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Compatibility Between Wood Volume Estimation Methods In A Eucalyptus Stand

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ABSTRACT

This research evaluated different method to estimate logging volume in a eucalyptus stand, aiming to: 1) verify compatibility between volume estimated from volumetric and taper methods; and 2) evaluate precision of the forest inventory for total volume and assortment. Using volume data from 33 trees, volumetric and taper models were adjusted, and the ones with better performance, were selected. These models were used to estimate volume of trees measured in the inventory, and then, the Student's t test was applied to verify differences between volume estimation models, allowing studying their compatibility. The taper model was also used to estimate the volume in different assortments of the bole. Volumetric and taper models are compatible to estimate the volume, and the last has the advantage of providing volume by assortments of the bole. The use of taper functions allows the realization of forest inventories, with good accuracy for both the total volume, as to the volume of assortments of boles.

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INTRODUCTION

Volume is one of the most important variables to diagnose the production potential of a forest, representing a basic information to plan forest production (Azevedo *et al*., 2011). The volume equation is the most usual way to predict trees' volume individually (Batista *et al*. 2014).

However, considering that the market is more demanding and competitive every day, determining logging volume is not sufficient, but quantifying products existing in a forest (assortment). One of the techniques that can be applied for this goal is using taper models, which express diameter-decreasing taxes towards the bole (Miguel *et al*., 2011; Campos and Leite, 2013; Campos *et al*., 2014).

These models allow predicting three basic characteristics of trees: diameter on any height of the bole, total height or which is found in a specific diameter limit and the volume between any positions of the bole (Silva *et al*., 2006; Horle *et al*., 2010; Leite *et al*., 2011; Miguel *et al*., 2011; Campos and Leite, 2013; Môra *et al*., 2014), in function of trees diameter and height. Besides, they allow estimating the number of logging products that a tree can provide (Figueiredo *et al*., 2006).

Therefore, using taper functions, when compared to volume equations, beyond providing trees total volume, allows obtaining volume of any bole portion (assortment). According to Campos *et al*. (2014), the tree conversion in multi-products is an alternative that has been used on the forestry sector, increasing the income originated by the forestry stand. However, it is important to emphasize that volume estimated by taper function must be compatible to what was obtained by volumetric models, generating precise estimates, independent from the used method.

Another relevant factor on planning and optimizing forestry activities is estimates precision on the forestry inventory, which depend on the equations used to estimate the interest variable. According to Campos *et al*. (2014), using the correct techniques for forestry inventories is important to quantify and classify logging products precisely. Nevertheless, when it comes to multi-products in a forestry population, only the total volume precision (sampling error) is verified, ignoring precision for bole assortments.

Considering these aspects, this study evaluated different methods to estimate logging volume in a eucalyptus stand, aiming to: 1) verify the compatibility between volume estimates from volumetric and taper models; and 2) evaluate the precision of the forestry inventory for total volume

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and per assortment, obtained from the adjusted models.

MATERIAL AND METHODS

Data:

The study was conducted at the Água Limpa Farm (FAL), which belongs to University of Brasília, Distrito Federal, Brazil, between the coordinates 15º56' and 15º59' South and 47º55' and 47º58' West, in a 1.100 m altitude. The soil is Red-Yellow Latosol. The local climate, according to the Köppen classification, is Aw, with minimum and maximum temperature at 12 and 28,5°C, respectively. The annual average rainfall is 1.500 mm, with a drought season from July to September.

Data was obtained from a eucalyptus stand of the GG100 clone (*Eucalyptus urophylla* S. T. Blake, in a 5 ha area, planted in a spacing 2.75 x 2.00 m, at the age of 54 months. In order to perform a forestry inventory, nine plots measuring 600 m² (30 x 20 m) were randomly selected. The measured variables were diameter at breast height (DBH), measured with a caliper, and total height (H), measured with a Suunto model PM-5 1520. In total, were meansured 925 trees, with DBH varying from 5.0 to 16.87 cm and height from 11.4 to 19.4 m.

A total of 33 trees of the stand was felled and strictly cubed, distributed in 11 DBH classes, measuring the diameter through the bole on positions from 0.1, 0.7 and 1.3 m from the soil, from that point the sections were measured every 1 m, until reach the total height. The trees DBH varied from 5.0 to 16.7 cm and the height from 9.6 to 20.5 m. The tree cubing was performed using the Newton method.

The cubed trees were used on the volumetric models adjusting and taper, to obtain individual volume of trees for each plot measured during the forestry inventory.

Volumetric models:

With volume provided by 33 cubed trees, volumetric models were adjusted, aiming to select the model that estimated trees individual volume, more precisely. The adjusted models were:

a) Spurr Model

$$V = \beta_0 + \beta_1 DBH^2 H + \varepsilon$$

b) Schumacher & Hall Model

$$V = \beta_0 DBH^{\beta_1} H^{\beta_2} \varepsilon$$

c) Takata Model

$$V = \frac{DBH^2 H}{\beta_0 + \beta_1 DBH} + \varepsilon$$

In which: V = total volume (m³); DHB = diameter at breast height (cm); H = total height (m); β_i = model's coefficient; ε = random error.

Taper models:

Based on diameter data for different bole heights of cubed trees, taper models were adjusted, whose functional relations and expressions to estimate diameter (di) at any height are presented below:

a) Schöepfer Model (Polynomial of 5th degree):

$$\frac{di}{DBH} = \beta_0 + \beta_1\left(\frac{hi}{H}\right) + \beta_2\left(\frac{hi}{H}\right)^2 + \beta_3\left(\frac{hi}{H}\right)^3 + \beta_4\left(\frac{hi}{H}\right)^4 + \beta_5\left(\frac{hi}{H}\right)^5 + \varepsilon$$

By isolating di, we obtain the taper function:

$$di = DBH\left[\beta_0 + \beta_1\left(\frac{hi}{H}\right) + \beta_2\left(\frac{hi}{H}\right)^2 + \beta_3\left(\frac{hi}{H}\right)^3 + \beta_4\left(\frac{hi}{H}\right)^4 + \beta_5\left(\frac{hi}{H}\right)^5\right]$$

b) Hradetzky Model (Polynomial of whole and fractional potencies)

$$\frac{di}{DBH} = \beta_0 + \beta_1\left(\frac{hi}{H}\right)^{p1} + \beta_2\left(\frac{hi}{H}\right)^{p2} + ... + \beta_5\left(\frac{hi}{H}\right)^{pn} + \varepsilon$$

By isolating di, we obtain the taper function:

$$di = DBH\left[\beta_0 + \beta_1\left(\frac{hi}{H}\right)^{p1} + \beta_2\left(\frac{hi}{H}\right)^{p2} + ... + \beta_5\left(\frac{hi}{H}\right)^{pn}\right]$$

The potencies used to adjust this model were selected by the Stepwise method, the following potencies were tested: 0.005; 0.09; 0.08; 0.07; 0.06; 0.05; 0.04; 0.03; 0.02; 0.01; 0.9; 0.8; 0.7; 0.6; 0.5; 0.4; 0.3; 0.2; 0.1; 1; 2; 3; 4; 5; 10; 15; 20 and 25. A 5% significance level was considered by the F test, for input and output of variables.

c) Kozak Model

$$\left(\frac{di}{DBH}\right)^2 = \beta_0 + \beta_1\left(\frac{hi}{H}\right) + \beta_2\left(\frac{hi}{H}\right)^2 + \varepsilon$$

By isolating di, we obtain the taper function:

$$di = DBH\sqrt{\beta_0 + \beta_1\left(\frac{hi}{H}\right) + \beta_2\left(\frac{hi}{H}\right)^2}$$

In which: di = diameter at a determined bole height (cm); DBH = diameter at breast height (cm); hi = bole height where a determined diameter occurs (m); H = total height (m); β_i =model's coefficient; ε = random error.

Adjusting methods and model's selection:

For both, volumetric and taper methods were adjusted by the ordinary minimum square method (MQO), for linear models, Microsoft Office Excel 2010 was used. For non-linear models, we used the Statgraphics program, using the Levenberg-Marquardt algorithm.

For each category, the best model was selected based on the adjusted determination coefficient (R^2_{aj}), absolute residual standard error (S_{yx}), and percentage (S_{yx}%), beyond the graphic distribution of residual (Draper and Smith, 1998). Additionally, the Akaike Information Criteria (AIC) compared the adjusted models. According to Akaike (1974), AIC is a quality measuring related to the adjust defined by $AIC = -2Ln\ (Lp) + 2p$. Then, Bayesian Information Criteria (BIC) was used, which, according to Schwarz (1978), is determined by $BIC = -2Ln\ (Lp) + Kp$. In which: k = Ln (n) and Lp = value that maximizes the maximum-likelihood function of the estimated model; p = model's parameter number; n = observations number.

Both, AIC and BIC increases proportionally with the square sum of errors. Therefore, as smaller AIC or BIC of the models, smaller their estimated general discrepancy, and, consequently, their relative distance from real values decreases.

In order to help choosing the best-taper model, values of diameter through the bole were estimated, allowed comparing the profile of the estimated bole for every adjusted model to the observed profile. After selecting the taper function, the function was integrated, being possible to obtain total volume and multiple products for every tree.

Compatibility Among Volume Estimation Methods:

To evaluate compatibility among volume obtaining methods, in other words, values estimated from the volumetric model and taper models selected, the 925 trees measured on the forestry inventory, obtained their volume estimated on both methods. The Student's t Test ($\alpha = 0.05$) was applied to verify whether the measures of these volumes are statistically equal.

Bole Assortments And Inventory Processing:

Taper models, when compared to volumetric models, provides volume per bole assortment, considering that, were defined some possibilities for results obtained for stand (Table 1). The choice of distinct assortments, is justified for being a product with great demand in Distrito Federal and its surrounding areas, and it is more valuable than the market for wood designed for energy.

Table 1: Dimensions considered in definition of the assortment of bole to be used in the stand.

Assortment	Diameter (cm)	Length (m)
Fence Post I	Greater than 12.0	2.2
Fence Post II	Between 8 and 11.9	2.2
Fence Post III	Between 6 and 7.9	2.2
Firewood	Between 3 and 5.9	1.0
Waste	Smaller than 3.0	-

Then, the forestry inventory precision was calculated for logging volume existing in each product. To obtain the volume for several products, the taper function selected was integrated and applied on every tree individually.

Total volume and assortment for each plot was obtained by sum the values estimated for every tree. The results were extrapolated to $m^3\ ha^{-1}$. The forestry inventory precision (sampling error) for these volumes was evaluated considering the simple random sampling (Péllico Netto and Brena, 1997), allowing verifying whether the taper functions provide precise estimates of logging volume per area unity.

RESULTS AND DISCUSSION

Volumetric models:

The values obtained for the regression coefficient with the volumetric models adjusting, and its respective adjusting statistics are presented on Table 2. It is verified that with 33 cubed trees, all models we well adjusted to the database. It can be explained by the variation coefficient (CV), which influences the sampling intensity directly. According to the criteria proposed by Gomes (2000), CV < 10% is considered low, so, a small sampling intensity guarantees low error and samples stability. In this study, for the variables diameter and height of the stand, CV was under 8%.

Table 2: Regression coefficients and adjustment statistics for the volumetric models.

Model	Coefficient	R^2_{aj}	S_{yx}	S_{yx} %	AIC	BIC
Spurr	$\beta_0 = 0.00431$	0.9849	0.0059	7.10	735	725
	$\beta_1 = 0.00003$					
Schumacher & Hall	$\beta_0 = 0.00006$	0.9862	0.0056	6.79	705	718
	$\beta_1 = 1.82083$					
	$\beta_2 = 0.97645$					
Takata	$\beta_0 = 22667.6$	0.9869	0.0055	6.61	698	706
	$\beta_1 = 426.264$					

R^2_{aj} = Adjusted determination coefficient; S_{yx} = Absolute residual standard error (cm); S_{yx} % = Relative error standard (%); AIC = Akaike Information Criteria; BIC = Bayesian Information Criteria.

The R^2_{aj} we over 0.98, indicating, a high level of variable adjusting in function of the independent variables. The S_{yx} and S_{yx}% values were inferior to 0.0060 m³ and 7.10%, respectively, showing the low dispersion of estimated values regarding the average values. By analyzing the AIC and BIC statistics, it is verified the same tendency to small values for models that present lower S_{yx} values, in which low values for AIC and BIC are preferable.

However, according to Drapper and Smith (1998), even the adjust estimators being good indicators for models selection, the graphic analysis of residues is fundamental on choosing of the best equation, when working with modeling, because tendency errors can occur in a certain amplitude of a variable class, without being detected by the statistics.

While evaluating the graphic distribution of residues (Figure 1), it is verified that all models present satisfactory behavior regarding the residues dispersion, although the Spurr model presented a small tendency to overestimate the trees volume of smaller diameter, in other words, of trees with lower volume. Schumacher & Hall and Takata models presented similar behavior, without tendencies on their estimates. Therefore, for presenting adjust statistics slightly more favorable, the Takata model was selected to estimate trees' individual volume.

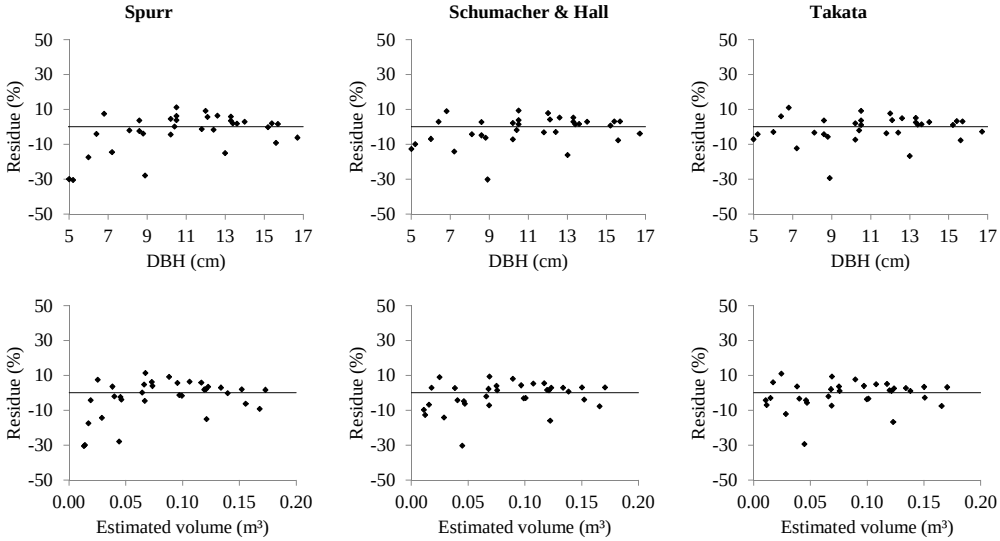

Fig. 1: Graphic distribution of residues in function of the diameter at breast height (DBH) and estimated volume for each of the models.

On the literature, some works highlighted the Takata model efficiency to estimate volume for *Eucalyptus* spp. trees (Miguel *et al*., 2010; Miguel and Leal, 2012; Miguel *et al*., 2014), *Pinus* spp. (Silvestre *et al*., 2014) and *Mimosa scabrella* (Machado *et al*., 2008). Miguel *et al*. (2010), while evaluating different volumetric models for *Eucalyptus grandis* stand in Goiás State (Brazil), it was verified that, among the several tested, the Takata model was the most stable, being recommended to estimate the volume of the studied stand, or in stands presenting similar characteristics.

Taper models:

The regression coefficients obtained with taper models adjusting are presented on Table 3. The potencies selected by the Stepwise proceeding, for the Hradetzky models were 4 (β_1), 5 (β_2), 0,7 (β_3), 3 (β_4), 0,1 (β_5) and 0.005 (β_6).

From the adjust statistics (Table 3) and from graphic distribution of residues from three taper models evaluated (Figure 2), it is verified that the Schöepfer and Hradetzky models presented a better performance to estimate diameter through the bole (di), being these models superior to the Kozak model. In all these models, the greater residues dispersion was verified on the superior part of the bole (top), where the smaller diameters occur. The Kozak model presented grater discrepancy between the values observed and estimated, presenting a tendency to overestimate the diameter values.

By comparing the observed bole profile for the average tree of stand with its estimated profile, for each one of the taper equations obtained (Figure 3), is confirmed the inferiority of the Kozak model, for the base estimate and the apex of the bole, corroborating with the results obtained on the adjusting statistics and on the graphic analysis of the residues. Schöepfer and Hradetzky models described the bole profile similarly, highlighting that the second presented a slightly superior performance on the bole base. Therefore, the Hradetzky model was selected to estimate the volume of the trees, as well its assortments.

Table 3: Regression coefficients and adjustment statistics for taper models.

Model	Coefficient	R^2_{aj}	S_{yx}	S_{yx} %	AIC	BIC
Schöepfer	β_0 = 1.22706	0.9835	0.4762	6.43	1080	1095
	β_1 = -3.67381					
	β_2 = 15.02206					
	β_3 = -33.28640					
	β_4 = 33.05868					
	β_5 = -12.35330					
Hradetzky	β_0 = 1.28656	0.9868	0.4280	5.78	1022	1058
	β_1 = 3.45661					
	β_2 = -1.90051					
	β_3 = -0.24579					
	β_4 = -2.17718					
	β_5 = -0.79282					
	β_6 = 0.37873					
Kozak	β_0 = 1.33991	0.9258	0.8816	11.76	1170	1195
	β_1 = -2.48298					
	β_2 = 1.18061					

R^2_{aj} = Adjusted determination coefficient; S_{yx} = Absolute residual standard error (cm); S_{yx} % = Relative error standard (%); AIC = Akaike Information Criteria; BIC = Bayesian Information Criteria.

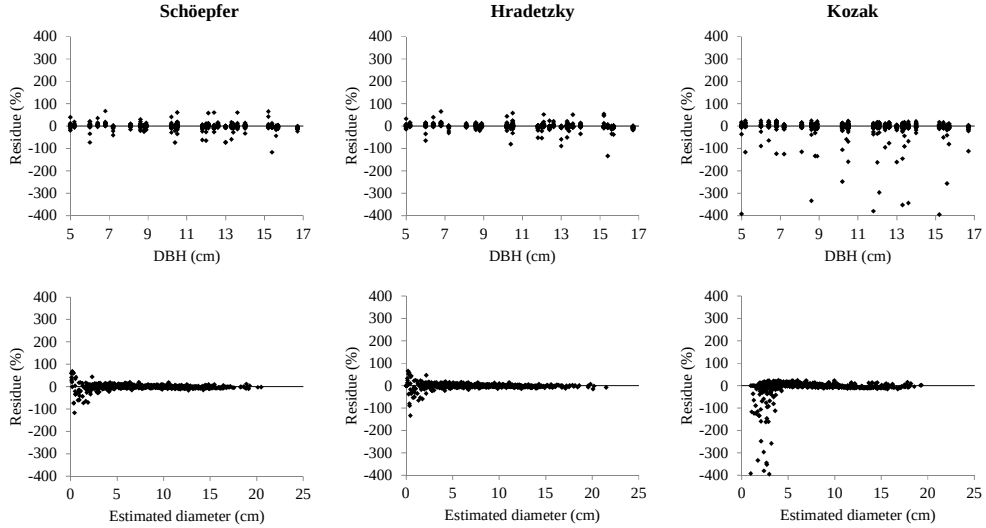

Fig. 2: Graphic distribution of residues for the taper models in function of the diameter at breast height (DBH) and estimated diameter along the bole.

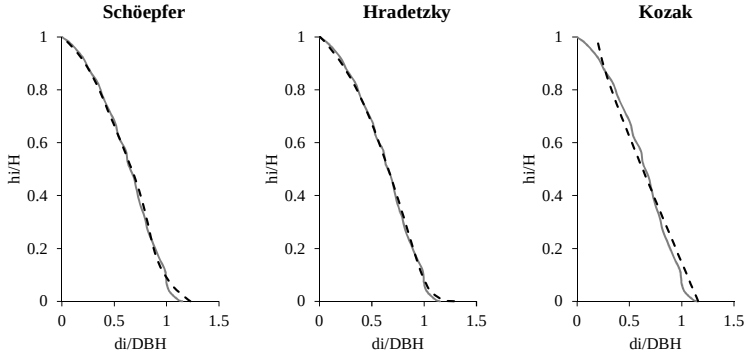

Fig. 3: Profile of the bole observed and estimated by taper models. Solid lines represent the observed profile and dashed lines represent the estimated profile.

The Hradetzky model is the most flexible to estimate form variation of the trees boles, therefore, it allows describing better the boles extremities. Because of that, the models is efficient to estimate bole form variation of some species, such as *Eucalyptus* sp. (Souza *et al*., 2008), *Pinus* spp. (Silva *et al*., 2011; Yoshitani Júnior *et al*., 2012; Kohler *et al*., 2013), *Mimosa scabrella* (Queiroz *et al*., 2008) and *Tectona grandis* (Figueiredo *et al*., 2006). On the other hand, also supporting this research, the Kozak model presented an unsatisfactory performance to describe trees' bole profile (Queiroz *et al*., 2008; Leite *et al*, 2011; Yoshitani Júnior *et al*., 2012; Ferreira *et al*., 2014). Such fact occurs due the non-

flexibility of this model to estimate the superior and inferior extremes of the trees' bole.

Therefore, the expression used to obtain total volume or any other assortment of the bole, from the Hradetzky model is obtained by the integral of the polynomial, defined by the expression:

$$\hat{V} = \frac{\pi}{40000} DBH^{2} \left[\begin{array}{l} c_0^2 hi + 2c_0c_1\left(\frac{hi^{(p_1+1)}}{p_1+1}\right) + 2c_0c_2\left(\frac{hi^{(p_2+1)}}{p_2+1}\right) + ... + 2c_0c_n\left(\frac{hi^{(p_n+1)}}{p_n+1}\right) + 2c_1c_2\left(\frac{hi^{(p_1+p_2+1)}}{p_1+p_2+1}\right) \\ + ... + 2c_1c_n\left(\frac{hi^{(p_1+p_n+1)}}{p_1+p_n+1}\right) + ... + 2c_{(n-1)}c_n\left(\frac{hi^{(p_{(n-1)}+p_n+1)}}{p_{(n-1)}+p_n+1}\right) + c_1^2\left(\frac{hi^{(2p_1+1)}}{2p_1+1}\right) + ... + \\ c_n^2\left(\frac{hi^{(2p_n+1)}}{2p_n+1}\right) \end{array} \right]_{h1}^{h2}$$

In which: $c_0 = \beta_0$; $c_1 = \beta_1/H^4$; $c_2 = \beta_2/H^5$; $c_3 = \beta_3/H^{0.7}$; $c_4 = \beta_4/H^3$; $c_5 = \beta_5/H^{0.1}$; $c_6 = \beta_6/H^{0.005}$; p_i = model's power, which assumed the values: 4 (β_1), 5 (β_2), 0.7 (β_3), 3 (β_4), 0.1 (β_5) e 0.005 (β_6), from the *stepwise* model. Other variables were previously defined.

Compatibility Between The Volume Estimate Methods:

The t test indicated which not occur significant differences between the individual volume averages of the trees, obtained from the Takata volumetric model, and the Hradetzky taper model (Table 4), indicating the compatibility between both model categories. These results corroborate with what was obtained by Leite *et al*. (2011), who did not verify differences between the volumes obtained by the Schumacher and Hall (log) volumetric model and the Schöepfer taper models, in *Eucalyptus urophylla* stand. These results indicate that taper equations can be used to obtain individual trees volume in for forestry inventories.

Table 4: Student's t test for data comparing trees average volume, obtained with different method of volume estimates.

Method	Average	Variance	t calculated	t tabled (5%)
Takata	0.150	0.0008	1.5130	1.9612
Hradetzky	0.1171	0.0009		

By analyzing the inventory precision for total volume obtained on the nine plots using both methods (Table 5), it is verified that they present satisfactory results, with sampling error inferior to 3%. The Hradetzky model, beyond presenting a performance similar to the Takata, with a 1.78% difference, allows estimating the volume for distinct bole assortments.

Table 5: Statistics of the forest inventory for total volume of wood by assortment.

Statistics	Total Volume		Assortments volume				
	Takata	Hradetzky	Fence post I	Fence post II	Fence post III	Firewood	Waste
$\overline{x}$	196.8294	200.3520	66.4978	94.4531	21.4298	16.1953	1.7760
S_x^2	90.8126	97.4501	73.5073	32.3303	1.1472	0.9331	0.0123
CV	4.8415	4.9272	12.8931	6.0199	4.9980	5.9644	6.2433
$S_{\overline{x}}$	2.9577	3.0639	2.6610	1.7648	0.3324	0.2998	0.0344
Ea	5.5001	5.6975	4.9483	3.2817	0.6182	0.5575	0.0640
Er	2.7943	2.8438	7.4414	3.4744	2.8846	3.4424	3.6034

In which: $\overline{x}$ = Average ($m^3\ ha^{-1}$); S_x^2 = Variance $(m^3\ ha^{-1})^2$; CV = Variance coefficient (%); $S_{\overline{x}}$ = Mean standard error ($m^3\ ha^{-1}$); Ea = Absolute sampling error ($m^3\ ha^{-1}$); Er = Relative sampling error (%).

The assortment which the main part of the stand wood volume would be sent to is fence post II (47.14%), followed by fence post I (33.19%), fence post III (10.70%), firewood (8.08%) e waste (0.89%). The precision for volume assortments was also considered satisfactory, with sampling error inferior to 4%, except for fence post III, that reached 7,44%. This result is explained by the slight difference between the bole base profile observed and the estimated by the model.

The results obtained in this work demonstrate the compatibility between the volumes obtained by two methods evaluated. Although the volume equations being widely used on forestry inventories, it is recommended the use of tape functions to obtain reliable estimates of this variable. The taper functions presented the advantage of allowing obtain volume per bole assortment, which improves the stand utilization, adding value to the final product.

Conclusions:

With this study it can be conclude that:

1. The volume and taper models are compatible to estimate the volume in eucalyptus stand, being that

the last present the advantage to obtain the volume per bole assortment.

2. The use of taper functions allows performing forestry inventories of eucalyptus stand, being precise, for both total volume and bole assortments volume.

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