

VOLUMETRY AND TRUNK SHAPE OF *Araucaria angustifolia* (Bertol.) Kuntze IN MIXED OMBROPHILOUS FOREST FRAGMENTS AT DIFFERENT ANTHROPIZATION LEVELS

Victória Varela Silva^{1*}, Marcos Felipe Nicoletti², Isabelle da Silva Wolff³, Thiago Floriani Stepka⁴, Daiani Aparecida Mafra⁵, Elder Schons Junior⁶

¹Universidade do Estado de Santa Catarina, Programa de Pós-Graduação em Engenharia Florestal, Lages, Santa Catarina, Brasil – victoria.vs2511@edu.udesc.br*

² Universidade do Estado de Santa Catarina, Departamento de Engenharia Florestal, Lages, Santa Catarina, Brasil – marcos.nicoletti@udesc.br

³ Universidade do Estado de Santa Catarina, Programa de Pós-Graduação em Engenharia Florestal, Lages, Santa Catarina, Brasil – isaawolff1@gmail.com

⁴ Universidade do Estado de Santa Catarina, Departamento de Engenharia Florestal, Lages, Santa Catarina, Brasil – thiago.stepka@udesc.br

⁵ Universidade do Estado de Santa Catarina, Curso de Engenharia Florestal, Lages, Santa Catarina, Brasil – daiani62@hotmail.com

⁶ Universidade do Estado de Santa Catarina, Curso de Engenharia Florestal, Lages, Santa Catarina, Brasil – elderjrshons@gmail.com

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Resumo

Volumetria e forma do fuste de Araucaria angustifolia (Bertol.) Kuntze em fragmentos de Floresta Ombrófila Mista com diferentes níveis de antropização. O objetivo principal deste estudo foi obter informações sobre a forma e volumetria da espécie *Araucaria angustifolia* em fragmentos clímax e secundários, usando abordagens não destrutivas em áreas de Floresta Ombrófila Mista com diferentes graus de intervenção humana. A medição da cubagem rigorosa foi realizada em 30 árvores de cada área, utilizando o Critério RD 1000. Os resultados revelaram um fator de forma de 0,61 e 0,62 para a espécie em florestas clímax e secundárias, respectivamente. Entre os 4 modelos volumétricos ajustados, o modelo de Spurr obteve o melhor ajuste em ambas as áreas, com erros de, em sequência: 18,7% e 22,2%. Para o perfil longitudinal, observou-se que o crescimento foi mais homogêneo em áreas clímax do que nas secundárias. Quanto à função de afilamento de Kozak, essa produziu resultados satisfatórios para a estimativa do diâmetro, mas não para a determinação do volume, sendo necessária uma amostra maior. Esses resultados destacaram as diferenças dendrométricas e morfológicas da espécie em áreas com diferentes níveis de antropização e tempo de recuperação, ressaltando a importância de compreender essas variações em pesquisas florestais.

Palavras-chave: Função de afilamento; fator de forma; Critério RD 1000.

Abstract

The main objective of this study was to obtain information on the trunk shape and volumetry of the *Araucaria angustifolia* species in mature and secondary fragments, using non-destructive approaches in Mixed Ombrophilous Forest areas with different degrees of human intervention. The rigorous cubage was measured on 30 trees in each area using the Criterion RD 1000. The results revealed a form factor of 0.61 and 0.62 for the species in mature and secondary forests, respectively. The Spurr model obtained the best fit in both areas among the 4 fitted volumetric models, with errors of 18.7% and 22.2% in sequence. It was observed that growth for the longitudinal profile was more homogeneous in mature areas than in secondary areas. The Kozak tapering function produced satisfactory results for estimating the diameter, but not for determining the volume, requiring a larger sample. These results highlighted the dendrometric and morphological differences of the species in areas with different anthropization levels and recovery times, highlighting the importance of understanding these variations in forest surveys.

Keywords: Tapering function; form factor; Criterion RD 1000.

INTRODUCTION

The Mixed Ombrophilous Forest (MOF) stands out for its physiognomy marked by *Araucaria angustifolia* (Bertol.) Kuntze, a conifer of great importance in Brazil in both ecological and economic terms (HESS *et al.*, 2014; DOBNER JR., 2022). The MOF is currently a diverse landscape comprising native forest areas, exotic forests, and agriculture and pasture to a lesser extent (SILVA *et al.*, 2023). As a result, evaluating forest fragments affected by human-caused disturbances at different intensities reveals distinctions in the vegetation structure (MELLO; EISFELD; SANQUETTA, 2003; LIEBSCH *et al.*, 2016).

The *A. angustifolia* species, better known as Brazilian Pine, played an important role in the timber cycle of the 20th century (DOBNER JR *et al.*, 2019), being considered vulnerable on the list of threatened species of the Brazilian Institute of Environment and Renewable Natural Resources (*Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis - IBAMA*). Furthermore, the species was more recently classified as “critically endangered” (CR) on the Red List of Threatened Species of the International Union

for Conservation of Nature (IUCN) (MELLO; EISFELD; SANQUETTA, 2003), requiring several studies to understand the ecology and dynamics of this tree.

It is clear that imposing restrictions on use does not represent the most effective approach to conservation, leading to disinterest and devaluation of the species and the environment in which it is found, as indicated by Silva *et al.* (2023). Thus, in line with a trend towards conservation through sustainable use, studies are being conducted to recover, conserve and make responsible use of the benefits provided by forests (MACHADO *et al.*, 2009; DOBNER JR., 2022).

However, as emphasized by Fariars, Nicoletti and Aguiar (2019), in order to enable sustainable management, it is important to start by determining the volume, as this is a fundamental step in assessing the timber stock, which can be obtained through direct or indirect approaches. According to Heberle, Stepka and Nicoletti (2022), the Criterion RD 1000 (a clinometer which has been used to measure the cubature of standing trees), is an important technology that serves as an option for volumetric studies of MOF, and mainly of *A. angustifolia*. Furthermore, Rodriguez *et al.* (2014) considered the equipment applicable for estimating individual volume and for developing tapering equations. In this context, the main objective was to obtain information on the trunk shape and the volumetrics of the *A. angustifolia* species using non-destructive approaches in MOF fragments with different anthropization levels. The following hypotheses were established for this study:

- Fragments with older interventions will have a greater volume than those with more recent interventions;
- The trunk shape will vary between fragments with recent and older interventions;
- The longitudinal profile will be represented in a more rectilinear way due to the characteristic of the species in having an almost cylindrical trunk.

MATERIAL AND METHODS

Study location

The study was conducted in the municipality of Campo Belo do Sul, Santa Catarina, Brazil, located at latitude 27°53'57"S and longitude 50°45'39"W, with an altitude of 1,017 meters. The region has a humid mesothermal climate (Cfb) according to the Köppen climate classification, characterized by mild summers, an average temperature of 14°C and an average annual precipitation of 1562 mm (ALVARES *et al.*, 2013).

The fragments where the measurements were taken were grouped based on their history of interventions. The secondary fragments represented an area that had been subjected to more recent human interventions, dating back to 1960, with a period of approximately 50 years of recovery after timber exploitation. The mature fragments had not been disturbed for a longer period according to information from the owners, since these areas had been chosen for preservation during the “timber cycle” in the 20th century.

Measurement methodology

A total of 30 trees were chosen from each area in order to cover several diameter classes and represent the entire population. Diameter measurements were taken using the Criterion RD 1000 optical equipment at specific heights starting at 0.1 m, and continuing at 0.3 m, 0.5 m, 0.9 m, 1.3 m, 2 m, and then at each meter above these points until the tree trunk was no longer visible. The maximum height reached was 30 m for trees in mature forests and 24 m for those in secondary forests.

It was first necessary to measure the distance to the tree to use the equipment, and it is important to note that this distance and the measurements along the trunk varied according to several factors, such as location, canopy cover, terrain slope, and other elements that affected the visibility of the trees of interest. The guidelines established in a previous study (HEBERLE; STEPKA; NICOLETTI, 2022) were followed in order to maintain accuracy of the measurements, ensuring a minimum of 10 measurements per tree and following all the steps for configuring the equipment for the “Diameter” function. The individual volume was determined using the Smalian method after measurements in both areas and in separate databases according to the forest history.

Data analysis and volumetry

The descriptive analysis of the data involved determining the mean, median, maximum, minimum, standard deviation and coefficient of variation statistics, represented in boxplot graphs. In addition, the forest parameters of basal area (G) and volume (V) were calculated based on the number of trees (N) from the study by Vaz (2022), which was conducted in the same fragments as this study.

The individual trunk shape factor was calculated from the individual volume of the *A. angustifolia* trees, identifying the space that the tree occupies in a cylinder, with the closer to 1, the closer the tree trunk is to the limits of the geometric shape. Thus, the formula for the average artificial shape factor of each fragment was used, taking into account the cylinder volume calculated from measuring the Diameter at Breast Height (DBH).

Next, 4 volume models described in Table 1 were evaluated for establishing a volume equation for *A. angustifolia* trees in mature and secondary forests in the region.

Table 1 – Volume models evaluated for trees of the *A. angustifolia* species in mature and secondary forests located in the municipality of Campo Belo do Sul, Santa Catarina State, Brazil.

Tabela 1 – Modelos de volume avaliados para árvores da espécie *A. angustifolia* em florestas clímax e secundárias situadas no município de Campo Belo do Sul, Santa Catarina, Brasil.

| Author | Model |
|-----------------|---|
| Meyer | $tiv = b0 + b1 * DBH^2$ |
| Spurr | $tiv = b0 + b1 * (DBH^2 * ht)$ |
| Schumacher-hall | $\ln tiv = b0 + b1 * \ln DBH + b2 * \ln th$ |
| Stoate | $tiv = b0 + b1 * DBH^2 + b2 * (DBH^2 * th) + b3 * th$ |

Legend: *tiv*, total individual volume in m³; *DBH*, Diameter at Breast Height in cm; *th*, total tree height in m; and *b0*, *b1*, *b2* and *b3*, model coefficients. Source: Adapted from Finger (2006).

The adjusted coefficient of determination (R^2_{adjust}) was calculated to evaluate the most appropriate regression model, in which higher values indicate greater explanation of the dependent variable by the independent variable. The standard error of the absolute estimate (*Syx*) and in percentage (*Syx%*) were also calculated, representing the error generated by the model; lower values of these errors suggest better model fit for estimating the dependent variable. These errors also include variations in the equipment itself. In addition, the F-value was used as an evaluation criterion, analyzing the relationship between the model and the error, in which higher values reflect higher model quality. Finally, the percentage of residuals was analyzed and illustrated by means of scatter plots, where values closer to 0 indicate smaller residuals generated by the equation.

Longitudinal profile and tapering function

The longitudinal profile was constructed from trunk measurements during cubing with diameters obtained at various heights. Together with the shape factor, this representation helps in analyzing the species' trunks within the fragments, observing whether there is a difference between individuals. To conclude, a regression was performed using the Kozak model in order to obtain a tapering equation for the species, which would enable calculating the volume, diameter at any height and height at any diameter, as described in Equation 1. Equations 2 and 3 were used for diameter and volume estimates. The resulting variables were evaluated in the same way as for the volumetric equations. All calculations and data processing for this study were performed in the R Core Team Software (2021) using tidyverse packages, such as dplyr for data manipulation and ggplot2 for visualization.

$$\left(\frac{di}{DBH}\right)^2 = b0 + b1 * \frac{h}{ht} + b2 * \left(\frac{h}{th}\right)^2 \quad (1)$$

$$di = DBH * \sqrt{b0 + b1 * \frac{h}{th} + b2 * \left(\frac{h}{th}\right)^2} \quad (2)$$

$$v = \frac{\pi}{40000} * DBH^2 * (b0 * (h2 - h1) + \frac{b1 * (h2^2 - h1^2)}{2 * th} + \frac{b2 * (h2^3 - h1^3)}{3 * th}) \quad (3)$$

In which: *di* is the diameter of the section in cm; *DBH* is the Diameter at Breast Height in cm; *h* is the height of the section in m; *th* is the total height of the tree in m; *v* is the volume of the section in m³; π is a mathematical constant; *h2* is the height of the end of the section desired for the calculation, in this case considering the total height of the tree in m; *h1* is the initial height of the section desired for the calculation, in this case considering 0.1 m; and *b0*, *b1* and *b2* are the coefficients of the equation.

RESULTS

Data analysis and volumetry

Regarding the DBHs evaluated in the study, Figure 1 demonstrated that the mature forest presented a wide variation between the minimum and maximum values, with an average of 39.1% for DBH, 23.4% for total height and 79.8% for volume, suggesting that the evaluation covered all diameter classes. On the other hand, the secondary forest exhibited a smaller variation range between the measurements when compared to the mature forest, resulting in 20.3% for DBH, 20.2% for total height and 44.2% for individual volume. It was noted that the variable with the greatest difference between the forests was volume, and this value was expected, since this variable combines the two previous ones. In turn, the variation regarding the shape factor was greater in the secondary forest (20.1%) compared to the mature forest (13.5%), thus obtaining more coniform trees, mainly in the smaller diameters, as demonstrated in Figure 1.

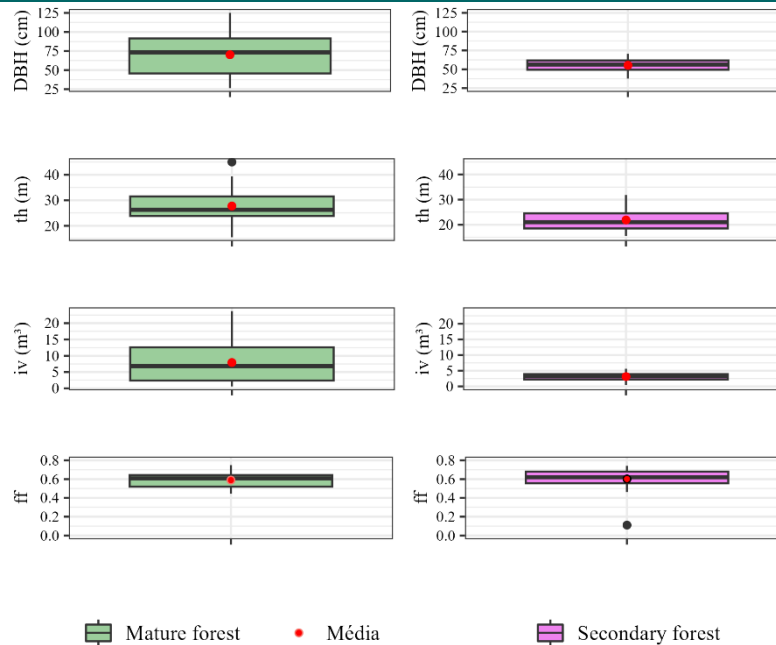


Figure 1 – Boxplot graphs of the DBH, total height and individual volume (m^3) of *A. angustifolia* from mature and secondary Mixed Ombrophilous Forest in Campo Belo do Sul, Santa Catarina State, Brazil. In which: DBH is the Diameter at Breast Height; th is the total height; iv is the individual volume; and ff the form factor.

Figura 1 – Gráficos boxplot do DAP, altura total e volume individual (m^3) das *A. angustifolia* de floresta clímax e secundária da Floresta Ombrófila Mista em Campo Belo do Sul, Santa Catarina, Brasil. Onde: DAP é o Diâmetro à Altura do Peito; ht é a altura total; vi é o volume individual; e ff o fator de forma.

Due to the wide range and variation of the variables, the median was chosen as the central measure given that the mean is greatly affected by extreme values. Thus, the median for DBH was 73.21 cm for the mature forest and 56.02 cm for the secondary forest. In terms of total height, the median in the mature forest was 26.25 m and 20.9 m in the secondary forest. The values in terms of individual volume were 6.8041 m^3 and 3.2521 for the mature and secondary forests, respectively. The values for the shape factor were similar, with 0.61 for the mature forest and 0.62 for the secondary forest. As observed in the data and boxplots, differentiation in the forests mainly occurred in diameter and volume, followed by height, while the shape factor presented minimal differentiation.

Based on data from the study by Vaz *et al.* (2022) conducted in the same area and clusters represented in this study, a total of 90 trees ha^{-1} were obtained for the mature forest and 52 trees ha^{-1} for the secondary forest, constituting a discrepancy that interfered with the other parameters. Therefore, a difference between the areas of 438.4 $m^3 ha^{-1}$ and 24.8 $m^2 ha^{-1}$ was obtained in the analyses of V and G for mature forests (608.7 $m^3 ha^{-1}$ and 37.7 $m^2 ha^{-1}$, respectively) and for secondary forests (170.3 $m^3 ha^{-1}$ and 12.9 $m^2 ha^{-1}$, respectively).

Next, the regression analysis was performed based on the volumetric models, the estimated volume was calculated and the evaluation criteria were determined (Table 3) from the coefficients of the equations (Table 2).

Table 2 – Regression coefficients of the volumetric models fitted for the *A. angustifolia* species in mature and secondary Mixed Ombrophilous Forest fragments in Campo Belo do Sul, Santa Catarina State, Brazil.

Tabela 2 – Coeficientes de regressão dos modelos volumétricos ajustados para a espécie *A. angustifolia* em fragmentos clímax e secundários da Floresta Ombrófila Mista em Campo Belo do Sul, Santa Catarina, Brasil.

| FOREST | MODEL | b0 | b1 | b2 | b3 |
|-----------|-----------------|--------------------------|--------------------------|-------------------------|--------------------------|
| MATURE | Meyer | -0.6040203* | 0.0015089* | - | - |
| | Spurr | -2.053e-01* | 4.890e-05* | - | - |
| | Schumacher-Hall | -10.04962* | 2.16459* | 0.81034* | - |
| | Stoate | 2.529e-01 ^{ns} | -7.073e-05 ^{ns} | 5.155e-05* | -1.798e-02 ^{ns} |
| SECONDARY | Meyer | 0.0201868 ^{ns} | 0.0010152* | - | - |
| | Spurr | 2.438e-01 ^s | 4.328e-05 ^s | - | - |
| | Schumacher-Hall | -8.9899 ^s | 1.8037 ^s | 0.9287 ^s | - |
| | Stoate | -1.099e+00 ^{ns} | 6.123e-04 ^s | 1.663e-05 ^{ns} | 5.769e-02 ^{ns} |

Legend: b0, b1, b2 and b3, coefficients of the equations; *, significant coefficients; ^{ns}, non-significant coefficients.

Table 3 – Evaluation criteria of volumetric models analyzed in mature and secondary Mixed Ombrophilous Forest fragments in Campo Belo do Sul, Santa Catarina State, Brazil.

Tabela 3 – Critérios para avaliação dos modelos volumétricos analisados em fragmentos clímax e secundários da Floresta Ombrófila Mista, em Campo Belo do Sul, Santa Catarina, Brasil.

| FOREST | MODEL | F-VALUE | R ² adjust | Syx (m ³) | Syx% |
|-----------|-----------------|---------|-----------------------|-----------------------|------|
| MATURE | Meyer | 176.00 | 0.8578 | 2.3860 | 30.1 |
| | Spurr | 501.71 | 0.9452 | 1.4807 | 18.7 |
| | Schumacher-Hall | 416.10 | 0.9345 | 1.6189 | 20.4 |
| | Stoate | 425.05 | 0.9411 | 1.5353 | 19.4 |
| SECONDARY | Meyer | 55.00 | 0.6506 | 0.8176 | 26.1 |
| | Spurr | 86.70 | 0.7472 | 0.6955 | 22.2 |
| | Schumacher-Hall | 81.75 | 0.7333 | 0.7142 | 22.8 |
| | Stoate | 73.47 | 0.7384 | 0.7074 | 22.6 |

Legend: F, regression criterion; R²adjust, adjusted coefficient of determination; Syx, standard error of the estimate in m³; and Syx%, standard error of the estimate in percentage.

The Spurr model was classified as the best in both forests for volume estimates with the highest F-value, indicating superior quality of the model, along with the highest R²adjusted, demonstrating a stronger correlation between the independent and dependent variables (MIRANDA; BERNARDINO; GOUVEIA, 2015), and the lowest Syx and Syx% among the others, resulting in a smaller error in the volume estimate.

However, when analyzing the residual graphs (Figure 2), it was observed that the Spurr model was not classified as the most appropriate. A greater grouping of points on the 0 axis in the Schumacher-Hall model was noted in the mature fragment, while the points were closer to the axis in the Stoate model in the secondary fragment.

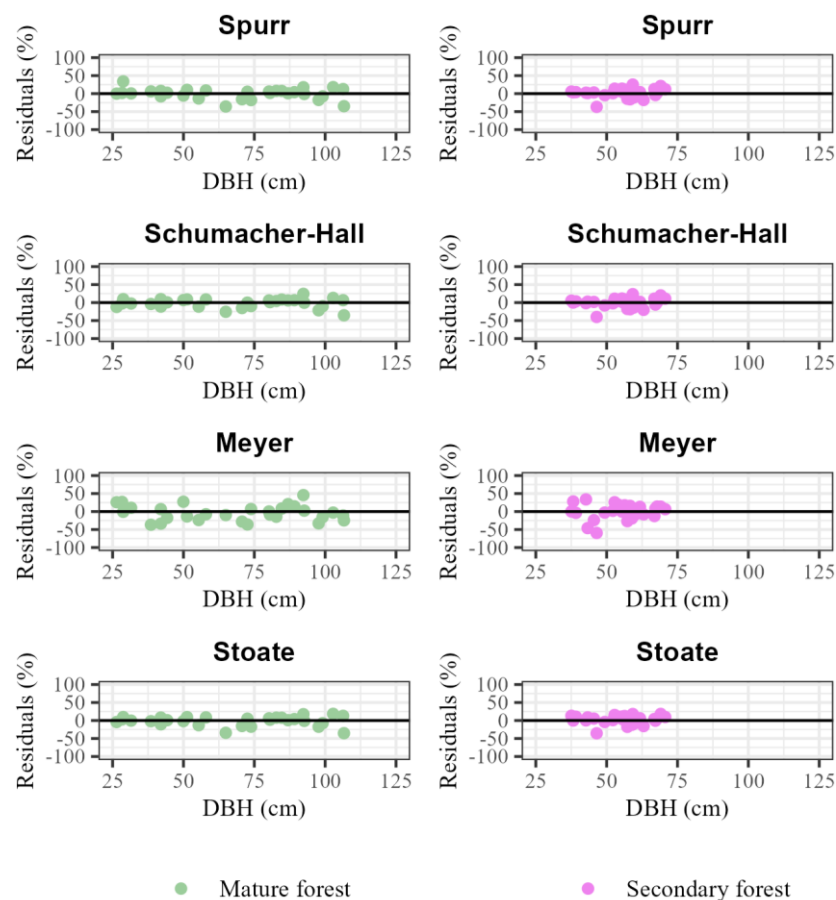


Figure 2 – Residual plots of volumetric models applied to *A. angustifolia* in mature and secondary Mixed Ombrophilous Forest fragments, Campo Belo do Sul, Santa Catarina State, Brazil.

Figura 2 – Gráficos de resíduos dos modelos volumétricos aplicados para *A. angustifolia* em fragmentos clímax e secundários da Floresta Ombrófila Mista, Campo Belo do Sul, Santa Catarina, Brasil.

Longitudinal profile and tapering function

When analyzing Figure 3, it was noted that the growth of *A. angustifolia* in mature forests was more uniform among individuals compared to secondary forests. It was evident in the latter that several points deviated from the majority.

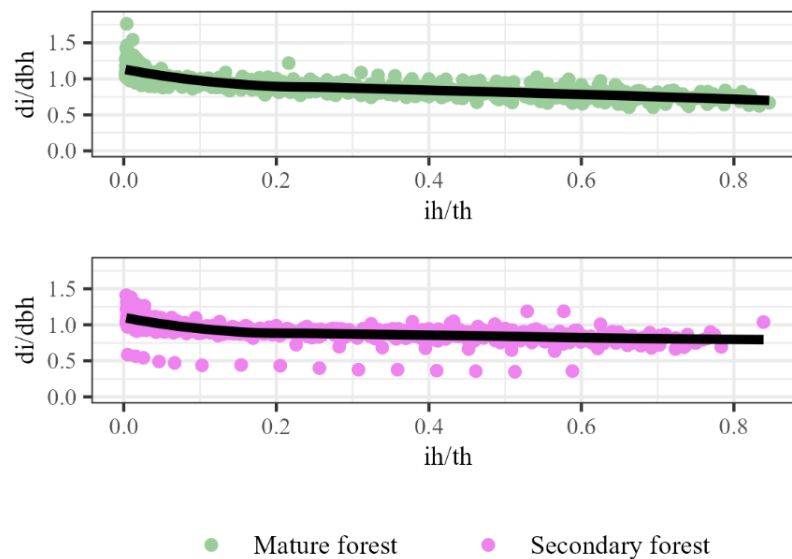


Figure 3 – Longitudinal profile of the *A. angustifolia* species in mature and secondary fragments of Mixed Ombrophilous Forest, in Campo Belo do Sul, Santa Catarina State, Brazil.

Figura 3 – Perfil longitudinal da espécie *A. angustifolia* em fragmentos clímax e secundários da Floresta Ombrófila Mista, em Campo Belo do Sul, Santa Catarina, Brasil.

The coefficients were obtained by regression using the Kozak model, as shown in Table 4. These coefficients can be used to estimate the tree volume, the diameter at any height and the height at any diameter. In this study, we only focused on estimating the diameter and volume, evaluated through the modeling criteria summarized in Table 4 and the residual graphs in Figure 4.

Table 4 – Regression coefficients of the Kozak thinning function for the *A. angustifolia* species in mature and secondary Mixed Ombrophilous Forest fragments in Campo Belo do Sul, Santa Catarina State, Brazil.

Tabela 4 – Coeficientes de regressão da função de afilamento de Kozak para a espécie *A. angustifolia* em fragmentos clímax e secundários da Floresta Ombrófila Mista, em Campo Belo do Sul, Santa Catarina, Brasil.

| FOREST | MODEL | b0 | b1 | b2 | | |
|-----------|----------|----------------------|-----------------------|----------------------|------|--|
| MATURE | Kozak | 1.18921 ^s | -1.78653 ^s | 1.28170 ^s | | |
| SECONDARY | | 1.12835 ^s | -1.59900 ^s | 1.34966 ^s | | |
| | | F-Value | R ² adjust | Syx | Syx% | |
| MATURE | Kozak di | 11337.12 | 0.9410 | 6.5990 | 10.2 | |
| SECONDARY | | 178.65 | 0.6517 | 7.1494 | 15.0 | |
| MATURE | Kozak iv | 9.17 | 0.1981 | 2.3763 | 30.0 | |
| SECONDARY | | 5.61 | 0.1108 | 1.3043 | 41.7 | |

Legend: b0, b1, b2, coefficients of the equation; ^s, significant coefficients; di, diameter, in cm; iv, individual volume, in m³; F, regression criterion; R²adjust, adjusted coefficient of determination; Syx, standard error of the estimate, in m³; and Syx%, standard error of the estimate in percentage.

It was observed that the diameter variable was estimated with greater precision in *A. angustifolia* from mature fragments. In this case, the evaluation criteria had a significantly high F-value, a compatible R²adjustment and a remarkably low error when compared to the others. However, there was a decrease in the quality of the estimates in secondary fragments, mainly due to the significant decrease in the F-value, the R²adjustment, and the 5% increase in error. Both fragments presented unsatisfactory results regarding volume, above the error stipulated at 20% for native forests.

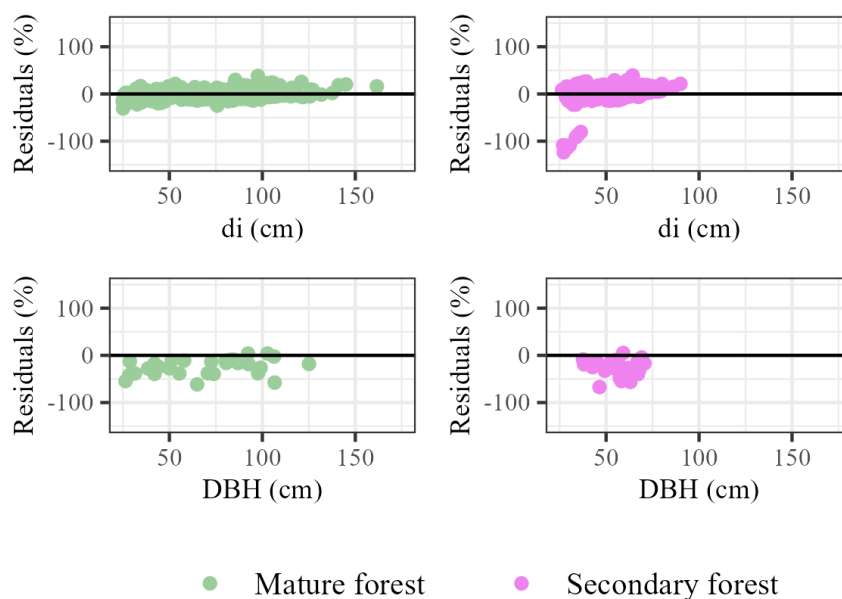


Figure 4 – Residual plots by the Kozak thinning function applied to *A. angustifolia* in mature Mixed Ombrophilous Forest fragments, in Campo Belo do Sul, Santa Catarina State, Brazil.

Figura 4 – Gráficos de resíduos pela função de afilamento de Kozak aplicado para *A. angustifolia* em fragmentos clímax da Floresta Ombrófila Mista, em Campo Belo do Sul, Santa Catarina, Brasil.

DISCUSSION

Data analysis and volumetry

First, it was noted from the analysis of the variables in the boxplot graphs that the results of the dendrometric variables for the secondary forest were considerably lower, which was expected as shown by the results of Vaz *et al.* (2022) due to the fact that there is a shorter recovery time after anthropization. This behavior can be explained because the area does not have a high number of large mature trees, which were possibly extracted during the timber cycle in the 20th century (VAZ *et al.*, 2022). It was also observed from the field analyses that smaller trees tend to be found closer to the edges of the fragments, in places of easier access, possibly representing facilitated regeneration due to greater sunlight incidence (SCIPIONI *et al.*, 2018) and the beginning of recovery in establishing previously removed individuals.

Next, although the median diameters for the mature and secondary forests showed a difference (73.21 cm and 56.02 cm, respectively), individuals of smaller size were found in the mature forest compared to the secondary forest. However, this information may be inaccurate, since it was exclusively based on the sample of this study. In addition, the lower uniformity of the mature forest can be attributed to its more complete structure, encompassing diameters which vary due to different environments, reflecting factors such as competition or growth conditions (FIGUEIREDO FILHO *et al.*, 2017). However, height differed to a lesser extent (26.25 m for mature and 20.9 m for secondary forests), probably because their growth is limited by the site quality. Furthermore, this observation can be explained by the fact that trees first grow in height in search of light, and then later in diameter (ENCINAS *et al.*, 2005).

Despite the median of 0.61 and 0.62 for the form factor for mature and secondary forests, respectively, it was observed that some individuals had a value of 0.44, which is similar to the characteristics of commercial species, such as *Pinus* sp., which, in a study by Nicoletti *et al.* (2021), approached 0.50. However, as larger trees were analyzed, the form factor increased for the vast majority of them, reaching 0.81 and resulting in a variation of 13.5%. This suggests that larger trees with a more uniform trunk closer to a cylinder were found in this case and according to the field assessment as one advanced into the fragment. However, following the thinking of Martins *et al.* (2017), the trunk of *A. angustifolia* becomes more cylindrical until it reaches a certain diameter, and then returns to having a more conical shape.

The volume values per hectare for *A. angustifolia* varied between studies. Vaz *et al.* (2022) observed larger volumes in mature forests than those of this study (608.7 m³ ha⁻¹), and similar values were reported by Longhi *et al.* (2017) in Rio Grande do Sul and Dalla Lana *et al.* (2015) in Paraná. The results of this study for secondary forests (170.3 m³ ha⁻¹) were close to those of Vaz *et al.* (2022) and Mello, Eisfeld and Sanquetta (2003) in southern Paraná. Regarding basal area, Longhi *et al.* (2017) observed a similar average in mature forests in Rio

Grande do Sul to that found in the results of this study ($37.7 \text{ m}^2 \text{ ha}^{-1}$). However, Vaz *et al.* (2022) reported low values for basal area, but which still exceeded the results of this study ($12.9 \text{ m}^2 \text{ ha}^{-1}$), and can be attributed to differences in the samples analyzed.

The Spurr model was considered the best for volume estimation for both forests. The same equation also demonstrated superiority in other studies with *A. angustifolia*, such as those by Sanquetta *et al.* (2016), in which it was the second best model, being slightly below the Spurr log equation with a minimal difference in the results. In analyzing the relative error of volume estimation through volumetric equations and considering the maximum limit of 20% for native forests (SYDOW *et al.*, 2017), only the equation selected for mature fragments met this criterion. The error was exceeded in the secondary forest, indicating the need to volumetrically measure more trees to reach the admitted error, as discussed by Finger (2006). Similar results were also observed by Sanquetta *et al.* (2016), Dobner Jr *et al.* (2019) and Vaz *et al.* (2022), demonstrating that the error in native areas may be higher than expected depending on the model and sampling.

The large difference between the variables, as well as between the forests, resulted in a high sampling error, indicating the different growth conditions (MIRANDA; BERNARDINO; GOUVEIA, 2015) in trees of different ages, with differentiated modeling in diameter classes being a possible option for future studies. In addition, this discrepancy between the forests meant that the secondary *A. angustifolia* forest still has great potential for growth and wood stock, being only at the beginning of its resilience and restoration process (MACHADO *et al.*, 2009). All of these values demonstrate the importance of the species for the ecosystem in which it is inserted (MOF) (LIEBSCH *et al.*, 2016; VAZ *et al.*, 2022), and determine the importance of its conservation and studies to reduce its risk of genetic loss and extinction.

Longitudinal profile and tapering function

Studying the longitudinal profile of a tree can help in several inferences; in this case, it was used to compare the growth of *A. angustifolia* between different areas. However, this approach could be used in studies of tree health, wood anatomy, as well as to determine age, requiring a more in-depth analysis of the species (ENCINAS *et al.*, 2005). When analyzing the longitudinal profile of the trunks in the secondary forest, it was observed that several points moved away from the majority, suggesting that some individuals are being impacted by environmental or ecological factors of the existing population; as explained by Scipioni *et al.* (2018), even the conicity of the trunk itself and interventions from different sources prevented uniform growth, unlike that observed in mature forests. Despite these results, the longitudinal profiles showed a predominantly rectilinear trunk in both forests, with the exception of the tree base. There was little differentiation between the forest profiles, with the mature fragment showing a slight tendency to be more conical compared to the secondary fragment. This aspect was also reflected in the analysis of the shape factor and can be explained by the fact that it has larger trees, following the theory of Martins *et al.* (2017).

The tapering function showed a better fit for the diameter of *A. angustifolia* in mature forests, with a similar relative error to that observed in other studies, such as that of Martins *et al.* (2017). However, both forests showed unsatisfactory results for the volume estimate with errors greater than 20%. Similar results were reported by Costa *et al.* (2016), who also observed an increase in error when comparing the diameter estimate with that of volume. The residual plot analysis in this study revealed that an overestimation of DBH, height, and volume was responsible for much of this error, something already pointed out by Cardoso and Ribaski (2015), who also reported overestimations in tree measurements in plantations. Accumulated errors can be caused by several factors, as discussed by Finger (2006). The equipment error stands out in this study, as observed by Nicoletti *et al.* (2021), and the difficulties of measurement in native forests. Unlike homogeneous plantations where the trunk is easier to see, native forests are more complex due to the presence of several species in different strata (COSTA *et al.*, 2016).

Furthermore, *A. angustifolia* trees were measured up to the height at which the trunk was visible, with an average height of 19.7 m for the mature and 15.1 m for the secondary forest, while the remainder of the trunk (8 m for the mature and 6.5 m for the secondary forest) was estimated using the cone equation; this may have contributed to the increased error in the estimates, since this represented just over 1/3 of the trunk length. Therefore, the higher error can be justified considering the conditions of this study and the sample size.

The equipment proved to be an option for measuring diameters at different heights for the species. However, the results did not meet the expected error for native species in volume estimates using tapering equations, with the exception of determining the diameter, in which the adjustments were satisfactory. Finally, it is necessary to measure a larger number of *A. angustifolia* samples in both fragments, whether they are mature or secondary, in order to obtain more accurate results when applying the tapering equations to determine volume.

CONCLUSION

Based on the results obtained, it is concluded:

- The volumetry of *A. angustifolia* using non-destructive approaches (Criterion RD 1000) revealed differences between MOF fragments with different anthropization levels, being 608.7 m³ ha⁻¹ for mature forests and 170.3 m³ ha⁻¹ for secondary forests. This confirms the hypothesis that fragments with older interventions have greater volume;
- The equipment did not demonstrate the expected precision for equation fit, presenting acceptable errors for native forests only in the volume estimate by the Spurr model, specifically for the mature forest, and in the diameter estimate by the Kozak taper model, in this case in both fragments;
- A predominantly rectilinear profile was observed regarding the trunk shape, in agreement with the initial hypothesis and the characteristics expected for the species. However, minimal differentiation was found between the areas when evaluating the shape factors, with values of 0.61 for the mature fragment and 0.62 for the secondary, being differing from what was expected in this aspect.

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