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Models for estimating the diameter at breast height as a function of the diameter of the stump *Pinus taeda* L.

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Abstract
The study addressed the use of models to estimate dendrometric variables in a commercial plantation of *Pinus taeda* L. Allometric relationships were applied to estimate diameter at breast height (DBH) based on stump diameter (SD), providing a mathematical approach to relate these two variables. Additionally, a "conventional" measurement exclusively of DBH was conducted to compare the values obtained with traditional approach to the results of the proposed modeling. The study also explored hypsometric relationships to estimate tree height as a function of DBH, enabling an efficient and economical assessment of tree characteristics in the forest stand. Furthermore, a forest census was conducted in the area, allowing a comprehensive comparison between the methods used and the actual data from the forest stand, reinforcing the importance of these approaches for effective forest resource management. The results showed that the models were effective in estimating volume, basal area, and the number of trees per hectare, with consistent results compared to the forest census. Therefore, the study concludes that stump inventory methods are effective in estimating dendrometric data in *Pinus taeda* L. plantations, even after forest cutting events, thereby supporting forestry experts in conducting precise assessments in areas with completed timber harvesting and in making informed decisions. This contributes to the effective and sustainable management of forest resources and the enforcement of laws in cases of environmental or economic damage.

Keywords
Allometric Relations — Forestry Expertise — Forest Inventory — Stump Inventory

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1. Introduction

The planted forest sector plays an extremely important role in the Brazilian economy. According to Moreira and Oliveira (2017), Brazil stands out in the forest products market due to its advantageous soil and climate conditions and technological progress in forestry and forest management. According to data from Ibge (2022), the country has around 9.5 million hectares of planted forests, forestry production reaches approximately $ 5,204,431.00, with $ 2,990,060.00 corresponding to the value of production of logs, the South Region is responsible for 35.8% of this value (The values in reais were converted to dollars based on the average price for the year 2022 - R$ 5.27 for every $ 1.00). These numbers reflect the importance of this sector for the country's economy, which represents approximately 5% of the Brazilian Gross Domestic Product (GDP) (Ibá, 2023).

Quantifying resources in forest areas is essential to provide producers with greater control over production. However, when it comes to planted forests, measuring each tree individually is an expensive task, making it unfeasible. In this context, forest inventories are conducted through sampling, which reduces process costs. As highlighted by Higuchi et al. (1982), the application of sampling theory in forest inventory dates back to the 19th century in Europe and represents a technique widely used today. The methodology in question makes an efficient and less costly assessment of forest resources possible.

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In forest inventories, measuring DBH (Diameter at Breast Height) is a common practice due to its ease of obtaining. According to Souza et al. (2013), DBH serves as an initial variable to estimate other crucial information, such as tree height and volume, which can be more difficult to measure directly in the field. Still according to Souza et al. (2013), the application of statistical modeling has become increasingly common in forest inventory procedures, simplifying the data collection process, making it more economical and, in most cases, offering estimates as accurate as individual measurements. the height of each tree in the plot.

According to Nicoletti et al. (2016), the use of hypsometric and volumetric equations plays a crucial role in inventories, enabling precise estimates of the volume of areas subject to management. Aiming to save costs during data collection, several studies focus on analyzing the relationship between the diameter and height of trees. As highlighted by Imaña-Encinas, et al. (2002), determining tree height using instruments is a costly task. Therefore, it is common to measure the height of just a few trees, later using models to estimate the height of the others.

However, in situations where the forest no longer exists, it is essential to develop methods to estimate the DBH, thus providing the necessary basis for reconstituting what was in the forest after events such as wood theft, fires or post-harvest inventories by whatever the reason. The objective of this work is to develop a model capable of estimating DBH based on stump diameter, in commercial stands close to the end of the rotation, thus allowing the recreation of information related to DBH after such events.

2. Material and Methods

2.1 Study Area

The study was carried out in a plot of *Pinus taeda* L. established in 1998, which was thinned on three occasions (one systematic and two selective thinnings) with a total area of 6.64 hectares, as represented in Figure 1. This research site is located in the municipality of Lages, state of Santa Catarina, Brazil. Its approximate geographic coordinates are 27°48'35.37" South latitude and 50°16'11.06" West longitude.

The region has a temperate climate of the Cfb type, according to the Köppen classification, characterized by rainfall evenly distributed throughout the year, with an average annual rainfall ranging from 1100 to 2000 mm. There is no distinctive dry season, and the average temperature during the hottest month does not exceed 22℃, resulting in a cool summer, according to Alvares et al. (2013).

2.2 Forest Measurement

In August 2023, a conventional forest inventory was carried out, using the fixed area method, in which ten circular sampling units of 873 m² were established and randomly distributed throughout the plot area (Figure 1).

During this inventory, two perpendicular measurements of the diameter at breast height (DBH) of the trees obtained with suta were recorded, at a height of 1.30 meters from the ground, with an angle of 90° between them. Additionally, the same measurement procedure was applied to the tree stump diameter (SD) (located approximately 10 cm from the ground). For the variable total height (h), 20% of the trees were measured, systematically selecting one in every five trees present in the sampling unit.

Table 1. Allometric models tested for the population.

Models	Expression
1	$Y = \beta_0 + \beta_1 X$
2	$Y = \beta_0 + \beta_1 X + \beta_2 X$
3	$Y = \beta_0 + \beta_1 \left(\frac{1}{X}\right)$
4	$Y = e^{\left(\beta_0 + \beta_1 \frac{1}{X}\right)}$
5	$Y = \beta_0 + \beta_1 \left(\frac{1}{X}\right)$

*Where: Y = h (m) or DBH (cm); X = DBH or SD (cm); β_n = model coefficients.

The established database was used to develop statistical models to estimate the diameter at breast height (DBH) as a function of the stump diameter (SD) and the height (h) as a function of the DBH. The models used are available in Table 1.

The selection of the best model for each adjustment modality was based on the highest adjusted coefficient of determination (adjusted R²), lowest standard error of the estimate in percentage (Syx%) and the significance of all model coefficients. In case of a tie, the selection was defined based on the smallest standard error.

To calculate the volume (v), a shape factor of 0.48 was used, a value obtained from cubing carried out in the area in February 2023, which is compatible with values obtained in the literature for the same species in the Southern Region of Brazil (Stepka et al. 2017 and Nicoletti et al. 2020).

In a second moment, in order to validate the results,

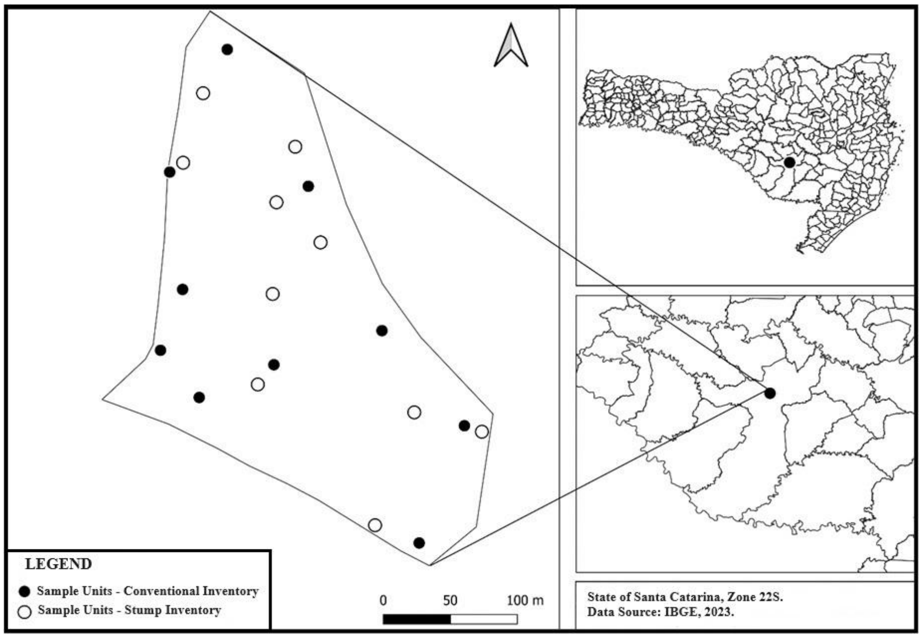

Figure 1. Location of the plot and sampling units in the study area in Lages, SC.

also following the fixed area method, ten new sampling units were installed (Figure 1) distributed randomly, with the aim of validating the method, these plots had an area of 600 m², where only SD (cm) was measured using two crossed measurements.

After measuring the new sampling units, the adjusted models were used to estimate DBH and H. After adjusting the models, the normality of the distribution of residuals was tested. Then the basal area and volume were calculated and the values were compared to those obtained in the conventional inventory and in the census of the area carried out in February 2023.

The formulas for estimating the basal area per hectare (G), number of trees per hectare (N) and volume per hectare (V) were as follows:
Basal area per hectare:

$$G.ha^{-1} = \sum gi \times \frac{10000}{a}$$

Where: $G.ha^{-1}$= basal area ($m^2.ha^{-1}$); gi= transversal area in m²; a= area of the sampling unit (m²).

Number of trees per hectare:

$$N/ha = \sum n \times \frac{10000}{a}$$

Where: $N.ha^{-1}$= number of trees per hectare; n= number of trees present per plot; a= area of the sampling unit (m²).

Volume per hectare:

$$V/ha = \sum vi \times \frac{10000}{a}$$

Where: $V.ha^{-1}$= volume ($m^3.ha^{-1}$); vi= individual volume in m³; a= area of the sampling unit (m²).

To define whether the model presents results compatible with reality, using grouped data, T tests were carried out for the variables volume per hectare V ($m^3.ha^{-1}$) and basal area per hectare G ($m^2.ha^{-1}$), assuming equivalent variances.

3. Results

In the conventional forest inventory, an average diameter of 39.1 cm (range of 27.1 to 53.0 cm) was observed, an average total height of 28.6 m (range of 21.0 to 34.8 m) and diameter with an average stump of 49.2 cm (range of 32.0 to 66.0 cm). This information is important as it was the data considered for statistical modeling.

3.1 Hypsometric relationship

For the hypsometric relationship, the values found for the coefficients β_0, β_1 and β_2, as well as the coefficient of determination (adjusted R²), absolute and relative error (Syx) and F value can be described in Table 2.

After analyzing the data presented in Table 2, it can be concluded that the most suitable model for the data was number 4. An analysis of the residual scatter plot was then carried out in relation to the DBH (Figure 2 A), in order to detect possible trends in waste. The adjustment

Table 2. Statistics and adjustment coefficients for the hypsometric models.

Models	β_0	β_1	β_2	Adjusted R²	Syx (cm)	Syx (%)	F
1	23.7203*	0.1536*	-	0.1271	1.9	6.3	12.18
2	19.1235*	0.3831ns	-0.0028ns	0.1263	1.9	6.4	5.54
3	32.7787*	-4457.004**	-	0.1226	1.9	6.3	10.64
4	3.5989*	-8.0583*	-	0.1278	1.9	6.3	12.12
5	35.9264*	-238.8358*	-	0.1273	1.9	6.3	11.06

*Where: Y = Height (m); X = DBH (cm); β_n = model coefficients; Adjusted R² = adjusted coefficient of determination; Syx = standard error of the absolute estimate (m); Syx = relative standard error of the estimate (%); ns = non-significant coefficient (P-value $>$ 0.05); * significant coefficient (P-value $<$ 0.05).

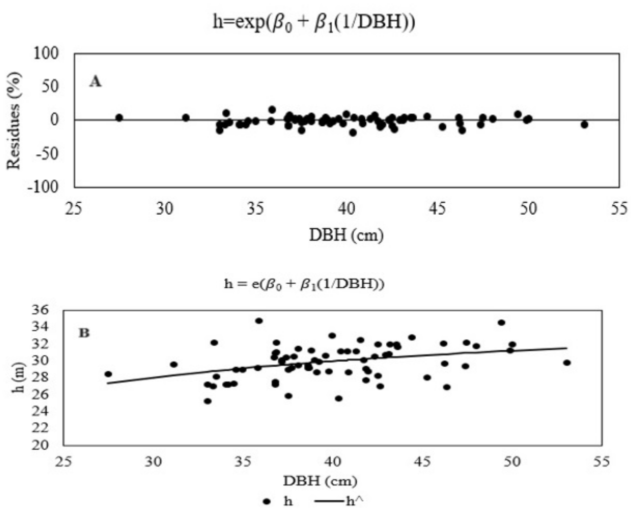

Figure 2. A - Residual dispersion (%) in relation to diameter at chest height of hypsometric model 4. B - Adjustment of the chosen hypsometric model showing the measured heights (H) and the estimated heights ($\hat{h}$) by the best selected model.

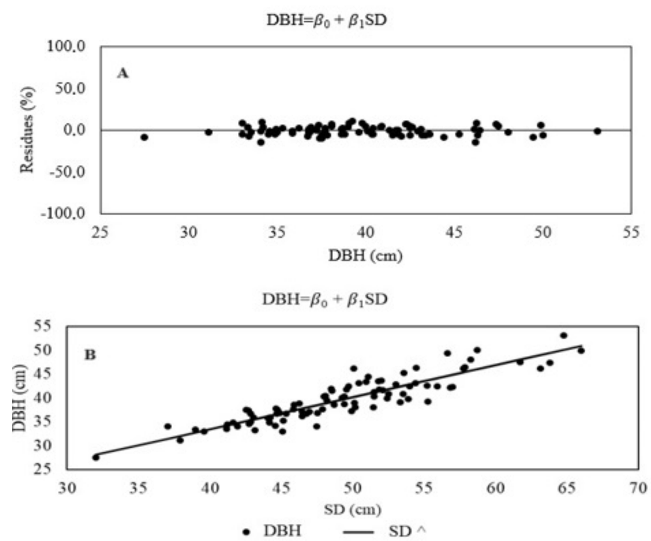

Figure 3. A - Residual dispersion (%) in relation to diameter at breast height of model 1 to estimate DBH as a function of SD. B - Adjustment of the model chosen to estimate DBH as a function of SD, showing measured diameters (DBH) and estimated diameters ($\widehat{DBH}$) using the best selected model.

of the model can be seen in (Figure 2 B), demonstrating the predicted height as a function of the measured DBH.

3.2 Relationship between SD and DBH

Table 3 shows the statistics of model adjustments to estimate DBH as a function of SD.

After analyzing the data presented in Table 3, it can be concluded that the most suitable model for the data was number 1. An analysis of the residual scatter plot was then carried out in relation to the DBH (Figure 3 A), in order to detect possible trends in waste. The model adjustment can be seen in (Figure 3 B), demonstrating the predicted DBH as a function of the measured SD.

3.3 Comparison between the grouped variables (G and V) obtained by the measured and estimated DBHs

For the sampling units that only had stump diameters measured, the DBHs and total heights were estimated with the best selected models. The basal areas per hectare and volume per hectare were also calculated, as in the conventional inventory. The resulting values were compared using the T test and P-values of 0.3961 and 0.4777 were obtained, respectively for G and V, representing that the data do not differ from each other

Table 3. Model adjustment statistics to estimate DBH as a function of SD.

Models	β_0	β_1	β_2	Adjusted R²	Syx (cm)	Syx (%)	F
1	6.5770*	0.6716*	-	0.8144	2.0	5.1	382.7
2	4.3127*	0.7634ns	-0.0009ns	0.8123	2.1	5.2	189.3
3	58.6565*	-28644.1359*	-	0.9331	2.1	5.3	1215.2
4	4.4842*	-39.2795*	-	0.8119	2.1	5.3	25525.9
5	71.4380*	-1539.2452*	-	0.7841	2.2	5.5	316.9

*Where: Y = DBH (cm), X = SD (cm); β_n = model coefficients; Adjusted R² = adjusted coefficient of determination; Syx = Standard error of the absolute estimate (cm); Syx = relative standard error of the estimate (%); ns = non-significant coefficient (P-value $>$ 0.05); * significant coefficient (P-value $<$ 0.05).

statistically, thus generating two graphs of the box-plot type (Figure 3). In Table 4, you can see the descriptive statistics of DBH in cm estimated by the model and directly measured, allowing comparison between both.

Table 4. Descriptive statistics of DBH measured directly and estimated using SD for the data set.

Method	X	S	MIN	MAX	EP
DBH CI	39.1	4.9	27.1	53.1	0.2
DBH SI	38.0	3.8	30.2	49.6	0.2

DBH CI: DBH (cm) measured in the conventional inventory; DBH SI: DBH (cm) estimated through the stump inventory; X: Arithmetic mean; S: Standard deviation (cm); MIN: lowest observed value (cm); MAX: highest observed value (cm); EP: Standard error (cm).

3.4 Forest Inventory

The results of the variables G, V and N related to measurements in the conventional inventory, stump inventory and census can be seen in Table 5. It is notable that the real volume and basal area, despite being overestimated, are contained within the confidence interval of both procedures used, the number of trees was overestimated in the stump inventory, being outside the calculated confidence interval.

Table 5. Descriptive statistics for volume per hectare (m³.ha⁻¹), basal area (m².ha⁻¹) and number of trees per hectare for the study area.

	Method	X	CV	LI	LS	AE	RE
	Census	774.7	-	-	-	-	-
V	CI	820.4	11.7	762.7	878.0	57.6	7.0
	SI	789.6	7.3	754.1	825.0	35.4	4.5
	Census	53.6	-	-	-	-	-
G	CI	57.1	11.4	52.8	61.5	4.3	7.6
	SI	55.4	7.1	52.7	58.1	2.7	4.8
	Census	438.7	-	-	-	-	-
N	CI	467.3	10.4	436.5	498.2	30.8	6.6
	SI	483.3	7.1	461.2	505.5	22.2	4.6

Where: V: Volume (m³.ha⁻¹); G: Basal area (m².ha⁻¹); N: Number of trees; Census: Forest Census; CI: Conventional inventory; SI: Stump inventory; X: Arithmetic mean (unit of measurement of the variable of interest); CV: Coefficient of variation in %; LI: Lower limit of the confidence interval at 95% probability; LS: Upper limit of the confidence interval at 95% probability; AE: absolute sampling error; RE: Relative sampling error (%).

4. Discussion

In the analysis of the hypsometric relationship, the parameters of all models evaluated in Table 2 were close to each other. Model 4, in which tree height is estimated by h = exp(β_0 + β_1*(1/DBH)), stood out slightly due to better statistics (adjusted R² and Syx%) in relation to the others and was chosen as the preferred method for estimating tree height based on diameter at breast height (DBH). By analyzing the residual distribution graph (Figure 2 A), the absence of trends can be seen and in the normality test carried out, the residuals presented a normal distribution. Furthermore, the data in Table 2 indicate that all models evaluated exhibited coefficients of determination (adjusted R²) and relative standard errors (Syx %) in close agreement with the results obtained by Nicoletti et al. (2016) for a stand in the same region, subjected to 3 thinnings and 18 years old. This reinforces the robustness and accuracy of model 4 in estimating the height of

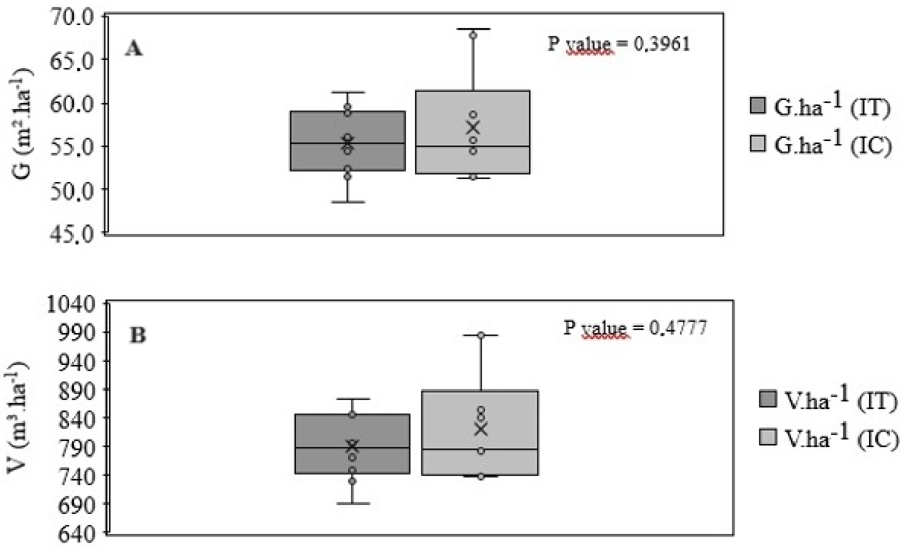

Figure 4. A - Box-plot graphs for the variables G (m².ha^{-1}) and B - V (m³.ha^{-1}) obtained by the conventional inventory and by estimating the IT starting from the IC.

the trees in question for the present database.

For the relationship between stump diameter and DBH, the adjusted models revealed remarkably high coefficients of determination, which reflects a strong correlation between stump diameter (SD) and diameter at breast height (DBH). Specifically, model 1, represented by the equation DBH = β_0 + β_1SD, was the preferred choice because it presented the lowest standard error of the estimate (Syx). Furthermore, in Figure 3 A, no discernible trends were identified in the residuals, and the results of the normality test indicated a normal distribution of the residuals.

It is interesting to note that the same model was adjusted by Costa et al., (2019), also for *Pinus taeda* in the same region as the present research, and the results presented a coefficient of determination (R^2) of 0.72 and a relative standard error (Syx) of 13.4%. These values indicate a lower precision compared to those obtained during the present study, this difference can be attributed to factors such as the smaller number of observations (20 trees) and because they are isolated trees, a factor that influences their morphometry, resulting in lower precision when in contrast to the context of the present study.

For Figueiredo Filho e Silva (2022), the p-value can be characterized as a probability that indicates the degree of disagreement of the observed data in relation to an expected theoretical model. Just as there was no statistical significance in the p-values for the grouped data (V and G), it is suggested that the estimated diameters as a function of the stump diameters can provide reliable and equivalent estimates in relation to the real V data. (m³.ha^{-1}) and G (m².ha^{-1}).

For a visual representation of these conclusions, two box-plot graphs were generated (Figure 4 A and B). These graphs also demonstrate the consistency between actual measurements and model estimates, reinforcing the equivalence of the results. The results presented in Table 4 show the proximity between the DBH measured directly in the field and estimated through the model, demonstrating that they are very close.

The comparison between sampling methods and forest census is a practice used in several studies in order to analyze their efficiency, Machado et al., (2023) carried out a comparison between the fixed area method and the Bitterlich method based on different K (basal area factors) in the estimation of G, V and N, comparing the results to the census of *Pinus taeda* stands with different intensities of thinning. Analysis of Table 5 reveals that the volume and basal area of the forest, obtained through the census, as well as in the work of Machado et al., (2023), are contained in the confidence intervals, both in the conventional inventory and in the stump inventory. This highlights the effectiveness of both methods in estimating the volume and basal area for the forest stand.

In the work of Herbele et al., (2022), which also compared estimates from different census sampling methods in *Pinus taeda* forests with different thinning intensities, it was notable that the average volume and basal area values obtained in the area method Fixed averages were higher than the census carried out, with the lower limit of the confidence interval for the basal area being above the census obtained, while the volume was included in the confidence interval. In the present study, the two inventories presented values slightly higher than the values found in the census. This small discrepancy can be attributed to the 7-month time interval between the census and the inventories, which may have influenced the additional growth of trees during this period.

In the case of the number of trees per hectare, the stump inventory generated an overestimated result, this fact can be explained by the random allocation of plots that may not have taken into account all the variation present in the population. The results found by Miranda et al., (2022) also found a discrepancy between the number of trees obtained through the fixed area method and the census. As the number of trees is the variable of least interest among those measured and the result was very close, there were no major problems.

5. Conclusion

Based on previous analyses, it is concluded that both the conventional inventory and the stump inventory proved to be effective in estimating the volume and basal area of the forest stand.

The consistency of the results, with values within the confidence intervals, confirms the precision and reliability of the inventory methods for *Pinus taeda* stands in the Santa Catarina mountains. Furthermore, it is important to highlight that these methods can be valuable for expertise and assessments in situations where it is necessary to estimate the volume and basal area, even after forest cutting, allowing for effective and sustainable management of forest resources and offering support for evaluation and expertise processes.

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Author Statements

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