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Volume prediction through form factor and regression models by age class for *Pinus taeda* L.

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Abstract
The objective of this research was to evaluate the use of form factor and volume models by age class for the volume prediction of a *Pinus taeda* L. forest located in the city of Telemaco Borba - PR. For this, 302 trees were measured and scaled by the Smalian method, which were distributed among the following age classes, obtained by Sturges formula: class I: 4.10 – 7.10; class II: 7.11 – 10.10; class III: 10.11 – 13.10; class IV: 13.11 – 16.10 and class V: 16.11 – 19.10. Four volume estimation methods were tested, such as the mean artificial form factor, form factor by age class, overall fitting of regression models and by age class. The selection of the best method was based on the fitting statistics of the models. The best fitted model for all data was Schumacher-Hall, while the best model by age group was Spurr, with the exception of class I. The comparative analysis among the techniques tested revealed that the mean form factor and by age group did not provide accurate estimates. The mean artificial form factor showed results superior to those obtained by the application of the average form factor for classes I, II and III. For the other classes, the average form factor per class performed best. For the volume equations, both the overall and per-class adjustment were satisfactory. There were no significant differences between treatments, however, the method that best estimated the volume of *Pinus taeda* L. was the fitting of volume models by age class.
Keywords: Forest Inventory, Forest production, Volumetry.

Introduction

Forest inventory has the main purpose of estimating the volume potential of a forest stand (Barros et al. 2009). The knowledge of the volume variable for individual trees and/or for the whole forest is extremely important for commercial plantations and also for native forests, especially for carbon quantification. In this regard, representative samples of the population are used, and the main data recorded are the Diameter at the Breast Height (DBH) and height. Using these two variables, it is possible to estimate the tree´s volume, considering the adjustment of regression methods and volume models based on form factor (Machado and Figueiredo Filho 2009).

The volume models get their parameters defined by regression, and they are adjusted using information of tree´s diameter and total height as the independent variables, and volume is the dependent variable to be estimated (Melo et al. 2013). Campos and Leite (2009) suggest that this method has limitations related to species and age, and, because of this, the adjusted equations should be chosen based on the stand's characteristics. Many volume equations are available in the literature, and, despite the efficient performance of some models, the adjustment is not always satisfactory. Thus, Silvestre et al. (2014) recommend to test such models, taking into consideration the adjustment and precision statistics, and to observe the best statistical fit in each situation.

Campos and Leite (2009) also highlight another method of volume quantification, known as scaling. This method involves the diameter measurement in different trunk sections, and it is a direct method of volume estimative.

Volume equations' fitting is widespread and widely used in forestry; however, there is another methodology frequently utilized for volume prediction: the form factor. This is conceptualized by Machado et al. (2005) as a ratio between the volume obtained through tree scaling and the cylinder's volume, acting as a correction factor. It is important to emphasize that the obtained estimates can be influenced by some stand´s characteristics, such as species, age, site, spacing and thinning (Machado et al. 2005).

Considering all of this, the precision and accuracy of the volume estimates play an important role to define the multiple uses of the forest and contribute to the production planning and sustainability, since inaccurate information could lead the company or the forest producer to losses.

Another element that must be considered is the influence of age on the trees volume prediction, since the production capacity of these individuals and/or the whole stand is directly related to this variable (Encinas 2005). Many researches have already been conducted studies about the performance of volume estimate methods by diametric classes, such as Colpini et al. (2009), Miranda et al. (2015), Sanquetta et al. (2016), Sanquetta et al. (2017) but investigations about age classes are still insufficient.

Therefore, this paper aimed to investigate the performance of form factor and adjustment of volume models by age classes in volume prediction of a *Pinus taeda* L. forest.

Methodology

This research was conducted in a forest of *Pinus taeda* L., installed in 1998 in the municipality of Telemaco Borba, central region of Parana state, Brazil. The area has an average altitude of 885 m.a.s.l., and the climate, according to Köppen classification, is classified as subtropical, with an average temperature of the coldest month of 16.3°C, and an average temperature of the warmest month of 23.2°C. The mean annual rainfall is about 1.478 mm (Alvares et al. 2013).

The data were collected in unthinned and unpruned stands of a 2.5 x 2.5 m spacing, of different ages, in a total area of approximately 10,000 hectares. There were no fertilizations.

Regarding the sampling process, 1000 rectangular plots of 30 x 25m were located, systematically, in the area. In the plots, all of the trees were measured in terms of Circumference at Breast Height (CBH), using a measuring tape. Subsequently, the CBH was converted in Diameter at Breast Height (DBH), in meters. The height of about 10% of the total trees and of the dominant trees in the plots was measured using a Haglof clinometer. These data were used to estimate individual tree volume.

The distribution of age classes was calculated through Sturges formula, as follows (Equation 1):

$$k = 1+3.322\left(\log_{10} n\right) \quad (1)$$

Note: k: number of classes; n: number of observations.

The 302 trees were scaled by the Smalian method according to the forest´s diametric distribution and by age classes, as described on Table 1. For that, the diameters at the sections 0.02 m; 0.7 m; 1.3 m and 2.0 meters were measured, and after that, the stem was measured up to the total height in 2.0 meters intervals. From the 302 scaled trees, a total of 250 were used for fitting equations and 52 for validation, in order to choose the best method.

Table 1. Trees distribution by age class for the volume predition in a forest of *Pinus taeda* L. in the municipality of Telemaco Borba – PR.

Class	Class center	Frequency	Validation	DBH	Height	Volume
I: 4.10 – 7.10	5.60	51	11	11.90	7.95	0.05913
II: 7.11 – 10.10	8.60	48	10	18.95	12.96	0.19832
III: 10.11 – 13.10	11.60	31	10	25.48	17.54	0.44597
IV: 13.11 – 16.10	14.60	46	10	27.13	20.92	0.64506
V: 16.11 – 19.10	17.60	74	11	36.22	25.64	1.26097
Total	-	250	52	23.93	17.00	0.52189

Note: DBH: diameter at breast height, measured at 1.30 m (cm); H: total height (m); Volume: estimated individual volume (m³).

With this data, four methodologies for volume estimative were tested, as described in the next topic.

Method A: Mean artificial form factor application

The artificial form factor of each tree was calculated by the division between the real volume, obtained through Smalian method, and the cylinder volume, using the DBH to calculate the cylinder transversal area (Soares et al. 2011).

The overall mean artificial form factor for the forest was defined by the ratio between the sum of the form factors calculated for all of the trees and the number of trees.

Thus, the individual volume estimated by this method was calculated by the product of the basal area, height and the mean artificial form factor calculated for the forest (Soares et al. 2011; Sanquetta et al. 2017).

Method B: Mean form factor by age class

The mean factor form for each age class was determined by the division of the sum of all the trees artificial form factors of a class by the number of trees in each class.

The estimated volume by this method was also a result of the basal area, height and the mean form factor of the respective age class (Soares et al. 2011).

Method C: General fitting of volume equations

A number of six volume equations were tested to estimate total individual volume for the studied forest, considering a total of 250 trees (Table 2).

Table 2. Volume equations tested for the individual volume estimative for *Pinus taeda* L. trees in a forest located in Telemaco Borba – PR.

Model	Model	Equation
1	Linear	$v = \beta_o + \beta_1\ DBH$
2	Kopezky-Gehrardt	$v = \beta_o + \beta_1\ DBH^2$
3	Hohenadl-Krenn	$v = \beta_o + \beta_1{*}DBH + \beta_2\ DBH^2$
4	Spurr	$v = \beta_o + \beta_1\ (DBH^2H)$
5	Husch	$Ln\ v = \beta_o + \beta_1\ Ln\ DBH$
6	Husch mod	$Ln\ v = \beta_o + \beta_1\ Ln\ DBH^2$
7	Schumacher-Hall	$Ln\ v = \beta_o + \beta_1\ Ln\ DBH + \beta_2\ Ln\ H$
8	Spurr log	$Ln\ v = \beta_o + \beta_1{*}Ln(DBH^2{*}H)$

Note: v: estimated individual volume (m³); H: total height (m); DBH: diameter at breast height, measured at 1.30 m (cm); βi: model´s parameters (i = 0, 1, 2).

For the mathematic models in logarithmic scale, which provide the volume´s logarithm, the antilogarithm was calculated to obtain the volume. This mathematic operation results in an error called logarithmic discrepancy. In order to correct this error, the Meyer Correction Factor (MCF) was adopted for the models that utilized the natural logarithm (Equation 2). From the MCF values, the fitted determination coefficients and the residual standard errors were recalculated, once the application of this factor results in different values of sum of residual squares.

$$MCF = e^{0.5*QM_r} \quad (2)$$

Note: MCF: Meyer Correction Factor; e: basis of the natural logarithm (2,718281828...); QMR: mean of the squared residuals.

Method D: Volume equations fitting by age class

The volume equations described on Table 1 were fitted for each age class. The logarithm models were also corrected by MCF (Equation 2).

Selection of the best method

The fitting quality of the models was based on the following criteria: the adjusted coefficient of determination (R² adjusted) (Equation 3), and standard error of estimate in percentage (Syx %) (Equation 5) and also the residual graphical analysis, as suggested by Nicoletti et al. (2016) and by Sanquetta et al. (2005). It is expected that the best model shows the highest adjusted coefficient of determination, the lowest standard error, a normal residual distribution and a residuals mean of zero.

$$R^2adj = 1-\left\{\left(1-R^2\right)*\left(\frac{n-1}{n-p}\right)\right\} \quad (3)$$

$$Syx = \sqrt{\frac{\sum (y-yi)^2}{n-p}} \quad (4)$$

$$Syx = \frac{Syx}{\hat{Y}}*100 \quad (5)$$

Note: R² adj: adjusted R²; n: number of scaled trees; n-1: degrees of freedom; p: number of equation´s parameters; Syx: residual standard error in percentage; y: observed volume; yi: estimated volume; Ŷ: average of the observed values.

In addition, the statistics of bias (Equation 6 and 7), precision (Equation 8 and 9) and accuracy (Equation 10 and 11) were determined, following Pretzsch (2009):

$$\bar{e} = \frac{\sum_{i=1}^{n} \hat{v}_i - v_i}{n} \quad (6)$$

$$\bar{e}\ (\%) = \frac{\bar{e}}{\bar{v}}*100 \quad (7)$$

$$S_e = \sqrt{\frac{\sum_{i=1}^{n} (\hat{v} - \bar{e} - v_i)^2}{n-1}} \quad (8)$$

$$S_e\ (\%) = \frac{S_e}{\bar{v}}*100 \quad (9)$$

$$m_v = \sqrt{\frac{\sum_{i=1}^{n} (\hat{v}_i - v_i)^2}{n-1}} \quad (10)$$

$$m_v(\%) = \frac{m_v}{\bar{v}} * 100 \quad (11)$$

Note: $\bar{e}$: bias; S_e: precision; m_v: accuracy; $\hat{v}_i$: predicted volume (m³); v_i: volume obtained by Smalian method (m³); $\bar{v}_i$: mean observed volume (m³); n: number of trees.

Statistical analysis

Statistical analyzes included the Bartlett test to verify the difference between the estimated volume variances and the volume observed, and the Kolmogorov-Smirnov normality test. It was considered a completely randomized design with five treatments: volume calculated by means of scaling, volume calculated using average artificial form factor, volume calculated by age class, volume obtained by the global fitting of volume equations and volume obtained by the fitting of volume equations by age class for 250 replicates. Such analyzes were performed in the statistical analysis program ASSISTAT® v.7.6.

Results and Discussion

Regarding the descriptive statistics for the first technique evaluated, it was found a mean form factor of 0.4614, varying from 0.3387 to 0.7376, a standard deviation of 0.0527, a variance of 0.0027 and a variation coefficient of 11.43%. Compared to the average form factors by age class, which showed a disparity from 0.4445 to 0.4925 and a mean variation coefficient of 10.48%, the first values presented higher discrepancy. The others statistics gathered for the age class method are illustrated on Table 3. Table 4 displays the precision statistics for the volume models tested.

Table 3. Statistics of the mean form factor by age class for a *Pinus taeda* L. forest in the municipality of Telemaco Borba – PR.

Class	$\bar{x}$	s	s^{2^2}	CV
4.10 – 7.10	0.4925	0.06774	0.00459	13.76
7.11 – 10.10	0.4445	0.05819	0.00339	13.09
10.11 – 13.10	0.4480	0.04195	0.00176	9.37
13.11 – 16.10	0.4566	0.03341	0.00112	7.32
16.11 – 19.10	0.4598	0.04087	000167	8.89
Average	**0.4603**	**0.04843**	**0.002506**	**10.48**

Note: $\bar{x}$: average; s: standard deviation; s^{2^2}: variance and CV: coefficient of variation.

Table 4. Statistical parameters of the tested models for the volume prediction in a *Pinus taeda* L. forest, considering all age classes.

Model	β_o	β_1	β_2	R² adj	Syx (%)
1	-0.56558	0.04663	-	0.8653	35.05
2	-0.12743	0.00096	-	0.9436	22.68
3	0.13671	-0.02549	0.00145	0.9541	20.46
4	0.01176	0.00003	-	0.9842	11.98
5	-9.67328	2.71802	-	0.9546	20.43
6	-9.67328	1.35901	-	0.9546	20.43
7	-9.99851	1.89949	1.02768	0.9910	11.67
8	-9.98909	0.97286	-	0.9910	11.79

Note: β0, β1, β2: model's parameters, Syx: residual standard error; Syx (%): residual standard error in percentage and R² adj: adjusted coefficient of determination.

The analysis of the obtained statistics (R² adj and Syx (%)) from the simple entry models (Linear, Kopezky-Gehrardt, Hohenadl-Krenn, Husch and Husch mod) allows to affirm that such models are not indicated for the volume prediction of this forest. For the Spurr, Schumacher-Hall and Spurr log models, the fitted coefficient of determination varied from 0.9842 to 0.9910, suggesting an elevated level of explanation of the real volume by these models. Besides that, the residual standard error in percentage was lower than 12%. Due to the high value of R² adj and low value of Syx, combined with the best residuals distribution on the regression line, the Schmacher-Hall model was elected as the most adequate to estimate the forest´s volume.

The performance of the fitted volume equations by age groups was similar to the overall fitting (Table 5). In general, the simple entry models did not reach satisfactory statistics. In all age classes, the Schumacher-Hall and Spurr models were superior to the others, as a result of the higher values of R²adj and lower rates of Syx (%). Therefore, the Schumacher-Hall was indicated to age class I and Spurr log was designated to the other age classes.

Table 5. Fitting´s precision statistics of the tested volume values in terms of age classes for the volume quantification in a forest of *Pinus taeda* L.

	Class I		Class II		Class III		Class IV		Class V	
Model	R² adj	Syx	R² adj	Syx	R² adj	Syx	R² adj	Syx	R² adj	Syx
1	0.8977	36.3	0.9140	22.1	0.9489	13.7	0.9270	16.2	0.8809	11.9
2	0.9721	18.9	0.9523	16.5	0.9617	11.9	0.9633	11.5	0.9074	10.9
3	0.9830	14.8	0.9519	16.5	0.9616	11.9	0.9630	11.6	0.9070	10.9
4	0.9960	7.1	0.9771	11.4	0.9658	11.2	0.9808	8.3	0.9452	8.4
5	0.9643	7.1	0.9523	7.1	0.9409	4.3	0.9782	4.9	0.8758	5.8
6	0.9643	7.1	0.9523	7.1	0.9409	4.3	0.9782	4.9	0.8758	5.8
7	0.9878	2.5	0.9736	4.6	0.9678	4.0	0.9870	3.5	0.9353	4.5
8	0.9864	2.6	0.9738	4.8	0.9682	3.9	0.9869	3.5	0.9358	4.4

Note: R² adj: adjusted coefficient of determination; Syx: residual standard error in percentage (%).

The comparative analysis between the tested techniques (Table 6) revealed that the utilization of mean form factor and mean form factor by age class did not demonstrate precise and accurate estimates due to the highest values of bias. The fitting of volume equations considering all data or age class generated acceptable values of precision and accuracy and the lowest biased estimates.

Table 6. Bias, precision and accuracy of the utilized methods to predict volume in a forest of a *Pinus taeda* L.

Method	Mean volume (m³)	Bias (%)	Precision (%)	Accuracy (%)
A - Mean FF	0.61342	2.68	12.77	13.05
B: FF class I	0.06553	10.83	23.97	26.35
B: FF class II	0.20697	4.36	13.05	13.78
B: FF class III	0.45942	3.01	14.02	14.35
B: FF class IV	0.64352	-0.23	8.26	8.26
B: FF class V	1.28345	1.78	9.69	9.85
C: Schumacher-Hall	0.59201	-0.89	11.59	11.62
D: Model Class I	0.05888	-0.41	5.56	5.58
D: Model Class II	0.19823	-0.04	11.12	11.12
D: Model Class III	0.44945	0.78	11.39	11.42
D: Model Class IV	0.64638	0.20	8.35	8.35
D: Model Class V	1.26387	0.23	8.25	8.25

Note: A: Mean FF (mean artificial form factor of the forest); B: FF class I: (mean form factor of class I); B: FF class II (mean form factor of class II); B: FF class III (mean form factor of class III); B: FF class IV (mean form factor of class IV); B: FF class V (mean form factor of class V); C: best fitted model for all 250 trees (Schumacher-Hall); D: Best fitted model for class I; D: Best fitted model for class II; D: Best fitted model for class III; D: Best fitted model for class IV; D: Best fitted model for class V.

Concerning the bias, the mean artificial form factor (Figure 1) produced superior results to the ones gathered by the application of mean form factor for classes I, II and III. The performance of the mean form factor showed good results only for classes IV and V. In terms of accuracy and precision, the mean form factor demonstrated values close to the ones exhibited by the global volume equations fitting.

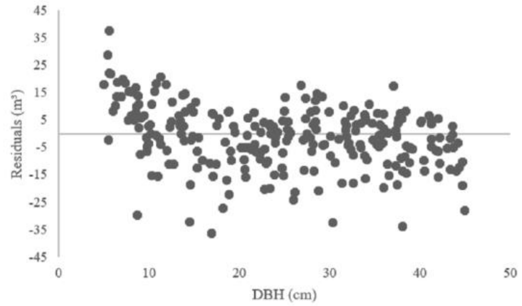
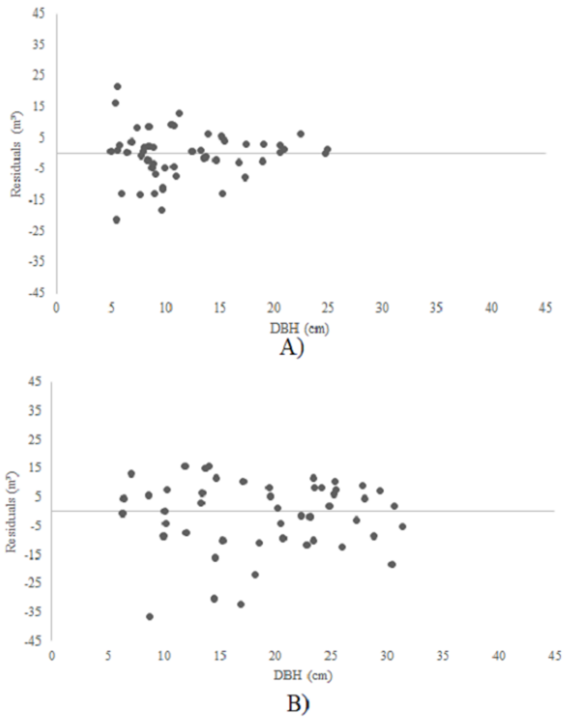


Figure 1. Graphical visualisation of the residuals for the volume estimates obtained by the mean artificial form factor for a forest of *Pinus taeda* L.

The output performance of the volume equations fitting by age class can be proven by its low bias and precise and accurate predictions. When comparing the results for class I, through this method, with the mean form factor per class, a divergence among the methods is easily noted, and it is enhanced by the residuals graphical analysis on Figure 2.



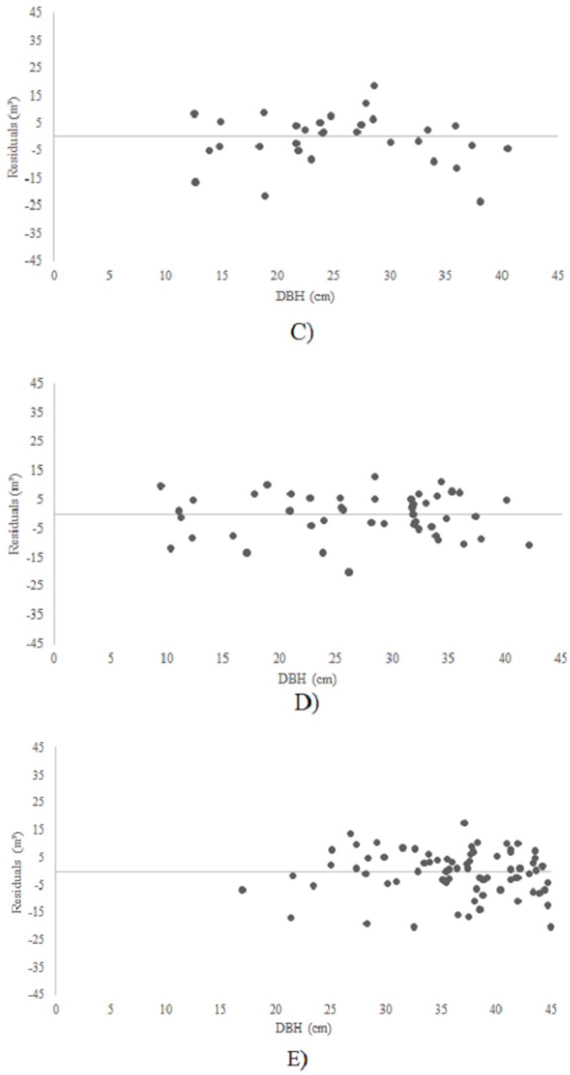


Figure 2. Graphical distribution of the waste for the adjusted models A) Schumacher - Class I, B) Spurr - Class II, C) Spurr - Class III, D) Spurr - Class IV and E) Spurr - Class V for a forest of *Pinus taeda* L.

The Bartlett test revealed that the variances of the treatments were not significant at the 5% probability level, concluding that there is homogeneity among them. The data presented normal distribution, demonstrated by the Kolmogorov-Smirnov normality test. The variance analysis was not significant at the 5% probability level, indicating that all forms of estimates tested presented the same mean. Thus, for this data set, the mean volume obtained through the estimation by average form factor in terms of age class and fitting data of volume models by age class did not differ from the mean of the observed volume.

The results on Table 7 emphasize the efficiency of the volume models' fitting by age class through its validation. Again, the mean artificial form factor and the mean form factor by age class showed the most biased estimates. On the other hand, the overall fitting of the volume equations acknowledged a lower bias and satisfactory values of precision and accuracy in all classes.

Table 7. Bias, precision and accuracy of the methods utilized to predict volume in a *Pinus taeda* L. forest (52 trees from the validation data).

Method	**Mean volume (m^3)**	**Bias (%)**	**Precision (%)**	**Accuracy (%)**
A - Mean FF	0.60356	6.31	18.64	18.45
B: FF class I	0.05817	7.66	22.70	24.07
B: FF class II	0.22311	2.66	11.76	12.09

B: FF class III	0.39454	2.60	6.98	7.50
B: FF class IV	1.04242	7.88	14.39	16.62
B: FF class V	1.30504	8.37	13.36	15.94
C: Schumacher-Hall	0.56326	-0.78	14.88	14.91
D: Model Class I	0.05437	0.63	4.15	4.21
D: Model Class II	0.21959	1.03	7.38	7.46
D: Model Class III	0.38607	0.40	6.70	6.71
D: Model Class IV	0.96402	-0.23	14.36	14.36
D: Model Class V	1.20899	0.39	10.74	10.75

Note: A: Mean FF (mean artificial form factor of the forest); B: FF class I: (mean form factor of class I); B: FF class II (mean form factor of class II); B: FF class III (mean form factor of class III); B: FF class IV (mean form factor of class IV); B: FF class V (mean form factor of class V); C: best fitted model for all 250 trees (Schumacher-Hall); D: Best fitted model for class I; D: Best fitted model for class II; D: Best fitted model for class III; D: Best fitted model for class IV; D: Best fitted model for class V.

The research developed by Kohler et al. (2013) evaluated the need of data grouping into age groups for taper models fitting for *Pinus taeda* L. trees. These authors recognized that the equations used in their research showed advantages in the estimates, in terms of the least average error in relation to the total of the equation. This suggests that fitted taper equations, considering stratification by age class, could improve the quality of diameter estimates.

Although there are many comparisons among methodologies of volume quantification, most of them approach diametric classes, as the studies of Sanquetta et al. (2016) and Sanquetta et al. (2017).

On the first one, the authors assessed the performance of form factor by age class to estimate volume and compared the results with regression models, for an *Araucaria angustifolia* (Bertol.) O. Kuntze forest located in the municipality of Quedas do Iguacu, state of Paraná. The authors concluded that the utilization of form factors by age classes expressed better statistics for the stand, and it was the methodology indicated to quantify the volume of the studied stand.

The second one, published by Sanquetta et al. (2017), also compared these two methods (form factor by age class and regression) to estimate volume for a *Pinus taeda* L. stand. The best estimate was reached by the mean form factor by diametric class, and the authors defined it as a robust and simple technique that can be easily applied to other cases. In both studies, the Spurr model showed the best performance.

The superiority of Schumacher-Hall volume model was also tested by the studies of Mendonça et al. (2015) and Rodrigues et al. (2017). The first one analysed the identity of a linear and a non-linear model to estimate the trees' volume for *Pinus caribaea* var. *hondurensis* and *Pinus oocarpa*, and they noticed that the Schumacher-Hall model was more precise than Spurr´s to estimate volume for the *Pinus* species.

The second one, led by Rodrigues et al. (2017), verified the identity of hypsometric and volume models in uneven-aged stands of *Pinus taeda* L. submitted to first thinning, to check out the possibility of grouping data according to the variable "age". In their study, all of the tested models presented reasonable statistical parameters; however, the authors selected the Schumacher-Hall model as the most adequate one to estimate individual volume of the studied *Pinus taeda* L. stand for all of the different assessed ages.

Conclusion

For the dataset analyzed in this article, there were no significant differences among the methods tested. However, the most precise and accurate estimates were obtained by the fitting of volume models by age class.

The mean artificial form factor and the mean form factor by age class generated imprecise and biased results, and are not recommended for volume estimation.

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