forest biomass is a laborious process with a high cost involved, since it is necessary to cut down representative trees of the plantation and determine the mass of its components: stem, live branches, dead branches, needles and sometimes, the roots. Nevertheless, determining biomass by the direct way is essential to generate the database used in fitting allometric models capable of estimating the total biomass and by tree component through easily obtainable dendrometric variables (SANQUETTA *et al*., 2015).

Studies have recently been developed to quantify biomass production and carbon stock (SCHIKOWSKI *et al.*, 2013; SCHUMACHER *et al.*, 2013; WATZLAWICK *et al.*, 2013; CUBAS *et al.*, 2016; OLIVEIRA *et al.*, 2016; PACHECO *et al.*, 2020; CARVALHO *et al.*, 2021). Oliveira *et al.* (2016) evaluated the carbon stock in the *Pinus elliottii* Engelm biomass at 12 years of age in southern Brazil and found 107.87 t ha^{-1} of carbon stored in the biomass. Likewise, Carvalho *et al*. (2021) evaluated and compared shoot biomass and carbon stock in different tree components in a mixed *Pinus taeda* L. and *Pinus elliottii* Engelm plantation, which produced 171.5 t ha^{-1} of biomass and 77.0 t ha^{-1} of carbon, with the stem being responsible for more than 60% of the biomass and total carbon.

Spacing in forest stands is a very important variable which has a direct influence on both biomass production and wood quality (PACHECO *et al*., 2015; RIBEIRO *et al*., 2017). Therefore, the variable has the potential to build models which aim to quantify biomass, especially aboveground at different spacings in order to assist in decision making for achieving the proper management of forest stands.

In view of the above, the objective of this study was to evaluate the influence of the initial density of planting in the production of individual biomass and per hectare in a *Pinus taeda* L. plantation in the Center-South region of the State of Paraná, Brazil.

MATERIAL AND METHODS

Description of the study area and data collection

The study was conducted in three *Pinus taeda* stands located at the *Universidade Estadual do Centro-Oeste* (*UNICENTRO*), Irati Campus, in the Center-South region of the state of Paraná, Brazil. The stands were established in 2003 at different initial planting densities (2.0 m x 2.0 m, 3.0 m x 2.0 m and 4.0 m x 2.0 m). Based on the diameter distribution (Figure 1) of each stand, 47, 43 and 46 trees were sampled by the direct method in the year 2018 (at 15 years of age and with a site index (SI) of 18), respectively, in the aforementioned spacings, totaling 136 trees.

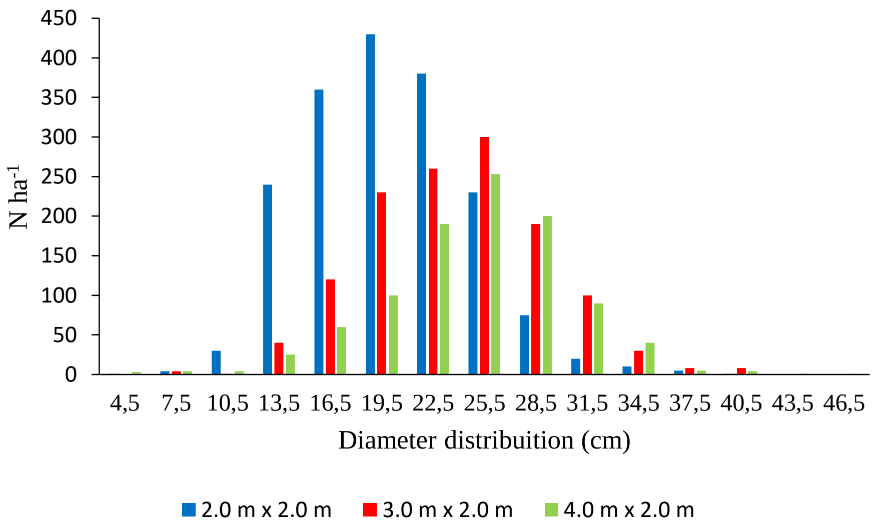

Figure 1. Diameter distribution of the 100% inventory in a 15-year-old *Pinus taeda* plantation in each spacing.

Figura 1. Distribuição diamétrica do inventário a 100% realizado em um plantio de *Pinus taeda*, com 15 anos de idade, em cada espaçamento.

Each tree was divided into four components after felling: stem, dead branches, live branches and needles, being weighed separately in the field to obtain the wet biomass, in kilograms (kg), with the aid of a mechanical scale. A representative sample was taken for each evaluated component; thus, samples for the stem component were collected systematically from the base to the apex. Random samples for live and dead branches were taken to cover all sizes and thicknesses of branches, while needle samples were collected in different regions along the crown. These samples were weighed on a digital analytical scale at the Forest Management Laboratory of *UNICENTRO*, Irati Campus and then taken to an oven at 70 ºC until reaching constant weight to determine dry mass in kilograms (kg).

Individual and per hectare biomass production for each component and by spacing

The total dry biomass and of each component for each individual at 15 years was determined as a function of the wet biomass of the tree measured in the field and the wet and dry biomass of the samples, according to equation (1). With the average dry biomass in each spacing, and based on the 2018 census, it was possible to infer the biomass per hectare, multiplying the average biomass of each component and in each spacing by the number of trees per hectare arising from the census, resulting in the dry biomass of each component per hectare.

$$BS = \frac{PU_{tree}.PS_{sam}}{PU_{sam}} \quad (1)$$

In which: BS = dry biomass of each component (kg); PU_{tree} = green biomass of each tree component (kg); PS_{sam} = dry biomass of the sample of each component (kg); PU_{sam} = green biomass of the sample of each component (kg).

Influence of initial density on individual biomass production

A Completely Randomized Design (CRD) was used to analyze the effects of spacing on biomass production at 15 years of age, for which each spacing was considered a treatment and each tree a repetition. Bartlett's test was applied to verify the homogeneity of variance of the data and then ANOVA was performed. Finally, Tukey's test was applied if the F test indicated significance. A significance level of 5% was considered in all tests.

RESULTS

Individual and per hectare biomass production for each component and by spacing

Based on the sample trees, the average individual biomass production (Table 1 and Figure 2) was quantified by the direct method, as well as the biomass per hectare (Table 2 and Figure 3) of each component by spacing.

Table 1. Average quantification of individual biomass (in kilograms per individual) for each component and total (by initial density) in a 15-year-old *Pinus taeda* plantation.
Tabela 1. Quantificação média de biomassa individual, em quilogramas por indivíduo, para cada componente e total, por densidade inicial, em um plantio de *Pinus taeda*, com 15 anos de idade.

Spacing (m x m)	Stem		Dead branches		Live branches		Needles		Total	
	kg ind^{-1}	%	kg ind^{-1}	%	kg ind^{-1}	%	kg ind^{-1}	%	kg ind^{-1}	%
2.0 x 2.0	150.66	88	6.74	4	7.77	5	5.12	3	170.30	100
3.0 x 2.0	178.24	90	8.64	4	7.74	4	4.78	2	199.40	100
4.0 x 2.0	191.85	84	16.26	7	12.17	5	8.81	4	229.10	100

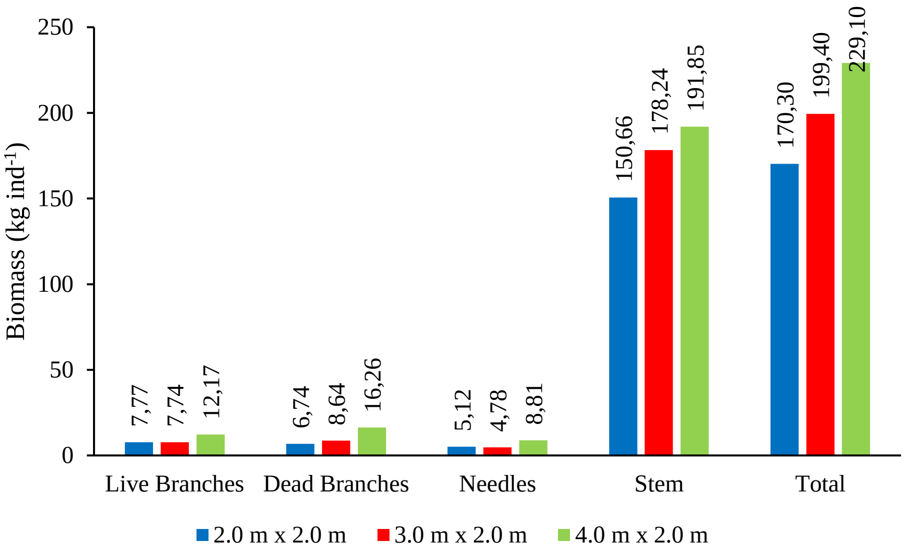

Figure 2. Average production of individual biomass for each component and total biomass in each spacing in a 15-year-old *Pinus taeda* plantation.
Figura 2. Produção média de biomassa individual, para cada componente e biomassa total, em cada espaçamento, em um plantio de *Pinus taeda*, com 15 anos de idade.

Table 2**.** Quantification of total biomass (in megagram per hectare), and each component by spacing in a 15-year-old *Pinus taeda* plantation.
Tabela 2. Quantificação de biomassa total, em megagrama por hectare, e para cada componente, por espaçamento, em um plantio de *Pinus taeda*, com 15 anos de idade.

Spacing (m x m)	N ha^{-1} (*)	Mort. (%)	Stem		Dead branches		Live branches		Needles		Total	
			Mg ha^{-1}	%	Mg ha^{-1}	%	Mg ha^{-1}	%	Mg ha^{-1}	%	Mg ha^{-1}	%
2.0 x 2.0	1787	28.5	269.29	88	12.05	4	13.89	5	9.16	3	304.39	100
3.0 x 2.0	1270	23.8	226.32	90	10.97	4	9.83	4	6.06	2	253.19	100
4.0 x 2.0	977	21.8	187.4	84	15.89	7	11.89	5	8.6	4	223.78	100

(*) Number of trees per hectare and by spacing from the 100% inventory at age 15 years; death = mortality in relation to the initial density of each spacing; Mg ha^{-1} = megagram per hectare.

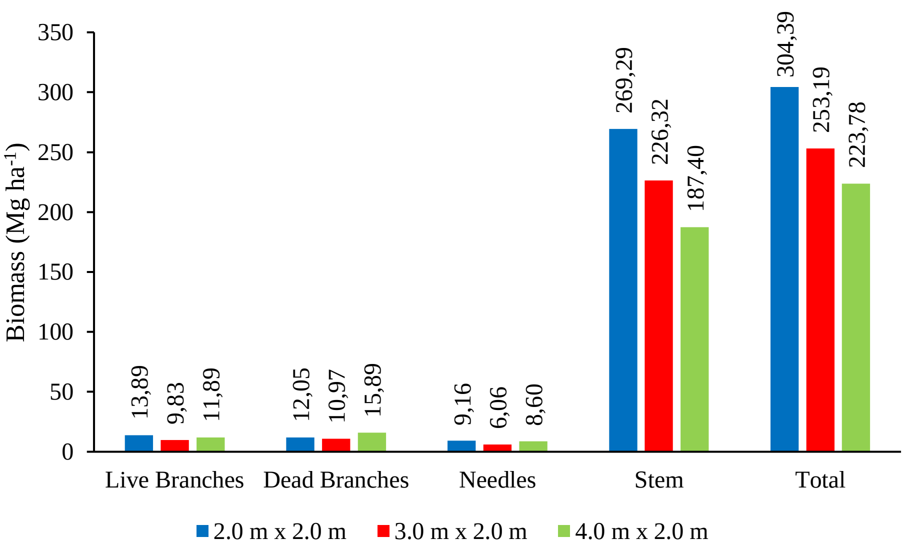

Figure 3. Average biomass production per hectare for each component and total biomass in each spacing in a 15-year-old *Pinus taeda* plantation.

Figura 3. Produção média de biomassa por hectare, para cada componente e biomassa total, em cada espaçamento, em um plantio de *Pinus taeda*, com 15 anos de idade.

The largest spacing (4.0 m x 2.0 m) produced the largest amount individual average biomass (191.85 kg ha^{-1}; 16.26 kg ha^{-1}; 12.17 kg ha^{-1}; 8.81 kg ha^{-1}; 229.10 kg ha^{-1}, for the stem, dead branches, live branches, needles and total, respectively) (Table 1 and Figure 2). The opposite is observed in the 2.0 m x 2.0 m spacing where competition for space and nutrients is greater, causing the growth of tree components to be lower than for other spacings, in turn causing a lower accumulation of biomass per tree. Next, not only the weight of the components is taken into account for the biomass per hectare (Table 2 and Figure 3), but also the number of individuals per unit of area. The spacing with the highest density of trees produces the highest amount of biomass per hectare (269.29 Mg ha^{-1}; 13.89 Mg ha^{-1}; 12.05 Mg ha^{-1}; 9.16 Mg ha^{-1}; 304.39 Mg ha^{-1}, for the stem, live branches, dead branches, needles and total, respectively).

The allocation of biomass in the components of 15-year-old *Pinus taeda* trees showed the following accumulation sequence: stem, dead branches, live branches and needles, except for the 2.0 m x 2.0 m spacing, where the production of live branches is greater than that of dead branches.

Influence of initial density on individual biomass production

Table 3 presents the Bartlett, ANOVA and Tukey's tests to compare the individual mean values of each component and the total biomass by spacing. The Bartlett test showed that the data variance is homogeneous, with no need for transformation, thus being able to proceed to ANOVA in which the calculated F was only significant for the components "dead branches" and "needles". When applying the Tukey's test for the components dead branches and needles, it was observed that only the individual average biomass of dead branches in the 4.0 m x 2.0 m spacing is different from the other spacings, producing a greater amount of biomass. However, the Tukey's test did not detect differences between the biomass averages of each spacing for the needle component, because the p-value of ANOVA (3.9%) is close to the limit of 5% where the averages do not differ, meaning it is not influenced by the spacing.

Table 3. Statistical analysis of individual mean averages of biomass by component and total by spacing in a 15-year-old *Pinus taeda* plantation.

Tabela 3. Análises estatísticas das médias individuais da biomassa por componente e total, por espaçamento em plantio de *Pinus taeda* aos 15 anos de idade.

Components	2.0 m x 2.0 m	3.0 m x 2.0 m	4.0 m x 2.0 m	χ^2 calc	F calc	p-value
		kg ind^{-1}				
Stem	150.66	178.24	191.85	9.44 *	1.4421 ns	0.2401
Dead branches	6.74 b	8.64 b	16.26 a	85.40 *	22.9097 *	0.0001
Live branches	7.77	7.74	12.17	98.13 *	2.6469 ns	0.746
Needles	5.12 a	4.77 a	8.81 a	190.92 *	3.3137 *	0.039
Total	170.29	199.40	229.10	14.52 *	2.1274 ns	0.1232

There is a critical value (α = 5%) of 5.99148 For χ^2; there is a critical F of 3.0633 for F>1; * significant at the 5% significance level; ns = not significant at the 5% significance level; means followed by the same letter on the line do not differ statistically by Tukey's test.

DISCUSSION

The highest concentration of biomass is in the stem with more than 80% of the total biomass, being typical of adult stands. This trend was confirmed by other authors who also quantified the biomass in *Pinus taeda* plantations (VIEIRA *et al*., 2011; SCHIKOWSKI *et al*., 2013; SCHUMACHER *et al*., 2013), where the stem represented more than 50% of the biomass total per tree.

The individual crown biomass ranged from 19.64 to 37.25 kg $ind.^{-1}$, corroborating the values found by Lima (2014), when evaluating the effect of different living spaces on the biomass and carbon production of *Pinus taeda* at 9 years old implanted in the Southeast region of Paraná. The crown biomass values obtained by the author ranged from 15.7 kg $ind.^{-1}$ to 54.1 kg $ind.^{-1}$ at 2.0 m x 2.0 m and 4.0 m x 3.0 m spacing, respectively.

Although the statistical tests did not show differences in the averages of most components, the average production per tree of the less dense spacing (4.0 m x 2.0 m) was 27.34%; 141.25%; 56.63%; 72.07% and 34.53% higher than the denser spacing (2.0 m x 2.0 m) for the stem components, dead branches, live branches, needles, and for total biomass, respectively. On the other hand, the average total production per hectare of the less dense plot (4.0 m x 2.0 m) was 36.02% lower than the denser spacing (2.0 m x 2.0 m).

On the other hand, there was an inversion of this trend for the individual components live branches, dead branches and needles, in which the spacing of 4.0 m x 2.0 m presented higher biomass values in relation to the others; this is because there is less competition for light in less dense stands, having more space for the development of the crowns, larger amount of branches and consequently, larger accumulations of biomass in the crown components. The smallest percentage difference found is 6.5% for the "needles" component between the densest and the widest spacings.

Vieira *et al.* (2011) evaluated the biomass and nutrient removal during the first thinning in a *Pinus taeda* stand at nine years of age in the state of Rio Grande do Sul, Brazil, at a spacing of 3.0 m x 2.0 m. They found a value of only 35.71 Mg ha^{-1}, which is much lower than that found in this study; a fact justified by the differences in age (9 and 15 years) and probably the site (IS = 18 m).

For Schikowski *et al.* (2013), the biomass of the other compartments in addition to the stem is extremely important and representative in the total biomass estimation. When quantifying the residue biomass in a *Pinus taeda* stand after silvicultural interventions, Ferreira *et al.* (2019) indicated the existence of great potential for the exploitation of residue biomass, especially in multiple-use reforestation, with 87.2% of residue remaining in the exploration area referring to the crown (branches and needles).

Around 36.9 million tons of residual biomass were generated in planted forests in 2018 in Brazil, with 98% of this residue being left in the field (IBÁ, 2019). Normally the crown (dead branches, live branches and needles) is the residual biomass left in the forest, which represents about 10 to 16% (Table 2) of the total biomass, while the highest productions per hectare in the present study occurred in the spacings 2.0 m x 2.0 m and 4.0 m x 2.0 m with 35.1 Mg ha^{-1} and 36.38 Mg ha^{-1}, respectively. In analyzing the energy potential of live branches in 9 different spacings, Pacheco *et al*. (2020) concluded that in addition to wood, spacing of 9 m² can provide residue for energy generation, cellulose or production of briquettes, indicating the use of residual biomass in forestry sector companies with cost effectiveness and reduced carbon dioxide emissions.

CONCLUSIONS

- The total individual aboveground biomass produced in the larger (4.0 m x 2.0 m) spacing is 14.9 and 34.5% greater than the medium (3.0 m x 2.0 m) and smaller (2.0 m x 2.0 m) spacings, respectively. This difference is accentuated for the "crown" component, in which the largest spacing is 76.0 and 89.7% greater than the medium and smallest spacing, respectively.
- Although there is no statistical difference in biomass production between the analyzed spacings, there is a tendency for greater biomass production per hectare in the smallest spacings, since the higher number of trees seems to have a greater weight in the biomass per hectare than the individual values. Thus, a more comprehensive survey in different sites, and with wider samples, could clarify the duality (number of trees per hectare vs. individual biomass) in the biomass production per hectare.
- The stem component represents 83.7 to 89.5% of the produced biomass, followed by dead branches, live branches and needles.
- The individual average biomass production for dead branches and needles were the only components that had a statistically significant influence on spacing.

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