

Are models of volumetric production at the diametric distribution and total stand level mutually compatible?

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Abstract The objective of this work was to compare estimates generated by a diametric distribution model and a total stand model against the pre-cut inventory. The model efficiency was also evaluated. Data were evaluated from 30 permanent sample plots in a *Eucalyptus urophylla* stand, comprising 24 sample plots used for model fitting, and six sample plots for validation. The volume of wood per hectare was estimated for different productive units (sites), using 7 years as the reference age. The model adjustment quality was verified by adjustment and precision statistics: the correlation between observed and predicted variables, root mean square error percentage, graphical analysis of residual distribution, and a frequency histogram for classes of relative errors and validation. Although the two-parameter Weibull probability density function adhered to the data for tree evolution in diameter classes for the reference age (7 years) in the different productivity classes, it generated imprecise estimates of the number of individuals. Consequently, it produced inaccurate volumetric production estimates. The total stand model provided reliable projections of production volumes in different productivity

classes for both adjustment types, showing compatibility with the pre-cut inventory according to a Tukey test. In summary, the total stand model generated estimates that were compatible with the pre-cut inventory while the diametric distribution model did not.

Keywords Clutter model · Diameter class · Eucalyptus · Prognosis

Introduction

The great economic and commercial relevance of eucalyptus plantations has led to their worldwide recognition (Eldridge et al. 1994; Nakhooda et al. 2014), with the Brazilian planted forest sector becoming one of the most globally relevant. It encompasses an area of 7.84 million hectares of planted trees and is responsible for 91% of wood produced for industrial purposes in the country. It also has great potential for contributing to building a green economy by meeting demand and preserving resources (Carijo et al. 2017; Ibá 2017). To optimize use of these forests, it is important to use models or techniques that provide reliable predictions of growth and production, providing support for structuring the industrial supply.

To estimate forest stand production, we used models that simulate natural dynamics and predict production over time, considering different exploitation possibilities (Vanclay 1994). According to Campos and Leite (2016), growth and yield models can be classified as total stand (TSM), individual tree (ITM), and diametric distribution (DDM) models, depending on the desired level of detail. In eucalyptus forests, TSMs and DDMs are commonly used.

Diametric distribution, as used in DDMs, is the simplest and most powerful tool for characterizing forest structure,

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since it correlates with other important forest variables such as height, volume, and product typification. When modeling a forest at the level of diameter classes, it is necessary to use a probability density function (PDF) that describes the current and future diameter distribution in previously determined amplitude classes (Araújo Júnior et al. 2013; de Azevedo et al. 2016). The Weibull PDF is currently the one most used in forestry (Binoti et al. 2010; de Azevedo et al. 2016) due to its flexibility to assume different forms and asymmetries, a favorable condition to adjust data from different sites (Soares et al. 2010).

TSMs estimate growth and/or yield from stand-level attributes, such as age, basal area, and site index (Campos and Leite 2016). To simulate population growth, TSMs require relatively little information but can generate more general information about the stand's future (Vanclay 1994). The main functions used in TSMs were developed by Schumacher (1939), Buckman (1962), Clutter et al. (1983), and Campos and Leite (2016).

Several studies related to predicting production in eucalyptus plantations have been reported, but no studies have compared different growth categories and production models with the purpose of optimizing and guaranteeing greater precision in estimating volume in forest stands of different ages.

The objective of this work was to evaluate and compare estimates of growth and total volume production at the DDM and TSM levels in a *Eucalyptus urophylla* stand, with a pre-cut inventory.

Materials and methods

Our data were obtained from a continuous forest inventory (2011–2015) in clonal *E. urophylla* plantations set at 3 m × 3 m spacing and located in the Central-West region of Brazil. We applied the fixed area method and used simple random sampling as the sampling procedure (Husch et al. 1982).

The regional climate, per Köppen classification, is type Aw, tropical humid, characterized by two well-defined seasons: drought, which corresponds to autumn and winter; and wet, with torrential rains in the spring and summer (Alvares et al. 2013). The study site has a mean elevation of 700 m and is located at 18°00'45"S–18°01'45"S and 50°52'45"W–50°53'15"W. Average annual precipitation ranges from 1200 mm to 1500 mm, with an annual mean of approximately 1300 mm; average annual temperatures are between 20 and 25 °C (Siqueira Neto et al. 2011). The regional soil is predominantly dystrophic, drained, and is a deep Red-Yellow Latosol (Embrapa 2013).

A total of 30 rectangular plots were sampled, each with an area of 500 m² (25 m × 20 m), with measurements

taken at ages 24, 36, 48, 60, and 72 months. We measured several variables: diameter outside the bark at 1.30 m height (diameter at breast height; DBH) of all trees with DBH greater than 5 cm; total height (TH) of trees using a Vertex hypsometer; and dominant height (DH) in each sample plot, per Assmann (1970).

The Schumacher equation (Eq. 1) was used to classify productivity units (sites), adjusted for the same area of study:

$$\text{Ln}S = \text{Ln}DH + 15.55011596 \left(\frac{1}{\text{Li}} + \frac{1}{\text{I}} \right) \quad (1)$$

($\gamma_{x\hat{x}} = 0.92$; RMSE% = 7.85)

where S = local index, dimensionless; DH = dominant height (m); Li = age index (72 months); Ln = natural logarithm; $\gamma_{x\hat{x}}$ = correlation between observed and predicted variables; and RMSE% = root mean square error percentage.

The volume of each tree was obtained by adjusting the Schumacher and Hall model (Eq. 2) (Schumacher and Hall 1933), using data from the cubage of 300 individuals from the stand, distributed at different ages (25, 35, 90, 90, and 60 individuals at the ages of 24, 36, 48, 60, and 72 months, respectively):

$$V = \exp(-10.8899\text{Ln}(\text{TH}) + 1.91625\text{Ln}(\text{DBH}) + 1.31456) \quad (2)$$

($\gamma_{v\hat{v}} = 0.9894$; RMSE% = 6.75)

where V = volume (m³); DBH = diameter at breast height (cm); TH = total height (m); Ln = natural logarithm; $\gamma_{v\hat{v}}$ = correlation between observed and predicted volumes; and RMSE% = root mean square error percentage.

In order to make the adjustments, the data were randomly separated into two sets. In the validation set, two sample plots were randomly assigned to represent each of the productive classes (sites), resulting in a total of six validation sample plots. The second set consisted of 24 sample plots that were used to adjust the DDM and TSM.

For the adjustment of the DDM, the trees from each sample plot and at each age were grouped according to their diameters, in classes with amplitudes of 2 cm (Araújo Júnior et al. 2013; de Azevedo et al. 2016). The lower limit of the first class was defined as the minimum inclusion diameter (5 cm).

The Weibull function with two parameters (2P) was adjusted for each sample plot at each age:

$$F(x) = 1 - \exp \left[- \left(\frac{x}{\beta} \right)^\gamma \right] \quad (3)$$

where x = center of diameter class (cm); β = scale parameter; γ = shape parameter; and $\beta > 0$ and $\gamma > 0$.

We used linear approximation in the Solver tool of Microsoft Office Excel 2013 to obtain the parameters of the Weibull PDF (Eq. 3). We used the Kolmogorov–Smirnov (KS) test described by Sokal and Rohlf (1995) to verify the adherence of the function to the data. To compare the estimated cumulative frequency with that observed, we sequentially compared the most divergent class D-value of the test to a tabulated D ($\alpha = 0.05$):

$$D = \max|F_o(x) - F_e(x)| \tag{4}$$

where D = absolute maximum difference; $F_o(x)$ = observed cumulative frequency; and $F_e(x)$ = expected cumulative frequency.

To recover the diametric distribution, the parameters of the 2P Weibull PDF were correlated with the stand characteristics, using linear and nonlinear regressions (Nogueira et al. 2005; Miguel et al. 2010; de Souza Retslaff et al. 2012; de Azevedo et al. 2016). The parameters of the 2P Weibull PDF at a future age were considered as dependent variables. Independent variables were function parameters at current age and population attributes at current and future ages (Binoti et al. 2012). The attributes correlated with the stand characteristics were age, number of trees per hectare, site, and combinations of these variables:

$$\gamma_2 = b_0 + b_1\gamma_1 + b_2\left(\frac{l_1}{l_2}\right) \tag{5}$$

$$\beta_2 = b_0 + b_1\beta_1 + b_2\left(\frac{l_1}{l_2}\right) + b_3S \tag{6}$$

$$N_2 = b_0 + b_1N_1 \tag{7}$$

where γ_2 , γ_1 , β_2 , and β_1 are Weibull function estimators; I_1 and I_2 = initial and final age; b_i = coefficients to be estimated; S = local index; and N_2 and N_1 = number of trees per hectare at future and current age, respectively.

Model adjustments were made using the data set containing the measurements for all ages, using Microsoft Office Excel 2013 and the Ordinary Least Squares (OLS) method. The best models were chosen based on the Pearson correlation, RMSE%, and graphical distribution of the residuals, thus establishing a system of equations projecting the frequency of individuals per hectare into diameter classes.

After obtaining the number of individuals per diameter class, the height for each site was obtained through the Richards model (Table 1).

To obtain the volume for each class, the volume equation (multiplied by the density of individuals projected for each diameter class) was applied successively with the values of the class centers of the diameters with their respective heights. The sum of the class volumes resulted in a projected total production per hectare for each age.

Table 1 Adjusted hypsometric equations and their respective precision values

Sites	Equations	RMSE%	γ_{hh}
1	$TH = \frac{32.59}{(1+\exp(5.91-0.29DBH))^{1/4.13}}$	8.59	0.92
2	$TH = \frac{31.91}{(1+\exp(4.74-0.26DBH))^{1/3.03}}$	8.52	0.94
3	$TH = \frac{29.79}{(1+\exp(3.94-0.25DBH))^{1/2.46}}$	7.99	0.94

TH total height (m), DBH diameter at breast height (cm), γ_{hh} correlation between observed and predicted heights, RMSE% root mean square error percentage

In the DDM evaluation, considering the six independent sample plots of the adjustment (validation), at the initial age of 24 months, the volume per hectare was projected for subsequent ages (36, 48, 60, and 72 months).

The model developed by Clutter et al. (1983) was used for the TSM. This model presents two types of adjustment: complete and simultaneous. The former was adjusted by the least squares method in a single stage, and the simultaneous adjustment was performed using the two-stage least squares method with EViews 7.1 software (IHS Global 2010).

The complete Clutter model allows future volume to be projected by fixing a single basal area and initial age (Scolforo 2006):

$$\begin{aligned} \text{Ln}V_2 &= b_0 + b_1\frac{1}{S} \\ &= b_2\frac{1}{l_2} + b_3\left(\frac{l_1}{l_2}\right)\text{Ln}G_1 + b_4\left(1 - \left(\frac{l_1}{l_2}\right)\right) \\ &\quad + b_5S\left(1 - \left(\frac{l_1}{l_2}\right)\right) + \varepsilon \end{aligned} \tag{8}$$

where V_2 = volume of wood with bark at a future age ($\text{m}^3 \text{ha}^{-1}$); S = local index; I_1 = current age (months); I_2 = future age (months); G_1 = basal area in the current year; b_i = model coefficients; Ln = natural logarithm; and ε = random error.

When adjusted simultaneously, the Clutter model (1983) comprises functional relationships (Campos and Leite 2016):

$$\text{Ln}G_2 = \text{Ln}G_1\left(\frac{l_1}{l_2}\right) + a_0\left(1 - \frac{l_1}{l_2}\right) + a_1\left(1 - \frac{l_1}{l_2}\right)S + \text{Ln}\varepsilon \tag{9}$$

$$\text{Ln}V_2 = b_0 + b_1\left(\frac{1}{I_2}\right) + b_2S + b_3\text{Ln}B_2 + \text{Ln}\varepsilon \tag{10}$$

where G_2 = basal area of stand at a future age ($\text{m}^2 \text{ha}^{-1}$); G_1 = basal area in the current year; I_1 = current age (months); I_2 = future age (months); S = local index; V_2 = volume of wood with bark of the stands at a future age

($\text{m}^3 \text{ha}^{-1}$); a_0 and a_1 = coefficients of the basal area model; b_i = coefficients of the volumetric model; Ln = natural logarithm; and ε = random error.

The quality of the adjustments for the complete and simultaneous Clutter model was verified using fit and precision statistics: correlation between observed and predicted volume (γ_{xx}), RMSE%, and a graphical analysis of the residuals (Leite et al. 2005; Castro et al. 2013; de Azevedo et al. 2016; Miguel et al. 2016).

Results and discussion

Diametric distribution modeling

The Kolmogorov–Smirnov test showed that the adjustment of the diametric function was not significant, and it demonstrated adherence of the 2P Weibull PDF to the observed distribution. Similar results were reported by Nogueira et al. (2005), Leite et al. (2005), Araújo Júnior et al. (2013) and de Azevedo et al. (2016). Table 2 shows the estimators of the Weibull PDF parameters (γ_2 and β_2) (Eqs. 5 and 6), the prediction equation for the future number of trees (N2) (Eq. 7), and their fit and precision estimates. We found RMSE% results with values under 10% and high correlation values.

The graphical analysis of the residuals showed that the adjusted equations were not biased, and β_2 obtained the best results, with a compact and uniform distribution of the data (Fig. 1: 2b) and an error frequency (Fig. 1: 2c) that determined the values were within the range of ± 10 . The γ_2 and N2 parameters had less compact distributions but with satisfactory results: the residual distribution comprised a range of $\pm 30\%$, correlation values were greater than 70%, and residual errors were less than 10%. These results concurred with other studies of eucalyptus (Araújo Júnior et al. 2013; Castro et al. 2016; Hirigoyen and Rachid 2014; Miranda et al. 2018).

The evolution of trees diameter classes by the 2P Weibull PDF for the different sites (Fig. 2) presented different symmetries. The flattening of the projection of the frequency of individuals per diameter class was more

pronounced for the most productive than for the less productive sites, presenting a greater amplitude between the lowest and the highest class. This demonstrates that growth was higher at the most productive sites; similar results were reported for eucalyptus by Marangon et al. (2017).

The distribution curves varied by site, shifting to the right with increasing age. The number of trees decreased in the lowest classes and tended to increase in the larger ones, corroborating similar results from several regions of Brazil (Scolforo and Thiersch 1998; Leite et al. 2005; Miguel et al. 2010; Araújo Júnior et al. 2013; Castro et al. 2016).

Modeling at total stand level

The adjusted complete Clutter model (Eq. 8) yielded satisfactory adjustment and precision results (Table 3) with a high correlation between the observed and predicted volume (0.98) and RMSE% (5.07%). The results demonstrated that the model can determine consistent projections of future volumes. The value of the coefficient b_1 was negative, attesting to the quality of the adjustment required to correctly design future volumes (Campos and Leite 2016).

The complete Clutter model showed a restricted dispersion of residuals (Fig. 3a), with most of the error frequency belonging to the $\pm 10\%$ class (Fig. 3c). According to Campos and Leite (2016), the closer the distribution of error frequencies is to zero, the better the model adjustment. When comparing estimated and observed volumes, the data adhered to the 45° slope line (Fig. 3b), which concurs with Silva (2017) when using the complete Clutter model in a eucalyptus stand.

Based on adjustment and precision estimates and the graphical analysis, the complete Clutter model closely corresponded to the data. This indicates that, when the basal area and initial age are fixed, this model can accurately project volume values for future ages. Similar results were presented by Scolforo (2006), who adjusted the complete Clutter model to determine the silvicultural rotation of *Eucalyptus* spp.

The adjustment of the Clutter model using simultaneous equations (Eqs. 9, 10) (Table 4) yielded strong

Table 2 Parameters for the equations estimated by the two-parameter Weibull probability density function of the stand

Parameters	b_0	b_1	b_2	b_3	RMSE%	γ_{xx}
γ_2	0.878189	0.657664	0.40191	–	9.35	0.73
β_2	2.845739	0.962627	3.14194	0.044493	2.08	0.98
N2	46.75652	0.928589	–	–	4.53	0.79

γ_2 and β_2 are estimators of the Weibull probability density function; b_0 , b_1 , b_2 , and b_3 = regression coefficients, γ_{xx} = correlation between observed and predicted variables; RMSE% = root mean square error percentage

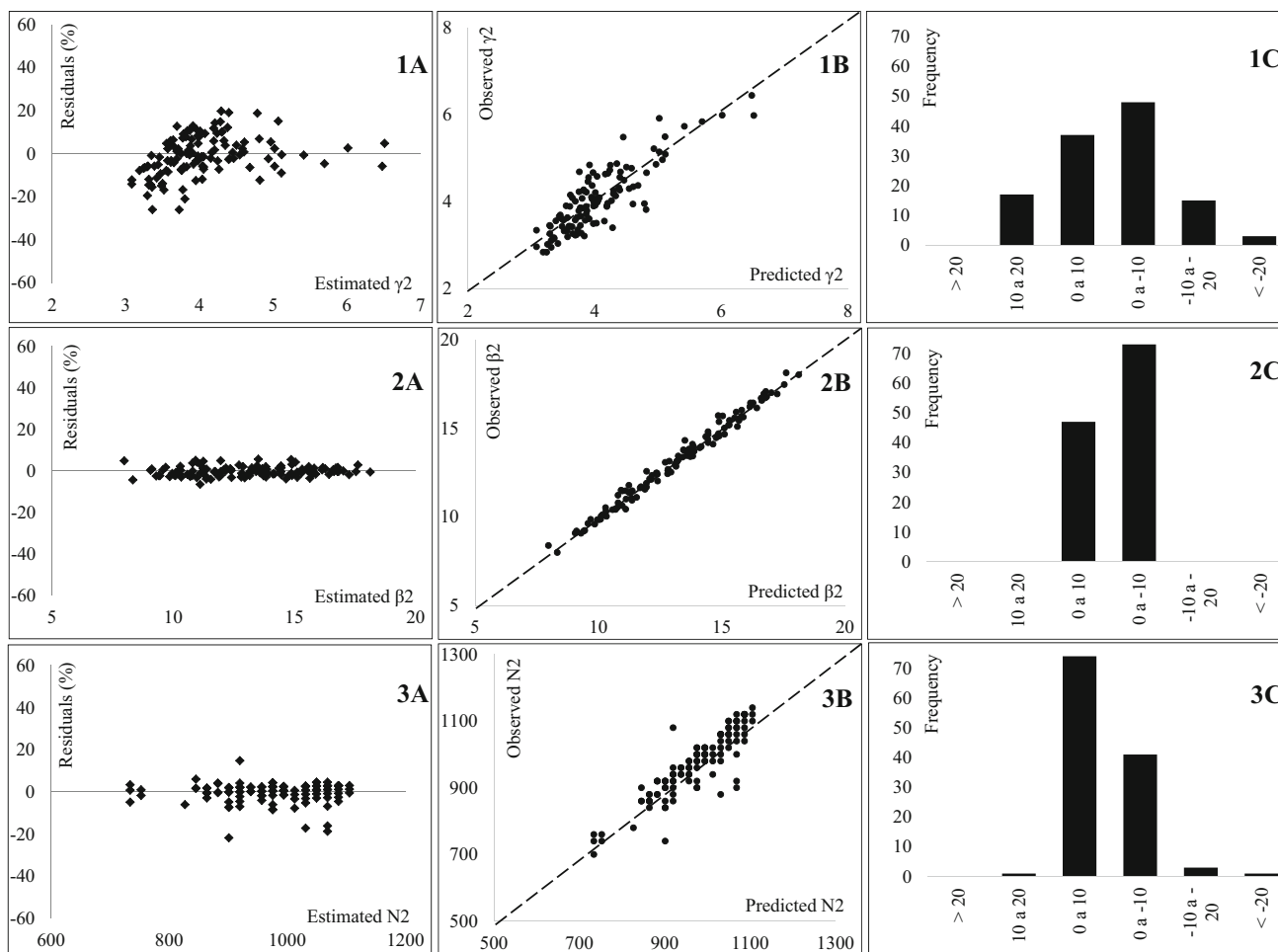


Fig. 1 Distribution of estimation errors (a), the correlation between estimated and observed volumes (b), and relative error frequency histogram (c) for γ_2 (1), β_2 (2), and N_2 (3)

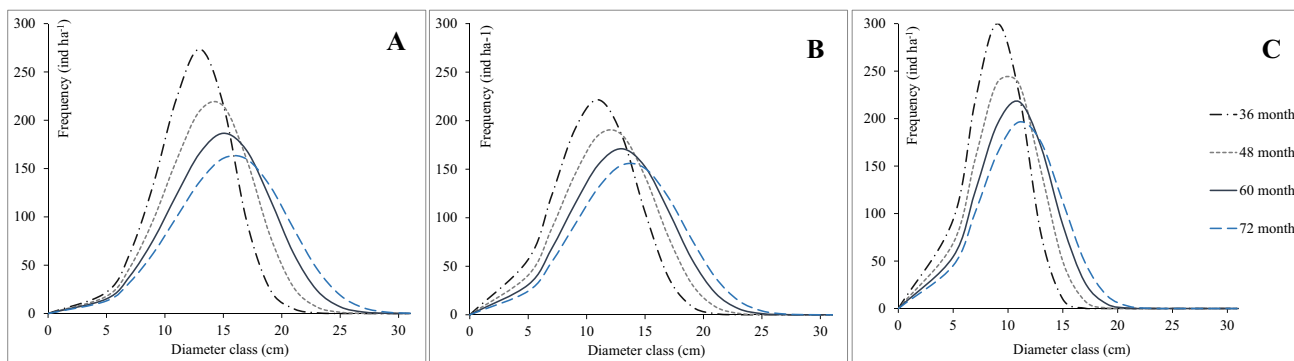


Fig. 2 Diametric evolution of site 1 (a), site 2 (b), and site 3 (c), estimated by the two-parameter Weibull probability density function at ages 36, 48, 60, and 72 months

Table 3 Coefficients and statistics for the complete Clutter model

Model	b_0	b_1	b_2	b_3	b_4	b_5	RSME%	γ_{VP}
Clutter	3.210	- 15.446	- 32.436	1.126	1.590	0.071	5.07	0.98

$b_0, b_1, b_2, b_3, b_4,$ and b_5 = regression coefficients; γ_{VP} = correlation between observed and predicted volumes; RMSE% = root mean square error percentage

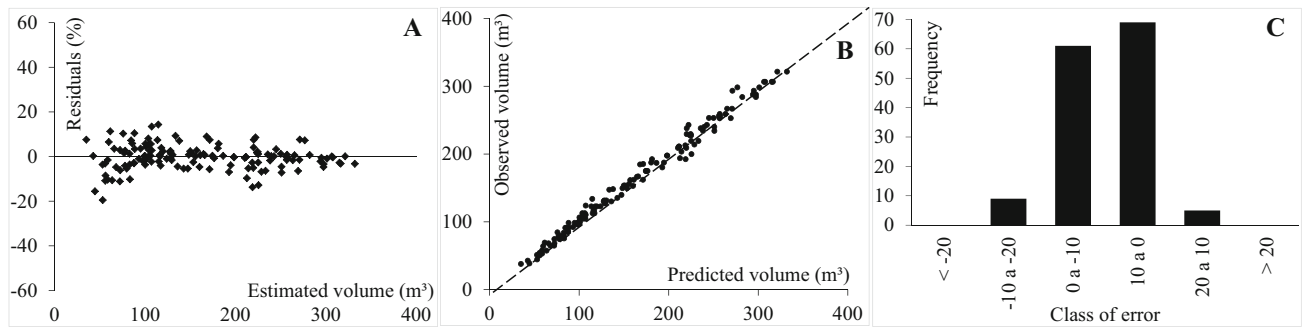


Fig. 3 Distribution of estimation errors (a), correlation between estimated and observed volume (b), and relative error frequency histogram (c) for the complete Clutter model

Table 4 Coefficients estimated by simultaneous Clutter equations (two-stage least squares method) for basal area and volume

	a_1	a_2	b_1	b_2	b_3	b_4	RMSE%	γ_{xx}
G	1.447	0.056	–	–	–	–	8.65	0.98
V	–	–	1.794	– 23.797	0.021	1.170	3.33	0.99

G = basal area; V = volume; a_1 , a_2 , b_1 , b_2 , b_3 , and b_4 = regression coefficients; γ_{xx} = correlation between observed and predicted variables; and RMSE% = root mean square error percentage

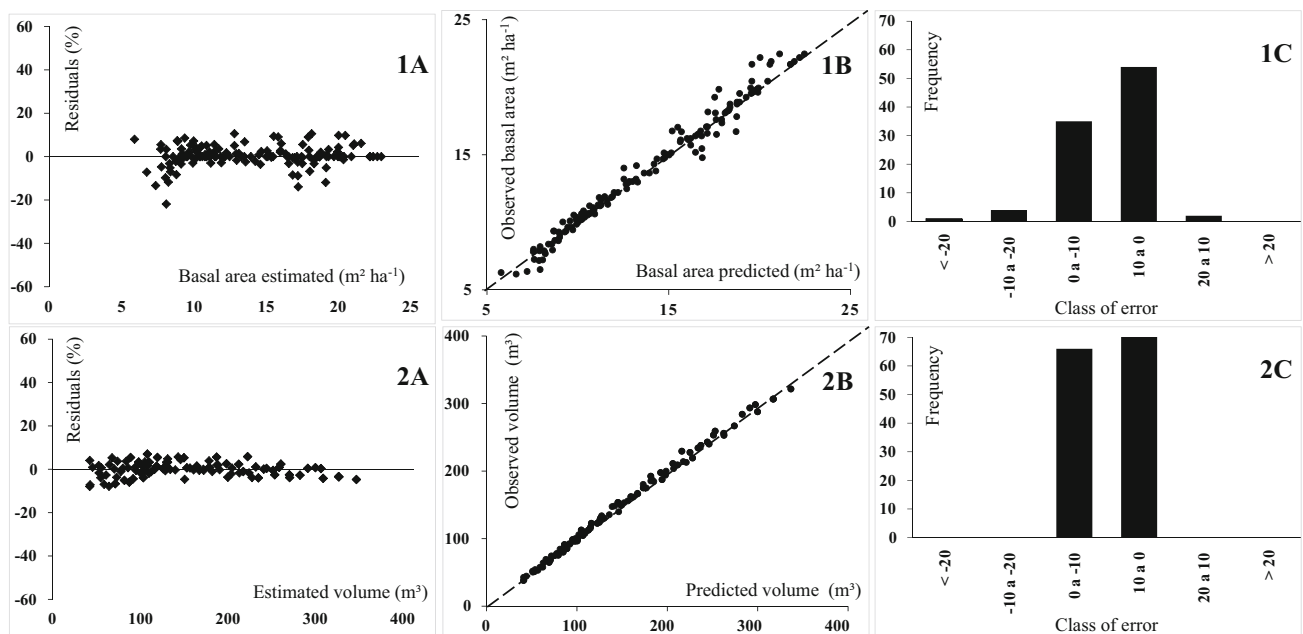


Fig. 4 Distribution of estimation errors (a), the correlation between predicted and observed variables (b), and the relative error frequency histogram (c) for the basal area (1) and volume (2) of the simultaneous Clutter model

correlation and low percentage of standard error for the two variables of interest. It therefore proved to be a satisfactory adjustment for the database, corroborating

results reported in the literature on modeling of eucalyptus stands (Castro et al. 2013; de Azevedo et al. 2016; Miguel et al. 2016).

Table 5 Results of the analysis of variance of the models

FV	DF	SS	MS	F	F tab.
Sites	2	73399.2229	36,699.6114	221.0673	10.9248
Treatments	3	3562.0589	1187.3529	7.1523	4.7571
Residual	6	996.0662	166.0110		
Total	11	77957.3481			

FV source of variation, DF degrees of freedom, SS sum of squares, MS mean squares

Table 6 Tukey test results at 5% probability for block (site) and treatment (model)

Site	I	II	III	
Average volume	287.78 a	202.93 b	96.61 c	
Treatment	1	2	3	4
Average volume	209.81 a	210.81 a	195.55 a	167.71 b

Treatments 1, 2, 3, and 4 are pre-cut inventory, complete Clutter model, simultaneous Clutter model, and diametric distribution model, respectively. The least significant difference (LSD) was 25 m³ for treatment and 26 m³ for the site

The signs of the coefficients a_1 and b_2 calculated to the stand were consistent with the expected results (Table 4). The coefficient a_1 was positive, indicating the effect of productive capacity on basal area, and the coefficient b_2 was negative. Thus, the estimates are consistent with those of Campos and Leite (2016). Similar data for modeling of stands were reported by Castro et al. (2013), de Azevedo et al. (2016) and Silva (2017).

Basal area showed a slight dispersion of the residuals along the line (Fig. 4: 1a), with a slight tendency to overestimate the smaller basal areas and underestimate the larger areas. These results concur with Castro et al. (2013). The volume variable presented a more compact and concise distribution of the residuals (Fig. 4: 2a), maintaining all error frequency data within $\pm 10\%$ (Fig. 4: 2c). The

estimates of the behavior of predicted against observed values were adequate, since the values were distributed close to the 45° slope line (Fig. 4: 2b). Even though there were tendencies in the estimates of future basal area, the volumetric model was consistent and fit well to the stand, without indicating either underestimation or overestimation of the volume.

The mean volumes for age 72 months, projected from the initial age of 24 months, were estimated for the validation data using adjusted DDM and TSM (simultaneous and complete Clutter models). The projected volume was compared to the volume of the pre-cut (control) inventory using the analysis of variance double factor ($\alpha = 0.05$) following Banzatto and do Kronka (2013) (Table 5).

The analysis of variance indicated that the null hypothesis (H_0) was rejected for site and treatment at a 5% level of significance, confirming significant differences between at least one pair of averages for site and treatment. The Tukey test also confirmed that there were significant differences between at least one pair of averages for site and treatment (Table 6).

The diametric distribution model underestimated the volume of pre-cut inventory for all sites (Fig. 5). The largest difference was observed for site II, similar to de Azevedo et al. (2016). The estimates calculated by the complete and simultaneous Clutter models were adequate, confirming the results obtained by the Tukey test and corroborating other studies in which Clutter models provide reliable estimates for eucalyptus plantations (Castro et al. 2013; de Azevedo et al. 2016).

Conclusions

The DDM and TSM presented conflicting volumes, and the DDM was incompatible with the volume results of the pre-cut inventory.

The TSM, regardless of which Clutter model adjustment system (complete or simultaneous) was used, was

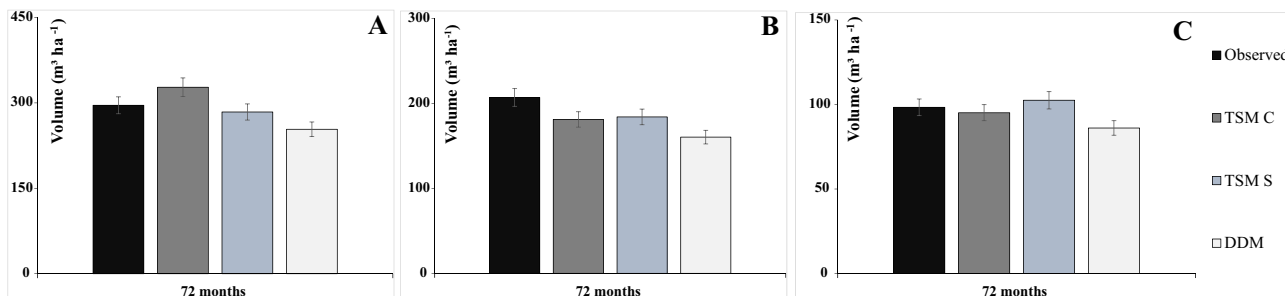


Fig. 5 Volume of wood observed (pre-cut inventory) and estimated by models of diametric distribution model (DDM), total stand model-complete Clutter (TSM C) and simultaneous Clutter (TSM S) for site 1 (a), site 2 (b), and site 3 (c)

compatible with and accurately represented the pre-cut inventory, providing reliable estimates of volumetric production.

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