







MODELING TREE HEIGHT AND MERCHANTABLE VOLUME OF NATIVE TREE SPECIES IN A MIXED OMBROPHILOUS FOREST

Larissa Mignosso Arruda¹ , Helena Grossl Almeida² , Thaiane Káren Martins^{3*} , Natalia Sasso Pinheiro⁴ 
Ivo Henrique Ribeiro de Souza⁵ , Thiago Floriani Stepka⁶ 

Universidade do Estado de Santa Catarina, Centro de Ciências Agroveterinárias, Programa de Pós-Graduação em Engenharia Florestal, Lages, Santa Catarina, Brasil – larissa2008@hotmail.com¹; helena_grossl@hotmail.com²; thaiane.karen@acad.ufsm.br^{3*}; natisassopinheiro@gmail.com⁴; ivosouzar@gmail.com⁵; thiago.stepka@udesc.br⁶

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Resumo

Modelagem da altura e volume comercial de espécies arbóreas nativas em Floresta Ombrófila Mista. O volume é considerado uma variável fundamental na avaliação do potencial de recursos madeireiros dos fragmentos florestais. Nesse sentido, o objetivo do presente estudo foi ajustar modelos hipsométricos e volumétricos para *Araucaria angustifolia* (Bertol.) Kuntze e espécies folhosas em áreas de Floresta Ombrófila Mista (FOM). Para isso, foram amostradas 15 parcelas retangulares de 500 m² em duas áreas da Fazenda Experimental do Centro de Ciências Agroveterinárias (FECAV) da Universidade do Estado de Santa Catarina (UDESC). Nessas parcelas, selecionaram-se, para cubagem indireta, as dez espécies com maior valor de importância (VI%). Foram cubados 30 indivíduos de *A. angustifolia* e 32 de espécies folhosas, com medições ao longo do fuste realizadas com auxílio do dendrômetro óptico Criterion® RD 1000. Os resultados demonstraram que as espécies de maior VI% refletem o padrão florístico característico da FOM, com destaque para *A. angustifolia*, *Lithraea brasiliensis* Marchand e *Myrcia splendens* (Sw.) DC. Entre os modelos testados, o exponencial apresentou o melhor desempenho ($R^2_{ajust.}$ 0,2678; Syx% 15,26 para Araucária e $R^2_{ajust.}$ 0,0817; Syx% 22,61 para Folhosas) para a estimativa da altura comercial, enquanto o modelo de Schumacher-Hall linearizado se mostrou mais adequado para a estimativa do volume comercial de ambos os grupos ($R^2_{ajust.}$ 0,9025; Syx% 14,14 para Araucária e $R^2_{ajust.}$ 0,8771; Syx% 21,14 para Folhosas). Assim, diante da dificuldade para obter-se dados volumétricos diretos em florestas naturais, a adoção de métodos indiretos, como o Criterion® RD 1000, mostrou-se eficiente quando comparada a ajustes realizados com dados de cubagem rigorosa, confirmando sua aplicabilidade em estudos de volumetria.

Palavras-chave: Equações Alométricas; Floresta de Araucária; Criterion RD 1000.

Abstract

Volume is a key variable for assessing the timber resource potential of forest fragments. In this context, this study aimed to fit hypsometric and volumetric models for *Araucaria angustifolia* (Bertol.) Kuntze and associated broadleaf species in areas of Mixed Ombrophilous Forest (MOF). We established fifteen rectangular plots of 500 m² across two areas at the Experimental Farm of the Center for Agroveterinary Sciences (FECAV), State University of Santa Catarina. Within these plots, we selected the ten species with the highest Importance Value (%) (IV%) for indirect scaling. We scaled 30 *A. angustifolia* trees and 32 broadleaf trees, measuring stem diameters using the Criterion® RD 1000 optical dendrometer. The results showed that the species with the highest IV% reflect the typical floristic pattern of MOF, with emphasis on *A. angustifolia*, *Lithraea brasiliensis* Marchand, and *Myrcia splendens* (Sw.) DC. Among the tested models, the exponential model provided the best performance for estimating merchantable height (R^2_{adj} = 0.27; Syx% = 15.3 for *Araucaria* and R^2_{adj} = 0.08; Syx% = 22.6 for broadleaf species), while the linearized Schumacher-Hall model was the most suitable for estimating merchantable volume for both groups (R^2_{adj} = 0.90; Syx% = 14.1 for *Araucaria* and R^2_{adj} = 0.88; Syx% = 21.1 for broadleaf species). Given the difficulty of obtaining direct volumetric data in native forests, the use of indirect methods, such as the Criterion® RD 1000, proved efficient and reliable, supporting their application in forest volumetric studies.

Keywords: Allometric Equations; Araucaria Forest; Criterion RD 1000.

INTRODUCTION

Originally, the Atlantic Forest biome and its associated ecosystems covered approximately 1.1 million km²; however, they are currently fragmented into only 296 thousand km² (MMA, 2024). Among these associated ecosystems is the Mixed Ombrophilous Forest (MOF), popularly known as the Araucaria Forest due to the presence of *Araucaria angustifolia* (Bertol.) Kuntze. This species is currently classified as critically endangered due to degradation and population decline driven by a reduction in the size and number of MOF remnants (FOREST *et al.*, 2018; RICKEN *et al.*, 2020).

Araucaria angustifolia was the most commercially important tree species in the country during the last century, generating income through the sale of its timber, which is highly valued due to the characteristics of its individuals, including straight and nearly cylindrical stems that can reach up to 250 cm in diameter at breast height when mature (TOPANOTTI *et al.*, 2019). In addition, *A. angustifolia* is highly valued for its non-timber forest

product, the pine nut (*pinhão*), which is considered a socioeconomic resource that directly contributes to income generation for many families (ATANAZIO *et al.*, 2022).

In addition to its socioeconomic and cultural relevance, the species plays a major ecological role by influencing ecosystem dynamics and local sociobiodiversity where it occurs (TAGLIARI *et al.*, 2021). Therefore, studies that support the implementation of sustainable forest management are necessary to prevent losses in diversity, sustainability, productivity, and regeneration of species occurring in the MOF (HESS *et al.*, 2024).

In this context, forest measurement plays a crucial role in forest management by providing qualitative and quantitative data to improve decision-making processes. Among these variables, volume is particularly important for assessing the timber resource potential of a forest area (NICOLETTI *et al.*, 2015a). To determine tree volume, several methods are employed, with rigorous scaling being the most widely used (NICOLETTI *et al.*, 2015a). This method relies on the relationship between diameter and height and uses mathematical formulas to estimate wood volume.

Traditionally, fitting volume equations requires destructive methods that involve felling trees to measure diameter and height and obtain the total and/or merchantable volume (BONAZZA *et al.*, 2015). However, in situations where tree felling is not feasible, such as in native forests or conservation areas, technological advances have enabled the development of optical devices, such as the Criterion® dendrometer, which can measure diameters along the stem indirectly with acceptable accuracy for forest inventories (NICOLETTI *et al.*, 2015a; NICOLETTI *et al.*, 2015b).

Because destructive methods involve higher costs and longer data acquisition times, forest measurement within inventories increasingly relies on electronic equipment to optimize time and resources. Optical dendrometers, in particular, provide a viable alternative for obtaining robust data without felling trees to estimate their volume (NICOLETTI *et al.*, 2015a; NICOLETTI *et al.*, 2015b). In addition, regression equations support the indirect estimation of forest parameters, increasing inventory efficiency while maintaining high predictive capacity of the mathematical models (SCHNEIDER, 1998).

In the state of Santa Catarina, few volumetric studies have been conducted on native species, with the study by Vibrans *et al.* (2013) standing out (CORREIA; FANTINI; PIAZZA, 2017). According to Biazatti *et al.* (2020), non-destructive techniques for volume estimation have gained relevance because they allow the acquisition of reliable quantitative data without the need for tree felling, which is particularly important in natural ecosystems, especially in remnant MOF areas where legal restrictions on tree removal apply.

Therefore, this study aimed to fit mathematical models for tree height and merchantable volume of *A. angustifolia* individuals and associated broadleaf species using data obtained through non-destructive methods.

MATERIALS AND METHODS

Study area

We conducted the study in the Lages, in the locality of Macacos, Santa Catarina, Brazil, at the Experimental Farm of the Center for Agroveterinary Sciences (FECAV) of the State University of Santa Catarina (UDESC). We collected data in two areas within this farm. Area “I” lies at an average altitude of 900 m (-27.753565° , -50.082603°) and comprises 8.28 hectares (ha) of native vegetation, where we established 10 rectangular sample units of 500 m² (10 × 50 m). Area “II” covers 6.03 hectares (-27.769903° , -50.073703°), with an approximate altitude of 1,030 m, where we established 5 rectangular sample units of 500 m² (10 × 50 m). According to the Köppen classification, the regional climate is Cfb (humid mesothermal), with mild summers, a mean annual temperature of 14°C, and an average annual precipitation of 1,562 mm (ALVARES *et al.*, 2013).

Scaling, Height Modeling, and Volume Determination

To select the trees for scaling, we first conducted a forest inventory in both study areas, recording diameter at breast height (DBH, d, at 1.3 m above ground) and botanically identifying all species. After completing the field measurements, we processed the data to calculate phytosociological descriptors, including the Importance Value, expressed as a percentage (IV, %). For scaling, we selected the ten species with the highest IV% in each area and grouped them into two categories: Araucaria and broadleaf species. In addition, we calculated estimators for the grouped variables basal area (G, m²) and volume (V, m³) per hectare.

In addition, we proportionally distributed the scaled trees across the established diameter classes, totaling 30 Araucaria trees and 32 trees from the broadleaf group, as shown in Table 1.

Table 1. Number of trees selected per diameter class for the Araucaria and broadleaf groups.
Tabela 1. Número de indivíduos selecionados por classe diamétrica para os grupos Araucária e Folhosas.

Group	DBH Class	LI (cm)	UL (cm)	Nº of trees
Araucaria	1	10.0	18.9	5
	2	19.0	27.9	6
	3	28.0	36.9	5
	4	37.0	45.8	7
	5	45.9	54.8	5
	6	54.9	63.8	2
Total				30
Broadleaf	1	10.0	15.6	12
	2	15.7	21.3	8
	3	21.4	27.1	8
	4	27.2	32.8	2
	5	32.8	38.5	2
Total				32

Where: DBH = diameter at 1.3 m above ground (cm); LI = lower limit of the diameter class (cm); and UL = upper limit of the diameter class (cm).

We measured tree diameters along the stem using the Criterion® RD 1000 optical device, starting at 0.10 m above ground and then at 0.7 m, 1.3 m, and subsequently at 1 m intervals, according to the recommendations of HEBERLE *et al.* (2022). During the same procedure, we measured the total height (h, in meters) and the merchantable height (hc, in meters) of the trees selected for scaling.

To calculate the individual merchantable volume (vc, in m³) of the trees, we applied the Smalian scaling method, considering each diameter measurement point along the stem as the boundary of the sections. In addition, using the ratio between rigorous volume and cylinder volume (based on the diameter measured at 1.30 m), we calculated the mean artificial form factor for both study groups (Araucaria and broadleaf species).

Furthermore, to establish equations representing the merchantable height (hc, m) and merchantable volume (vc, m³) for the scaled trees, we fitted five models for each variable, as described in Table 2. To select the best-fitting equation, we evaluated the hypsometric and volumetric models based on the adjusted coefficient of determination (R²adj), the relative standard error of the estimate (Syx%) - recalculated when the dependent variable was transformed - and the graphical analysis of residuals. Next, we subjected the residuals to the Shapiro-Wilk test ($\alpha \leq 0.05$) to meet the assumptions of the regression analysis (SCHNEIDER, 1998), and we assessed the statistical significance of all model coefficients using the t-test ($\alpha \leq 0.05$).

Table 2. Hypsometric and volumetric models fitted for hc (m) and vc (m³) data for Araucaria and broadleaf species.
Tabela 2. Modelos hipsométricos e volumétricos ajustados para dados de hc (m) e vc (m³) para Araucária e Folhosas.

Hypsometric models	
Number of models	Model
1	$hc = \beta_0 + \beta_1 * d$
2	$hc = \beta_0 + \beta_1 * d + \beta_2 * d^2$
3	$hc = \beta_0 + \beta_1 * d + \beta_2 * d^2 + \beta_3 * d^3$
4	$hc = \beta_0 + \beta_1 * (1/d^2)$
5	$hc = \exp(\beta_0 + \beta_1 * 1/d)$
Volumetric models	
Author – Nº of models	Model
Meyer – 1	$vc = \beta_0 + \beta_1 * d + \beta_2 * d^2 + \beta_3 * (d * hc) + \beta_4 * (d^2 * hc) + \beta_5 * hc$
Schumacher-Hall – 2	$\ln(vc) = \beta_0 + \beta_1 * \ln(d) + \beta_2 * \ln(hc)$
Spurr – 3	$vc = \beta_0 + \beta_1 * (d^2 * hc)$
Modified Meyer – 4	$vc = \beta_0 + \beta_1 * d + \beta_2 * d^2 + \beta_3 * (d * hc^2) + \beta_4 * (d^2 * hc)$
Modified Naslund – 5	$vc = \beta_0 + \beta_1 * d^2 + \beta_2 * (d^2 * hc) + \beta_3 * (d * hc^2) + \beta_4 * hc^2$

Where: hc = merchantable height (m); d = diameter at 1.3 m above ground (cm); exp = exponential function; vc = merchantable volume (m³); β_n = model coefficients; and ln = natural logarithm.

Finally, we assessed the multicollinearity using the Variance Inflation Factor (VIF), where VIF values > 10 indicate problematic multicollinearity among variables, suggesting that their correlation affects the model coefficients (Cruz *et al.*, 2019). For model selection, we prioritized those with all or the highest number of statistically significant coefficients with normally distributed residuals and VIF < 10.

RESULTS

Phytosociological descriptors and dendrometric characterization

Table 3 presents the phytosociological descriptors of the ten species with the highest IV% for Areas I and II, as well as the number of trees (N) of each species, the absolute and relative density (AD and RD), the absolute and relative dominance (DoA and DoR), and the absolute and relative frequency (AF and RF).

Considering the ten species with the highest IV%, *A. angustifolia*, *L. brasiliensis*, and *O. pulchella* were the most abundant species in Area I, while *A. angustifolia*, *M. splendens*, and *C. decandra* were the most abundant in Area II. The total basal area reached 42.1 m²·ha⁻¹ in Area I and 35.4 m²·ha⁻¹ in Area II.

Table 3. Phytosociological descriptors of the ten species with the highest importance value (IV%).

Tabela 3. Descritores fitossociológicos das dez espécies com maior valor de importância (VI%).

Area I								
Especies	N	AD	RD	DoA	DoR	AF	RF	IV%
<i>Araucaria angustifolia</i> (Bertol.) Kuntze	47	94	9.77	10.7	26.17	90	5.56	13.83
<i>Lithraea brasiliensis</i> Marchand	42	84	8.73	3.51	8.58	90	5.56	7.62
<i>Ocotea pulchella</i> (Nees) Mez	42	84	8.73	3.33	8.16	80	4.94	7.28
<i>Cinnamomum amoenum</i> (Nees) Kosterm.	28	56	5.82	4.04	9.87	80	4.94	6.88
<i>Myrcia palustris</i> DC.	49	98	10.19	1.65	4.05	70	4.32	6.18
<i>Myrceugenia oxypala</i> (Burret) D.Legrand & Kausel	38	76	7.90	2.19	5.37	40	2.47	5.25
<i>Ocotea puberula</i> (Rich.) Nees	16	32	3.33	2.58	6.32	70	4.32	4.66
<i>Matayba elaeagnoides</i> Radlk.	23	46	4.78	1.35	3.29	70	4.32	4.13
<i>Myrceugenia euosma</i> (O.Berg) D. Legrand	21	42	4.37	0.93	2.29	50	3.09	3.25
<i>Ilex paraguariensis</i> A. St.-Hil.	16	32	3.33	1.09	2.66	60	3.70	3.23
Area II								
Especies	N	AD	RD	DoA	DoR	AF	RF	IV%
<i>Araucaria angustifolia</i> (Bertol.) Kuntze	31	124	11.74	11.28	31.85	100	6.41	16.67
<i>Myrcia splendens</i> (Sw.) DC.	56	224	21.21	4.22	11.92	80	5.13	12.75
<i>Casearia decandra</i> Jacq.	19	76	7.20	1.41	3.97	80	5.13	5.43
<i>Xylosma ciliatifolium</i> (Clos) Eichler	12	48	4.55	2.69	7.59	60	3.85	5.33
<i>Matayba elaeagnoides</i> Radlk.	14	56	5.30	0.82	2.33	80	5.13	4.25
<i>Ocotea puberula</i> (Rich.) Nees	9	36	3.41	1.38	3.89	80	5.13	4.14
<i>Lithraea brasiliensis</i> Marchand	12	48	4.55	1.27	3.59	60	3.85	3.99
<i>Myrceugenia euosma</i> (O.Berg) D. Legrand	13	52	4.92	0.75	2.10	60	3.85	3.62
<i>Piptocarpha angustifolia</i> Dusén ex Malme	4	16	1.52	1.50	4.23	60	3.85	3.20
<i>Machaerium paraguariense</i> Hassl.	6	24	2.27	2.01	5.67	20	1.28	3.07

Where: N = number of sampled trees per species; AD = absolute density (trees ha⁻¹); RD = relative density (%); DoA = absolute dominance (m²·ha⁻¹); DoR = relative dominance (%); AF = absolute frequency; RF = relative frequency (%); and IV = importance value (%).

Dendrometric information for the fragments, including both individual and grouped variables, is presented in Table 4.

Table 4. Individual and grouped dendrometric characterization of the study areas.

Tabela 4. Caracterização dendrométrica individual e agrupada das áreas em estudo.

Dendrometric Characterization									
Area I									
Group	Variable	Minimum	Maximum	Mean	SD	CV	N	G	Vc
Araucaria	h (m)	9.4	22.0	15.9	13.51	22.11	104	10.7	95.2
	d (cm)	14.1	58.8	35.9	13.80	38.43			
	hc (m)	7.3	13.3	10.9	1.75	16.08			
	vc (m ³)	0.1088	2.0255	0.9379	0.65	69.32			
Broadleaf	h (m)	4.7	17.2	11.11	3.41	29.15	868	31.4	199.4
	d (cm)	10	36.7	20.8	8.11	39.36			
	hc (m)	4.3	12.3	7.66	1.66	21.96			
	vc (m ³)	0.0171	0.7350	0.2287	0.21	86.23			
Total							972	42.1	294.6

Dendometric Characterization									
Area II									
Group	Variable	Minimum	Maximum	Mean	SD	CV	N	G	Vc
Araucaria	h (m)	8.1	18.4	13.4	3.25	24.25	124	11.3	90.6
	d (cm)	10.0	46.7	25.4	15.02	59.07			
	hc (m)	7.3	14.3	11.4	2.42	21.22			
	vc (m ³)	0.0371	1.1922	0.4985	0.47	94.70			
Broadleaf	h (m)	8.1	17.2	12.27	2.89	23.51	932	24.1	153.1
	d (cm)	10	29.9	17.85	6.36	35.64			
	hc (m)	6.3	13.3	8.25	1.95	23.75			
	vc (m ³)	0.0323	0.5758	0.1751	0.14	81.14			
Total							1,056	35.4	243.7

Where: h = total height (m); d = diameter at 1.3 m above ground (cm); hc = merchantable height (m); vc = merchantable volume (m³); SD = standard deviation; CV = coefficient of variation (%); N = number of trees per hectare (trees ha⁻¹); G = basal area (m²·ha⁻¹); and Vc = merchantable volume (m³·ha⁻¹).

The values of N (trees ha⁻¹), G (m²·ha⁻¹), and Vc (m³·ha⁻¹) for the broadleaf group correspond to the total sum of trees in each area, not only those of the species with the highest IV (%). The mean form factor values, considering both areas, were 0.71 for the Araucaria and 0.77 for the broadleaf group.

Hypsometric and volumetric model fitting

Based on the tested hypsometric and volumetric models, we obtained the estimated coefficients (Table 5) and the results of the variable multicollinearity (Table 6). We selected the best model by considering the combination of higher adjusted R², lower Syx%, statistical significance of coefficients, VIF < 10, and graphical analysis of residuals as supporting criteria.

Table 5. Regression coefficients of the fitted hypsometric and volumetric models for Araucaria and broadleaf species, and model selection criteria.

Tabela 5. Coeficientes de regressão dos modelos hipsométricos e volumétricos ajustados para Araucária e Folhosas e critérios de seleção.

Hypsometric and Volumetric Models and Model Selection Criteria										
Hypsometric										
Group	Models	β_0	β_1	β_2	β_3			R ² adj	Syx%	P-Valor
Araucaria	1	8.9132*	0.0647*	-	-			0.2132	15.65	0.8380*
	2	6.9279*	0.2112 ^{ns}	-0.0022 ^{ns}	-			0.2349	15.43	0.5336*
	3	8.0830*	0.0716 ^{ns}	0.0025 ^{ns}	-0.00005 ^{ns}			0.2097	15.68	0.5610*
	4	11.7895*	-357.1178*	-	-			0.2156	15.62	0.3827*
	5	2.5565*	-4.3298*	-	-			0.2678	15.26	0.4585*
Broadleaf	1	6.6609*	0.0703 ^{ns}	-	-			0.0406	22.77	0.4344*
	2	4.9281 ^{ns}	0.2578 ^{ns}	-0.0045 ^{ns}	-			0.0257	22.95	0.1252*
	3	8.1723 ^{ns}	-0.2616 ^{ns}	0.0207 ^{ns}	-0.0004 ^{ns}			0.0000	23.26	0.1618*
	4	8.7559*	-185.4030 ^{ns}	-	-			0.0555	22.59	0.1531*
	5	2.2238*	-2.8130^{ns}	-	-			0.0817	22.61	0.2375*
Volumetric										
Group	Models	β_0	β_1	β_2	β_3	β_4	β_5	R ² adj	Syx%	P-Valor
Araucaria	1	-0.1759 ^{ns}	0.0139 ^{ns}	0.00003 ^{ns}	-0.0006 ^{ns}	0.00004 ^{ns}	0.0099 ^{ns}	0.9704	13.41	0.9752*
	2	-9.0854*	1.9799*	0.7322*	-	-	-	0.9025	14.14	0.7345*
	3	0.0539 ^{ns}	0.00005*	-	-	-	-	0.9693	13.65	0.0000 ^{ns}
	4	-0.0841 ^{ns}	0.0089 ^{ns}	0.00008 ^{ns}	-0.000005 ^{ns}	0.00003 ^{ns}	-	0.9716	13.14	0.9866*
	5	0.0098 ^{ns}	0.0004 ^{ns}	0.00001 ^{ns}	0.00006 ^{ns}	-0.0006 ^{ns}	-	0.9712	13.24	0.6898*
Broadleaf	1	-0.7216*	0.0663*	-0.0013 ^{ns}	-0.0109*	0.0003*	0.1160*	0.9498	18.34	0.2342*
	2	-9.6027*	1.9997*	0.9356*	-	-	-	0.8771	21.14	0.4327*
	3	0.0034 ^{ns}	0.00006*	-	-	-	-	0.9279	21.98	0.8992*
	4	0.0718 ^{ns}	-0.0030 ^{ns}	-0.0001 ^{ns}	-0.0001*	0.0001*	-	0.9558	17.21	0.0995*
	5	-0.0356 ^{ns}	-0.0003*	0.0002*	-0.0003*	0.0035*	-	0.9801	11.56	0.1199*

Where: β_n = equation coefficients; * = coefficients significant according to the t-test ($\alpha = 0.05$); ns = non-significant coefficients ($\alpha = 0.05$); R²adj = adjusted coefficient of determination; Syx% = percentage standard error of the estimate; and p-value = significance of the Shapiro-Wilk test for residual normality at 0.05.

Table 6. Variance Inflation Factor (VIF) results for the independent variables of the fitted models.
Tabela 6. Resultado do Fator de Inflação da Variância para as variáveis independentes dos modelos ajustados.

Variance Inflation Factor (VIF) – Hypsometric Model Fitting										
Group	Model	d	d ²	d ³	1/d ²	1/d				
Araucaria	1	1.0	-	-	-	-				
	2	27.1	27.1	-	-	-				
	3	232.2	1,604.3	533.0	-	-				
	4	-	-	-	1.0	-				
	5	-	-	-	-	1.0				
Broadleaf	1	1.0	-	-	-	-				
	2	30.9	30.9	-	-	-				
	3	575.8	2,359.6	658.4	-	-				
	4	-	-	-	1.0	-				
	5	-	-	-	-	1.0				
Variance Inflation Factor (VIF) – Volumetric Model Fitting										
Group	Model	d	d ²	d*hc	d ² *hc	hc	ln (d)	ln (hc)	d*hc ²	hc ²
Araucaria	1	1,136.1	1,329.3	1,821.4	1,735.1	34.0	-	-	-	-
	2	-	-	-	-	-	1.4	1.4	-	-
	3	-	-	-	1.0	-	-	-	-	-
	4	77.2	410.1	-	406.8	-	-	-	66.1	-
	5	-	89.3	-	220.9	-	-	-	76.9	8.5
Broadleaf	1	1,093.3	1,013.6	2,396.6	1,530.0	173.4	-	-	-	-
	2	-	-	-	-	-	1.0	1.0	-	-
	3	-	-	-	1.0	-	-	-	-	-
	4	40.4	81.2	-	74.9	-	-	-	24.4	-
	5	-	29.4	-	110.2	-	-	-	98.5	22.9

Where: d = diameter at 1.3 m above ground (cm); hc = merchantable height (m); and ln = natural logarithm.

In the hypsometric modeling, Model 5 showed the best performance for *A. angustifolia*, with $R^2_{adj} = 0.27$, $Syx\% = 15.3\%$, all coefficients statistically significant, and $VIF = 1.0$, with a Meyer correction factor of 1.0127. For the broadleaf group, Model 5 was also the most suitable, with $R^2_{adj} = 0.08$, $Syx\% = 22.6\%$, and $VIF = 1.0$, with a Meyer correction factor of 1.0235. Regarding multicollinearity, Models 1 and 4 are also considered adequate, as, together with Model 5, they are single-entry models and, therefore, do not exhibit multicollinearity among the variables.

In the volumetric modeling, Model 2, the linearized Schumacher–Hall model, showed the best performance for Araucaria, with $R^2_{adj} = 0.90$, $Syx\% = 14.1\%$, all coefficients statistically significant, $VIF = 1.4$ for both independent variables, and a Meyer correction factor of 1.0078. The same result was observed for the broadleaf group, with $R^2_{adj} = 0.88$, $Syx\% = 21.1\%$, all coefficients statistically significant, $VIF = 1.0$ for the independent variables, and a Meyer correction factor of 1.0081. These results demonstrate that even models fitted using simple linear methods meet regression assumptions and are suitable for application.

Residual plots for the best-fitting hypsometric and volumetric models for *A. angustifolia* and the broadleaf group are presented in Figure 1.

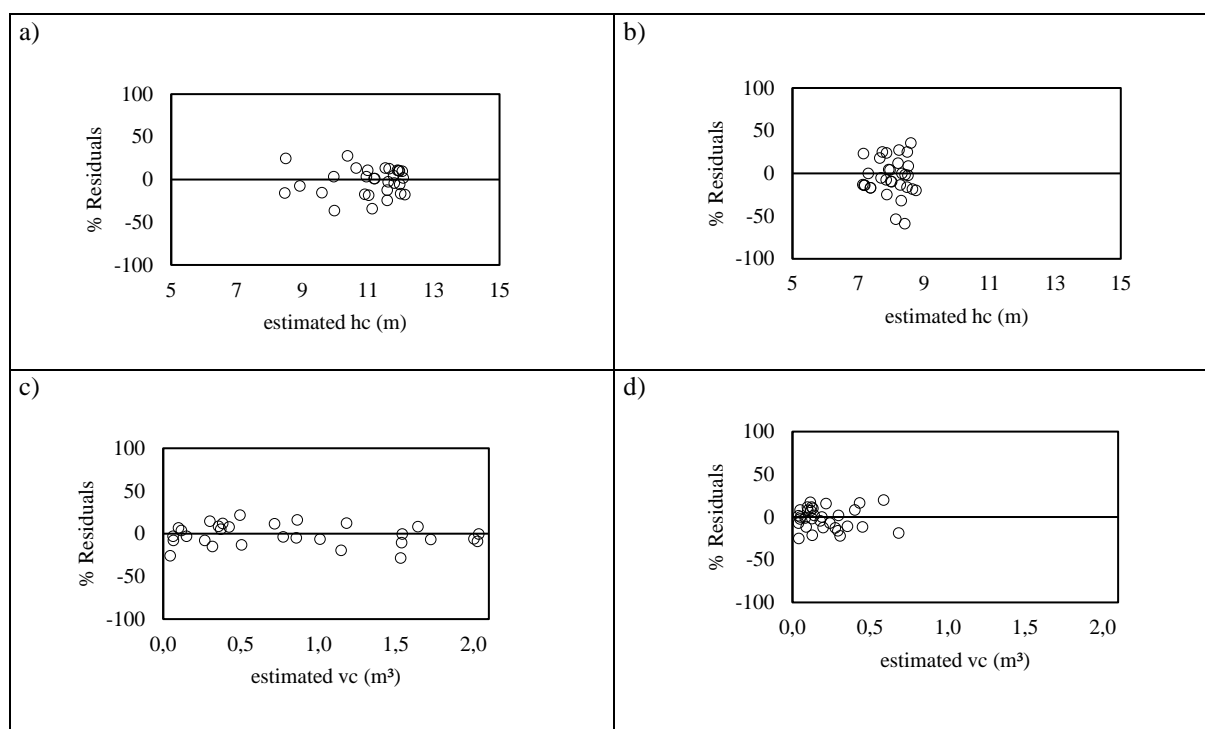


Figure 1. Residual scatter plots of the best-fitting hypsometric and volumetric models for *Araucaria* and the broadleaf group.

Figura 1. Gráficos de dispersão dos resíduos dos melhores modelos hipsométricos e volumétricos para *Araucária* e Folhosas.

Where: (a) best-fitting hypsometric model for *Araucaria* (Model 5); (b) best-fitting hypsometric model for the broadleaf group (Model 5); (c) best-fitting volumetric model for *Araucaria* (Model 2 – linearized Schumacher–Hall); and (d) best-fitting volumetric model for the broadleaf group (Model 2 – linearized Schumacher–Hall).

DISCUSSION

The high abundance of *A. angustifolia*, *L. brasiliensis*, *O. pulchella*, *M. splendens*, and *C. decandra* reflects the floristic pattern characteristic of southern Brazil, particularly in the mountainous region of Santa Catarina. In a study conducted in the Campos Novos region, Santa Catarina, Higuchi *et al.* (2016) also identified these species among the main components of the Mixed Ombrophilous Forest, with *A. angustifolia* presenting the highest importance value (IV = 14.44%), similar to the values found in this study (Area I: 13.83% and Area II: 16.67%).

Pscheidt *et al.* (2015) also reported results similar to those of this study when evaluating floristic–structural variations in a forest fragment in the Southern Plateau of Santa Catarina, identifying *A. angustifolia* as the species with the highest IV%. They also identified *L. brasiliensis* as one of the most relevant species in the community. In addition, Oliva *et al.* (2018), studying a Mixed Ombrophilous Forest in Paraná, observed that *M. splendens* (IV% = 8.8%) was among the species with the highest IV%, highlighting its role as a recurrent element in both regenerating forests and more structured fragments. These results demonstrate that the occurrence of these species is consistent across MOF fragments, reinforcing their importance as structural components and indicators of regional vegetation (HIGUCHI *et al.*, 2016).

Sanquetta *et al.* (2016), studying a commercial stand of *A. angustifolia* at 16 years of age in the state of Paraná, reported a mean form factor of 0.59, ranging from 0.49 to 0.97. Correia, Fantini, and Piazza (2017), when evaluating broadleaf species in Dense Ombrophilous Forest (DOF) in Santa Catarina, obtained a mean form factor of 0.80. The results obtained in this study, when compared with those reported in the literature, show variability in form factors, as expected for native species across different regions.

According to Costa *et al.* (2022) and Heberle *et al.* (2022), dominant species tend to exhibit greater predictability in the diameter–height relationship. We observed this behavior in the present study, where Model 5 showed the best performance for the *Araucaria* group, considering the selection criteria and the statistical significance of the coefficients of the t-test ($\alpha = 0.05$). For the broadleaf group, Model 5 also provided the best fit; however, it showed lower performance, which we attribute to morphological variability, different successional stages, and distinct growth strategies among species. Sanquetta *et al.* (2013) reported similar behavior for broadleaf

species in the Mixed Ombrophilous Forest. These characteristics may negatively affect the quality of model fits for the broadleaf group, particularly regarding the standard error of the estimate.

The lower precision observed in this study is consistent with the findings of Vibrans *et al.* (2013), who reported that the diameter–height (d–h) relationship in native forests can be influenced by environmental factors, light competition, crown architecture, age, and distinct growth rates, leading to high data dispersion. Even in species-specific modeling, these variables may exhibit weak relationships. Strategies such as stratification by functional groups or the inclusion of additional variables - such as crown base height, dominant height, or environmental factors - have proven effective in improving the accuracy of estimates in heterogeneous forests (COSTA *et al.*, 2022).

For volumetric modeling, the model selected in this study as the best fit for both groups (Araucaria and broadleaf species) was the linearized Schumacher–Hall model, even though it did not present the highest R^2 . Sanquetta *et al.* (2016) emphasize that, although there is a tendency to consider equations with high R^2 values as satisfactory, this metric alone should not be regarded as a definitive criterion, and other selection parameters - such as Syx (%), residual dispersion, and coefficient significance - must also be evaluated.

Moreover, Correia, Fantini, and Piazza (2017), in a study on Dense Ombrophilous Forest (DOF) in Santa Catarina, found that logarithmic models, such as the linearized Schumacher–Hall model, provided the best fit to volumetric data obtained through rigorous scaling, corroborating the results of this study. Sanquetta *et al.* (2016) also considered this model satisfactory and recommended it in a study on *A. angustifolia* in Paraná, as it produced estimates with high R^2 values, low Syx, and an adequate residual distribution along the fitted line, resulting in precise and unbiased estimates.

Regarding data multicollinearity, Cruz *et al.* (2019) reported the lowest VIF for the Schumacher–Hall model (VIF = 1.07), similar to the values found in this study for this model in both groups (Araucaria: VIF = 1.4; broadleaf: VIF = 1.0). The authors also highlight the Spurr model, as it includes only one independent variable and, therefore, does not exhibit multicollinearity, satisfying regression assumptions. In this context, the results obtained in this study support the applied methodology, particularly because simpler models are more general and require less computational effort (Cruz *et al.*, 2019).

CONCLUSION

- The best-fitting hypsometric model for both the Araucaria and broadleaf groups was the exponential model (Model 5).
- The best-performing volumetric model for both groups was Model 2 (linearized Schumacher–Hall).
- The use of indirect methods for volume estimation proved effective given the complexity of obtaining direct volumetric data in native forests.
- Validating the use of the Criterion® device for species characteristic of the Mixed Ombrophilous Forest represents a crucial step toward consolidating the use of non-destructive techniques in volume estimation.

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