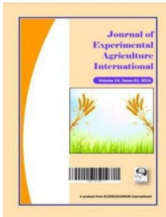

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Modeling and Biomass Quantification in *Eucalyptus saligna* Smith Stand at the End Rotation in the South of Brazil

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Authors' contributions

This work was carried out in collaboration among all authors. The author DRM was responsible for the statistical analyzes and execution of the manuscript. The author MVS is advisor and contributed to the discussion of the data. The author AAL helped in the discussion of the work. The author EFA was responsible for making the study area available. All authors read and approved the final manuscript.

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ABSTRACT

The quantification of wood stock and other components of biomass is fundamental for forest planning. Given the difficulty of obtaining these data, the present study aims at the formulation of equations and the estimation of the different components of biomass, volume with and without bark, form factor and height of the trees at the end rotation. The study was carried out in the municipality of São Gabriel state of Rio Grande do Sul, Brazil with *Eucalyptus saligna* 10-year-old. The experimental design of the inventory and biomass quantification were completely randomized. In the inventory the DBH of all individuals of the 5 plots were measured. After determination of 4 classes of diameter were felled 12 trees and quantified leaves, branches, bark and wood. The selection of the models obtained coefficients of determination higher than 97%. The total biomass

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was 269 Mg ha^{-1}, of which 89% was wood. The total volume was 546 and 494 m³ ha^{-1} with and without bark, representing an average annual increase of 54,6 and 49,4 m³ ha^{-1} year^{-1}. The mean form factor was 0,48. The modeling presented excellent adjustments and certainly serves for future estimates of the stock biomass.

Keywords: Forest biomass; eucalyptus productivity; harvest; sustainability.

1. INTRODUCTION

Currently Brazil has an area of 7.84 million hectares occupied by planted trees, a 2.67% share of the global area. The genus *Eucalyptus* spp. accounts for 72.3% of the total in the country [1]. Between the years 1990 - 2015 occupied area increased at an average geometric rate of 1.8%, although below the world average of 2.1% [2]. The advance of silvicultural techniques such as fertilization, correct management and genetic improvement were responsible for the increase in productivity. Brazil has the highest productivity with an average annual increase of 35.7 m³ ha^{-1} year^{-1} [1].

Although wood is the most desired product, the quantification of other components of biomass such as leaves, branches and bark is essential for the determination of management techniques [3]. According to Salvador et al. [4] with the advancement of the maturity of the stand, the relative contribution of the wood increases, in contrast the biomass of the canopy decreases. Harvesting is the main nutrient export route, however, harvesting only the wood, keeping the remaining residues distributed over the area (tree tops, bark, branches and leaves), minimizes the export of nutrients [5].

According to Momolli and Schumacher [6], timber stripping in the field reduces the amount of nutrients exported, which is important for the sustainability of the site. Based on the authors' review, nutritional replacement via chemical fertilizers does not meet the demands of the soil fauna because it requires organic matter. In addition, the maintenance of residues in the field increases soil moisture and decreases soil compaction [7].

Efficient forest planning requires knowledge of the wood stock. The modeling of regressive (indirect) equations, based on different combinations of independent variables (diameter at breast height and total height) are the most effective ways of estimating the different plant components [8]. Low costs and short time are the main advantages of adopting them [9]. However, it is necessary to quantify the biomass of a representative number of trees through the direct method as a form of adjustment of the models [10].

Given this importance, the present study aims to select models from independent variables. Then, estimate the different components of biomass, form factor, volume with and without bark beyond the total height of the trees of *Eucalyptus saligna* Smith stand at the end of rotation in southern Brazil.

2. MATERIALS AND METHODS

2.1 Characterization of the Experimental Area

The study was developed at Fazenda Santa Clara, owned by CMPC, in the municipality of São Gabriel, state of Rio Grande do Sul. The central geographic coordinates are 30º 29 '330 "S and 54º 34' 667"W (Fig. 1).

The clone of the species *Eucalyptus saligna* Smith was planted in 2008 with spacing of 2.14 m x 3.5 m and initial density of 1335 plants per hectare. At the time of the present study the stand was at harvest age at 10 years of age.

According to the climate classification of Köppen, the climate is classified as being of type Cfa, presenting well distributed rains throughout the year, average temperature of the coldest month in June, with 12.6°C and the warmest month in January with 24.2°C [11]. According to the authors, the historical average rainfall is 1854 mm. In Fig. 2 are presented to meteorological variables along the development of the stand [12].

During the summer months, temperatures rarely exceed the 35°C mark with some short dry season. In the winter months there is frost and minimum temperatures that can reach -5°C. The species *Eucalyptus saligna*, is classified with a medium climatic aptitude for the region of São Gabriel [13].

The soil of the experimental area was classified as dystrophic Red-Yellow Ultisols. The Ultisols are characteristic for presenting textural B horizon. This mineral horizon of the Franco-sandy texture presents an increase of clay when compared to the more superficial horizons. As for the third categorical level, dystrophic Red-Yellow soils present basal saturation <50% in most of the first 100 cm of B horizon [14]. Table 1 shows the chemical and physical attributes of the soil of the area at the time of planting.

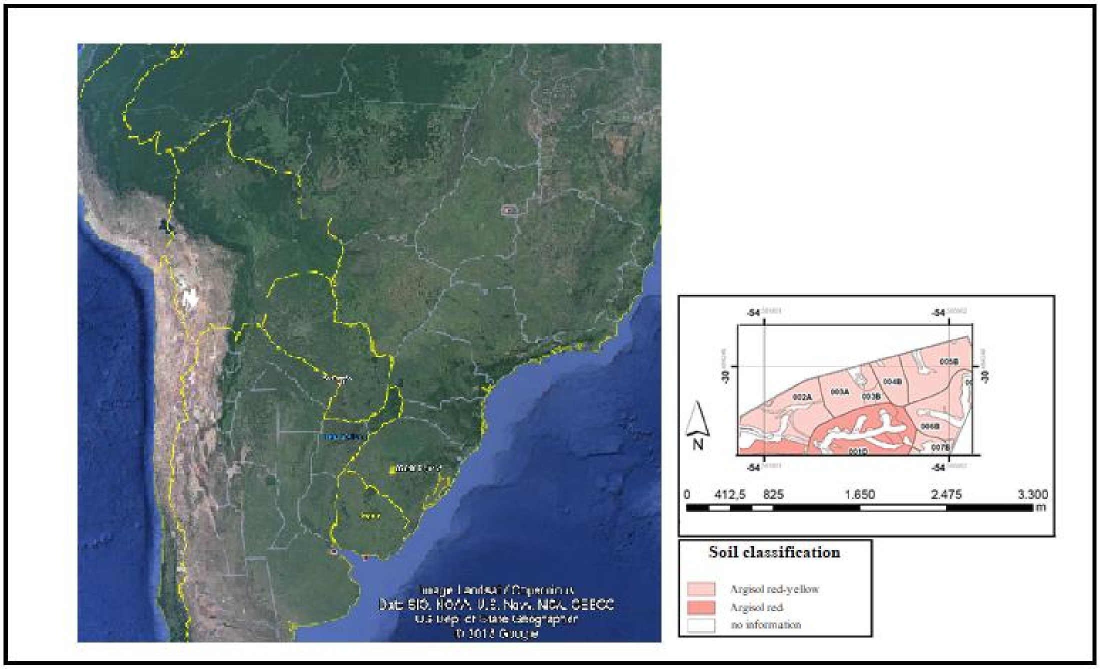

Fig. 1. Location of the municipality of São Gabriel in southern Brazil

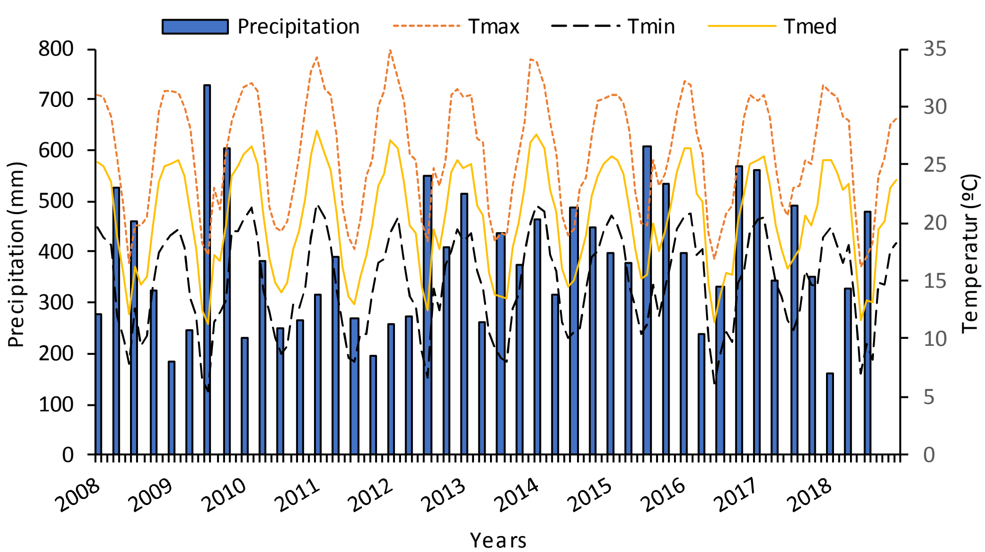

Fig. 2. Climatic diagram for the municipality of São Gabriel - RS
Source: [12]

Table 1. Chemical and physical attributes of the Dystrophic Red-Yellow Ultisol in São Gabriel - RS

Depth.	Clay	OM	pH	Al	H+Al	Ca	Mg	P	K	V	m
cm	%				cmolc dm³			mg dm³		%	
0-20	20,0	1,4	5,2	0,8	6,9	4,4	2,0	1,4	25,0	48,4	11,0
20-40	20,0	3,2	5,3	0,5	4,4	4,8	2,4	3,4	80,0	62,7	6,3

Where: OM = organic matter; V% = base saturation; m = saturation by aluminum

According to the manual of fertilization and liming, the organic matter content can be considered low for the layer 0-20 cm and medium for the layer 20-40. The pH for both depths was considered low. The Mg contents are high; P, too low; K, low in layer 0-20 and high in layer 20-40; Ca, low in the 0-20 layer and medium in the 20-40 layer. Base saturation is classified as low and aluminum saturation at depth 0-20 is average, and depth 20-40 is low [15].

2.2 Experimental Design and Data Collection

The experimental design was completely randomized. For the inventory, 5 plots of 21.4 m x 21 m were randomly demarcated, in which all DBH (diameter at breast height) of the trees were measured. In the possession of the data, by means of the formula of Sturges the number of classes was defined.

$$K = 1 + 3{,}322 \,.\, (log10\ N)$$

Where: K = number of classes by the Sturges formula; N = number of observations.

For each of the 4 diametric classes 3 trees were felled (DBH lower, upper and middle limit.). Through the Smalian method, the 12 trees were obtained to obtain the artificial form factor (Ff).

The quantification of above-ground biomass occurred through compartmentalization into 4 main components: Wood, bark, leaf and branch. The wood and bark components were subdivided into 3 positions: Base, middle and top. For determination of dry weight, the center of each of the positions was sampled.

The total wet biomass was obtained in the field in a precision scale of 100 grams. For determination of the dry biomass, wood and bark were sampled at the 3 different positions in addition to a sample of branches and leaves. They were packed in paper bags and dried in renovation and forced air circulation drying oven at 70°C until reaching constant weight. By means of the difference between wet and dry weight, the dry biomass content was defined.

$$\text{Dry content (\%)} = 1 - \frac{(\text{ww}-\text{dw})}{\text{ww}}$$

Where:

ww = wet sample weight; dw = dry sample weight.

2.3 Statistics and Data Analysis

For the modeling of the independent variables DBH (diameter at breast height) and H (height), SPSS Software 20.0 was used. The choice of equations and variables considered the Stepwise method (Criterion: Probability of $P \leq 0.05$). The combination of the independent variables were as follows: d (diameter at breast height), h (total height), d^2, d^3, h^2, h^3, dh, $(dh)^2$, $(dh)^3$, $d^2.h$, d.(dh), $1/d^2$, $1/d^3$, 1 / h, $1/h^2$, $1/h^3$, 1 / dh, $1/^3$, $1/d^2.h$, $1/d.h^2$, $1/d^3.h$, $1/d.h^3$, in addition to the neperian logarithms of each of these combinations above.

The verification of the determinants was by the Durbin-Watson test in which it evaluates the independence of the residues, that is, the dependence between the terms or correlation. The choice of the models considered the analysis of the following statistical indices: adjusted coefficient of determination R^2 adj., Standard error of the absolute estimate Syx, standard error of the relative estimate Syx (%), probability of error $P \leq 0.05$, F and residue graphical analysis%. The chosen models were used to estimate the biomass of the other trees of the plot, being the same in the sequence extrapolated per hectare.

3. RESULTS AND DISCUSSION

3.1 Distribution of Diameter Classes

The diameter class 3 (18.0 - 22.4) comprised 121 individuals or 46% of the total inventory in the plots. At 10 years of age, 75% of the individuals measured in the inventory had DBH between 18.0 and 26.9. The mean form factor was 0.48 and presented a decreasing behavior as the DBHs increased, from 0.52 in the class of the lowest DBHs to 0.47 in the class of the highest DBHs (Fig. 3).

Evaluating the biomass in a 10-year-old *Eucalyptus urophylla* x *Eucalyptus globulus* hybrid, Viera et al. [16] found 70% of the diameters between 17.0 and 25.0. Similar results were found for the present study, 71.2% of the trees are within the same range of DBH that the authors above. The highest frequency is around the mean diameter of the stand, with a decrease in the extent of advancement to the extremities [17].

The inventory showed a density of 1143 trees per hectare. The mean diameter and height were 20.0 and 29.9. The volume of wood with and without bark was 545.6 and 493.8 m³ ha^{-1}, and an AAI (average annual increase) of 54.6 and 49.4 m³ $year^{-1}$ (Table 2).

The productivity is due to the quality of the genetic material and the excellent climatic aptitude for the studied region. Evaluating the potential productivity of the *Eucalyptus saligna* species in southern Brazil, Pimenta [18] through clustering techniques and with the 3-PG model concluded that the central-west portion of the southern region, as well as the coast of the state of Paraná and Santa Catarina have the highest productivities. For the author, the variables altitude and air temperature were categorical for delimitation of the regions with the highest productivities.

Other productivity results with the genus *Eucalyptus* are found in recent literature. In a hybrid of *Eucalyptus urophylla* x *Eucalyptus globulus*, Viera et al. [16] found an AAI of 44.4 and 36.7 m³ ha^{-1} $year^{-1}$, with and without bark respectively. Salvador et al. [19] studying productivity in different textured soils found higher values: 64 and 67 m³ ha^{-1} $year^{-1}$ for sandy and clayey soils, respectively. Santana et al. [20] evaluated different progenies of *Eucalyptus saligna* in 5 different sites and observed that the IMA ranged from 28 to 77 m³ ha^{-1} $year^{-1}$.

The difference of the results shows that the productivity is due to favorable edaphoclimatic conditions. Both Salvador et al. [19] and Santana et al. [20] obtained good productive indices in soils with high clay contents, with 50% and 82% of clay, respectively.

Table 3 lists the models chosen for the estimation of the 4 components of the biomass, total, volume with and without bark, form factor and height. We can observe that with the exception of the form factor, all the chosen models have one of their coefficients combining the interaction of the independent variable diameter with the height.

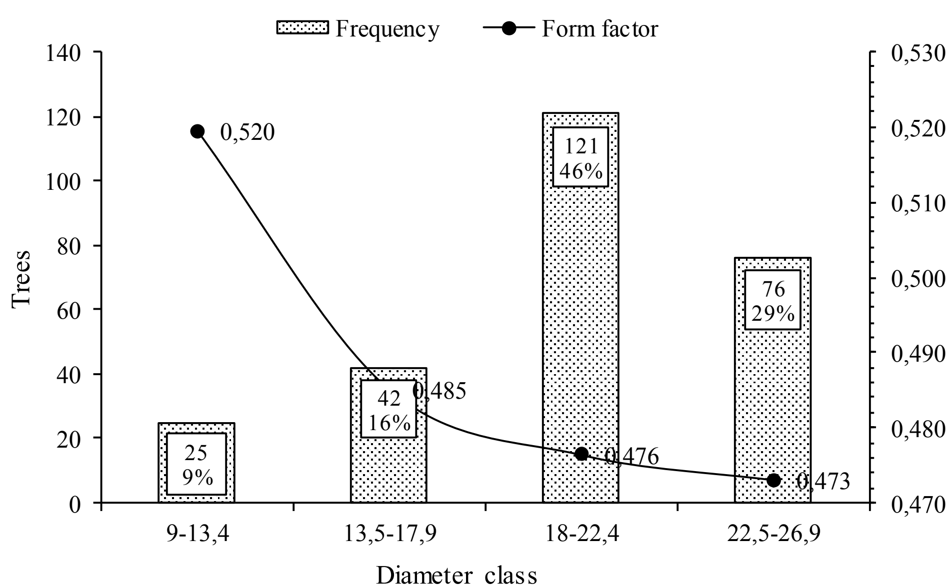

Fig. 3. Frequency of individuals and form factor by diameter classes

Table 2. Dendrometric characteristics in *Eucalyptus saligna* Smith stands at age 10 in São Gabriel, southern Brazil

Inventory					
N (ha^{-1})	DBH (cm)	High (m)	Basal area ($m^2\ ha^{-1}$)	Vb ($m^3\ ha^{-1}$)	Vw ($m^3\ ha^{-1}$)
1143	20,0	29,9	37,98	545,6	493,8
Average annual increaseVb ($m^3\ ha^{-1}$)			Average annual increaseVw ($m^3\ ha^{-1}$)		
54,6			49,4		

Where: DBH: diameter at breast high; Vb: volume with bark; Vw: volume without bark
Note: N, Basa area, Vb and Vw is unit per ha-1.

Table 3. Equations used to estimate the biomass of each component, form factor, volume with bark and without bark, and height of a stand of a 10-year-old *Eucalyptus saligna* stand in São Gabriel-RS

Variable	Model
Wood	$Y= b0 + b1 . (DBH.H)^2$
Bark	$Y= b0 + b1 . (DBH^2.H) + b2 . (DBH.H^3)$
Branch	$Y= b0 + b1 . (DBH^3) + b2 . (DBH.H)^2$
Leaf	$Y= b0 + b1 . (DBH.H)^3 + b2 . (DBH^3.H)$
Total	$Y= b0 + b1 . (DBH.H)^2$
Volume with bark	$Y= b0 + b1 . (DBH^2.H)$
Volume without bark	$Y= b0 + b1 . (DBH^2.H)$
Form factor	$Y= b0 + b1 . (1/DBH^2)$
High	$Y= b0 + b1 . (1/DBH)$

Table 4. Statistics of the regression equations and coefficients for each component, form factor, bark and without bark volume of a 10-year-old *Eucalyptus saligna* stand in São Gabriel-RS

Variable	b0	b1	b2	P≤0,05	R^2adj.	Syx	Syx%	F	DW
Wood	11,117746	0,000499	-	0	0,9988	4,22	2,51	8276	1,94
Bark	0,646834	0,000597	$1,4E^{-5}$	0	0,9974	0,41	3,14	2088	3,23
Branch	0,002973	0,002121	$-2,9E^{-5}$	0	0,9739	0,87	14,03	206	1,38
Leaf	1,327622	$3,94E^{-8}$	$-2,8E^{-5}$	0	0,9892	0,29	8,27	505	1,57
Total	12,442571	0,000567	-	0	0,9992	3,57	1,87	14886	1,61
Vb.	0,011202	$3,6E^{-5}$	-	0	0,9977	0,01	3,04	4839	1,0
Vw	0,005020	$3,3E^{-5}$	-	0	0,9972	0,01	3,42	3938	0,93
Ff.	0,463760	5,284059	-	0,002	0,5934	0,01	2,64	17	1,67
High	42,024961	-237,71730	-	0	0,9711	0,87	3,18	369	2,02

Where: Vb: volume with bark; Vw: volume without bark; Ff: form factor

The selection of the best models should aim at the smallest number of parameters, high precision and independent variables easily obtainable as seen in the present study [21,22,23]. According to Fonseca et al. [24], the interaction between the two variables is present in most models. The authors note that the DBH for being the easiest to obtain variable and less error, it is the one that has the best correlation with the volume.

Table 4 shows the equations chosen based on the best statistical indices: adjusted coefficient of determination R^2 adj., Standard error of the absolute estimate Syx, standard error of the relative estimate Syx (%), probability of error *P*≤0.05, F calculated and data independence by Durbin-Watson (DW).

For all variables the regressions had high adjustments with R^2aj always higher than 0.97. The standard error of the relative estimate is another important statistic to be analyzed and presented 1.87% for the total biomass and 2.51% for the wood component. The low errors allied to the high coefficients of determination allow us to conclude that the modeling of the independent variables by the Stepwise method are reliable and represent the stand characteristic.

The Durbin-Watson statistic (DW) verifies the independence of the residues are the same or have a certain degree of correlation. In general, when values are between 1 and 3 we conclude that the residues do not self-correlate.

High values of adjusted coefficients of determination were observed by Viera et al. [16] 0.99; 0.95; 0.92; 0.85 and 0.99 for wood, bark, branch, leaf and total. Similarly to the present study, the authors present low standard errors of estimation, 0.02 and 0.01 for volume with and without bark respectively.

The total above-ground biomass was 269.15 Mg ha^{-1}, with 89% of wood, 5.9% of bark, 3.2% of branch and 1.8% of leaf. The high percentage of wood biomass is mainly due to the maturity of the stands. Several studies show that as the age advances, the contribution of the wood component increases. The explanation for this can be given by Larcher [25] in the initial years the carbohydrates are used for canopy production (leaves and branches), however when closing them the relative production of wood increases significantly.

Work developed with *Eucalyptus* spp at 2, 4, 6 and 8 years of age by Schumacher et al. [26] show the increase of the relative contribution of wood, 54; 58; 82 and 83% at 2, 4, 6 and 8 years. The inverse was verified for leaves ranging from 12 to 3% at 2 and 8 years. The branch component obtained the same reduction behaviour: 26 and 7% at 2 and 8 years.

Table 5. Values of above ground Biomass (Mg ha^{-1}) in the different components of a 10-year old *Eucalyptus saligna* stand

	Biomass				
	Wood	**Bark**	**Branch**	**Leaf**	**Total**
Mg ha^{-1}	239,72	15,95	8,71	4,76	269,15
%	89,1	5,9	3,2	1,8	100,0

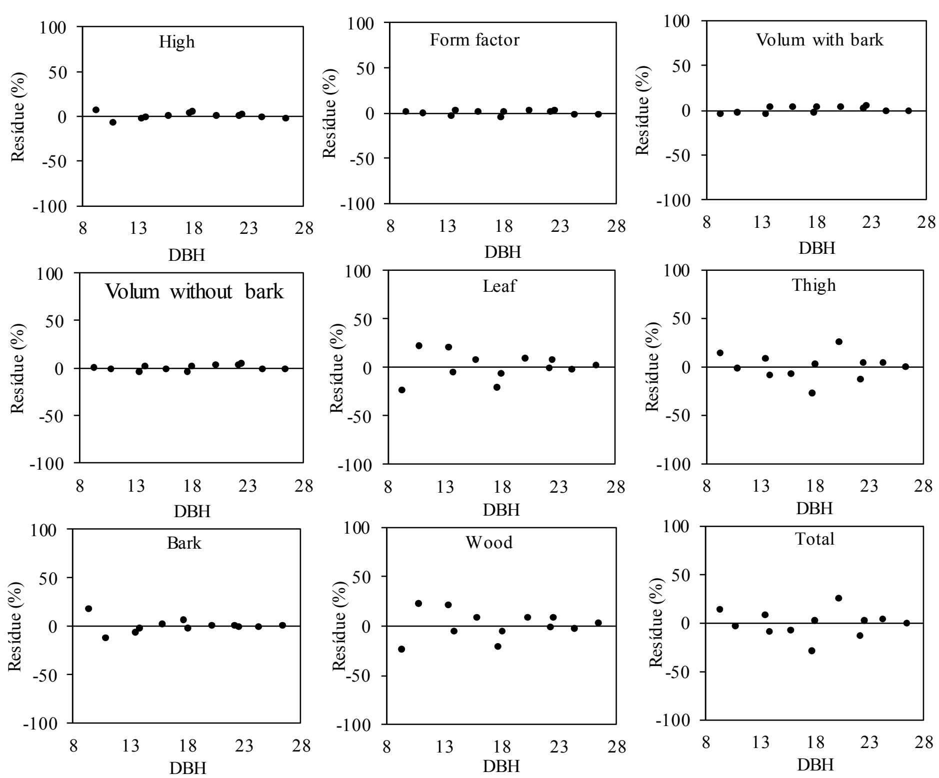

Fig. 4. Distribution of residues (%) as a function of DBH for the different dependent variables adjusted

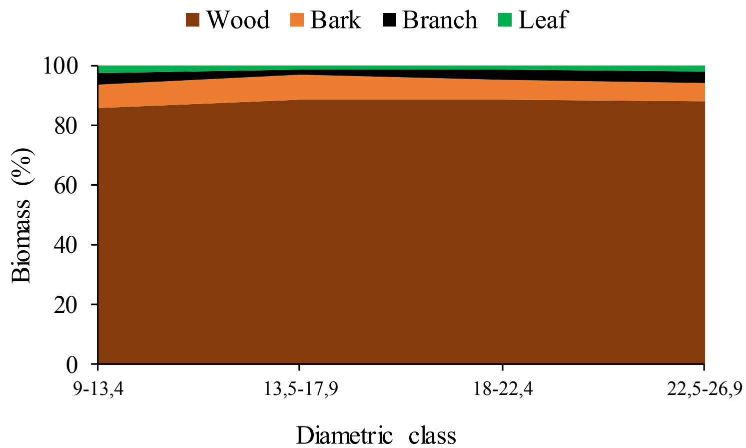

Fig. 5. Relative biomass by diameter classes in a 10-year-old *Eucalyptus saligna* stand

Work developed by Salvador et al [4] at different ages of a stand of *Eucalyptus saligna* stand located in Telêmaco Borba, Paraná, Brazil also shows the relative decrease of canopy components and relative increase of wood biomass. At the age of 6.7 the authors estimated a biomass of 211 Mg ha^{-1} of wood, representing 85% of above ground. In younger stand of the same species the contribution was lower: 45; 79 and 84% at 1.1; 3.6 and 5.5 years of age.

In Fig. 4 we observed the graphical distribution of the residues as a function of the DBH for each dependent variable. The distribution of residues (%) indicates good adjustments of the models.

The relative percentage of biomass components also varied among the different diameter classes. In Fig. 5 we can observe the relative biomass and observe a slight increase of wood of the class of 9 - 13.4 for the class of 22,5 - 26,9 of DBH. The increase was 3%, from 85% to 88%. For Viera et al. [16] this variation was more marked. The percentage of wood ranged from 68% to 80% of the class of 9.1-13 for the 25.1-29 class of DBH.

The total above-ground biomass in a 10-year-old *Eucalyptus saligna* stands was 231 Mg ha^{-1}, of these, 1.8; 4.1; 7.5 and 86.6% consisting of leaf, branch, bark and wood respectively [27]. For the same author evaluating the same species at 2 years of age, the percentages were 17.0; 16.9; 9.0 and 57% for leaf, branch, bark and wood.

4. CONCLUSION

The selection of models presented high adjustments and low relative errors, increasing the reliability of biomass estimates. By means of the graphical distribution of the residues we observed that the models meet the estimates with well distributed errors without the occurrence of tendencies to overestimate or underestimate. The interaction between the two independent variables estimates the biomass components satisfactorily.

The wood component was predominant, 89% of the total biomass. Considering the harvest only of the wood component, 11% of the biomass will remain in the site.

With the increase of the diametric class there is an increase in the percentages of wood and a decrease in the form factor. The average annual increase was 54.6 m^3 ha^{-1}.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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