

Commercial biomass quantification of *Ilex paraguariensis* A.St.-Hil. grown in the understory of a *Pinus elliottii* Engelm plantation

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ABSTRACT: This study estimated the commercial biomass of *Ilex paraguariensis* cultivated in the understory of a *Pinus elliottii* plantation in the Três Barras National Forest (FLONA) in Santa Catarina state (SC), Brazil, using mathematical models based on dendro-morphometric variables. Special emphasis was given to basal diameter (d_{base}), since the species typically lacks a stem at breast height (DBH) in commercial plantations. A total of 90 individuals were proportionally selected from a census-based frequency table, including 37 shaded trees (Plot 50 Shade), 13 in full sun (Plot 50 Full Sun), and 40 shaded trees (Plot 55). Measured variables included total height, crown height and diameter, d_{base} , diameter at breast height (DBH), number of branches per tree, and leaf and branch green biomass. After felling, commercial and branch biomass, and leaf moisture content were determined. These data were used to develop mathematical models to estimate both green and dry biomass, with independent variables selected through the stepwise procedure. Results showed that commercial biomass was not associated with crown dimensions but increased with the number of branches and branch biomass per tree. It was concluded that commercial biomass can be reliably estimated from key dendro-morphometric variables, particularly basal diameter at 0.10 m above ground.

Key words: Leaf biomass, Dendro-morphometric variables, Forest management, Yerba mate.

Quantificação de biomassa comercial de *Ilex paraguariensis* A.St.-Hil. Implantadas no sub-bosque de um plantio de *Pinus elliottii* Engelm

RESUMO: Este estudo teve como objetivo estimar a biomassa comercial de *Ilex paraguariensis* implantada no sub-bosque de um povoamento de *Pinus elliottii*, na FLONA de Três Barras, SC. A estimativa foi gerada por meio de modelos matemáticos baseados em variáveis dendro-morfométricas, com ênfase no diâmetro da base (d_{base}), devido à ausência de fuste na altura do dap em plantios comerciais da espécie. Foram analisados 90 indivíduos, selecionados proporcionalmente a partir de uma tabela de frequência obtida por censo. A amostragem compreende 37 árvores sob sombra (Talhão 50), 13 em condição de sol (Talhão 50) e 40 sob sombra (Talhão 55). As variáveis mensuradas incluíram altura total, altura e diâmetro de copa, d_{base} , dap, número de galhos e biomassa verde de folhas e galhos. Após o abate, determinou-se a biomassa comercial e de galhos, além do teor de umidade foliar. Com base nesses dados, foram desenvolvidos modelos matemáticos para estimar a biomassa verde e seca, utilizando o procedimento *stepwise* para seleção das variáveis independentes. Os resultados indicaram que a biomassa comercial não está relacionada ao aumento da copa, mas tende a crescer com o número de galhos e a biomassa de galhos por indivíduo. Conclui-se que a biomassa comercial pode ser estimada a partir das principais variáveis dendro-morfométricas, especialmente o diâmetro da base a 0,10 m do solo.

Palavras chave: peso das folhas, variáveis dendro-morfométricas, manejo florestal, erva-mate.

INTRODUCTION

Ilex paraguariensis A.St.-Hil., a characteristic species of Araucaria Forest, is a major source of employment and income for producers and, in turn, for the entire supply chain until the final product reaches consumers. Historically, yerba mate has played a central role in the development of states such as Rio Grande do Sul, Santa Catarina, Mato Grosso do Sul, and especially Paraná (GERHARDT & NODARI, 2009). According to ANDRADE (2002), yerba mate stands can be classified as wild (never

pruned), native, homogeneous (cultivated in full sun), intercropped (with agricultural and/or forest species), dense, and transitional (diversified with other species).

Characterized by extensive forest cover and widespread family farming, the Northern Plateau of Santa Catarina is one of the main regions producing native yerba mate (MARQUES et al., 2012). Beyond its economic and environmental importance, yerba mate is also culturally significant for local communities, where its production is rooted in regional and family traditions (CORREIA et al., 2011; MARQUES et al., 2012).

Because field surveys are time-consuming and costly, biomass is typically estimated from samples using fitted models. As noted by WENDLING et al. (2016), determining total biomass in yerba mate stands is impractical over extensive forest areas. Several researchers have attempted to relate commercial biomass to dendrometric variables, including FLEIG et al. (2003), VUADEN et al. (2009), VERES et al. (2019) and SIGNOR et al. (2024). However, even with available technologies, factors such as genetic quality, plant protection, nutrition, planting time, and harvesting practices are often overlooked by producers, substantially reducing biomass yields.

This study sought to improve understanding and management of the species and provide reliable estimates of leaf production before harvest. Specifically, we estimated the commercial biomass (leaves and branches) of *Ilex paraguariensis* and developed a mathematical model linking green and dry biomass to dendro-morphometric variables.

MATERIALS AND METHODS

Study area and experimental setup

The study was carried in the Três Barras National Forest (FLONA) in Três Barras, Santa Catarina, Brazil (Figure 1). The region has a temperate, humid climate with no dry season, cool summers and frequent frosts (Cfb, Köppen classification)

(ALVARES et al., 2013). Mean annual temperature and rainfall are 17.5 °C and 1,600 mm, respectively.

Forest measurements

Research was conducted in two plots: Plot 50 (1.29 ha) and Plot 55 (3.76 ha), where *Pinus elliottii* Engelm. And *Ilex paraguariensis* A.St.-Hil. were planted in the understory.

P. elliottii was established in 1963 at 2 x 2 m spacing (2,500 trees ha⁻¹) and has been thinned over time (OLIVEIRA et al., 2025), leaving 180 trees ha⁻¹. *I. paraguariensis* was planted in the interrow at 4 x 3 m spacing (833 trees ha⁻¹) in the early 1990s, with no management interventions or commercial exploitation recorded since that time. A strip of land in Plot 50 has no *P. elliottii* trees due to a power line, resulting in *I. paraguariensis* trees in this area growing in full sun rather than under canopy shade. This justified analyzing morphometric indicators separately for trees growing under shade and full sun.

Data from a complete inventory of all *I. paraguariensis* in both plots were classified by diameter class. Fifty trees were selected in Plot 50 (37 shaded, 13 full sun) and 40 trees in Plot 55 (all shaded), proportionally to each class. Selected trees were felled at ~1.0 m with a chainsaw and the number of branches per tree was counted. Branches were then separated from the stem, and new leaves and twigs were detached using electric pruning shears. Leaf and

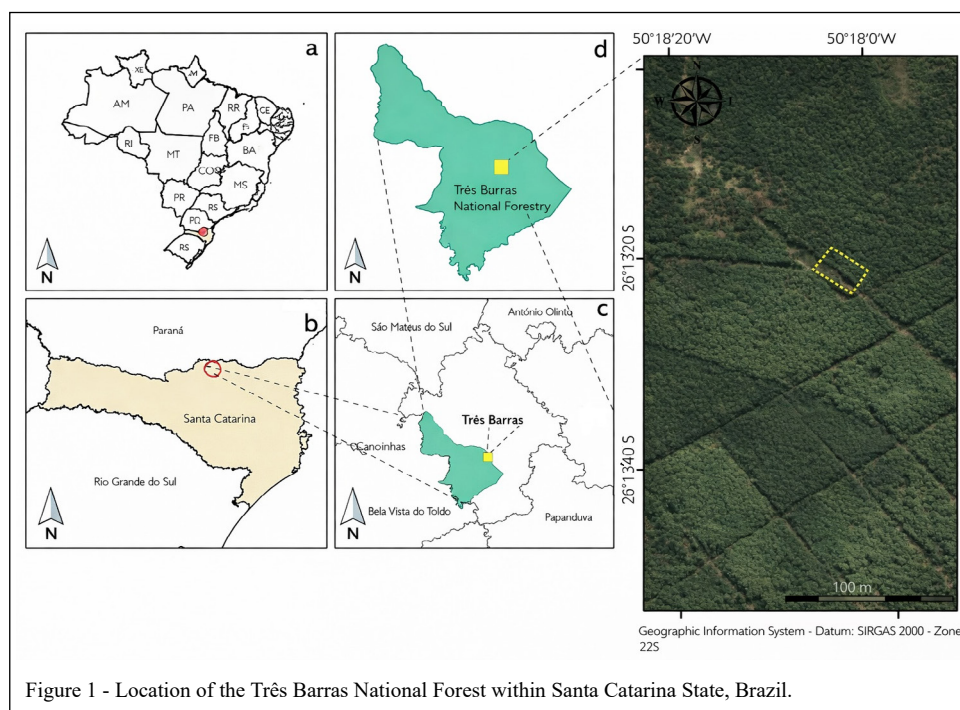


Figure 1 - Location of the Três Barras National Forest within Santa Catarina State, Brazil.

branch green biomass were measured by weighing them on a hanging scale using a tarp.

Leaf samples were collected for oven drying in the laboratory, weighed before and after drying, and 20 leaves per sample were measured for length and width. In the field, total height (h) and crown height (h_{crown}) were measured using a Vertex IV; crown diameter (d_{crown}), DBH, basal diameter (d_{base}), branch biomass, leaf biomass, and number of branches were recorded for all selected trees.

Dendro-morphometric variables were calculated, including cross-sectional area (g), basal area per hectare (G), slenderness ratio (SR), crown proportion (CP%), crown form (CF), prominence index (PI), crown coverage index (CCI), crown projection area (CPA), and potential number of trees per hectare for each crown area (Ni), following DURLO & DENARDI (1998).

Variables were evaluated by plot and by light condition (shaded vs. full sun), testing homogeneity of variance with Levene's test. Where significant differences were found, means were compared with Tukey's test at 95% probability.

Stepwise regression was applied to test all variables against commercial biomass across the 90 sampled trees. In addition to original measurements, combined variables were tested: DBH^2h (DBH

squared $\times$ total height), d_{base}^2h (basal diameter squared $\times$ total height), and $d_{\text{base}}^2h_{\text{crown}}$ (basal diameter squared $\times$ crown height).

Individual variables were grouped into four categories for stepwise selection (Table 1). Model I included all measured and derived variables; Model II excluded branch biomass, number of branches per tree, cross-sectional area, and DBH; Model III further excluded combined variables; and Model IV only included field-measured variables, excluding morphometric and combined variables.

Models were assessed using R^2 adjusted ($R^2 \text{ adj}$), standard error of estimate (Syx%), and residual dispersion, with the Shapiro-Wilk test for normality (95% probability).

The variance inflation factor (VIF) was calculated to check for multicollinearity, with $\text{VIF} \geq 10$ considered problematic (SILESHI, 2014).

RESULTS

Table 2 provides descriptive statistics for the *I. paraguariensis* individuals sampled for biomass.

Table 3 summarizes dendrometric and morphometric parameters of the 90 sampled trees in Plots 50 and 55, with Plot 50 further divided into

Table 1 - Independent variables used to develop models for predicting commercial biomass.

Variable	Model I	Model II	Model III	Model IV
DBH (cm)	✓			
d_{base} (cm)	✓	✓	✓	✓
h (m)	✓	✓	✓	✓
h_{crown} (m)	✓	✓	✓	✓
d_{crown} (m)	✓	✓	✓	✓
No. of branches	✓			✓
Leaf width	✓	✓	✓	
Branch biomass				✓
Leaf length	✓	✓	✓	
$\text{DBH}^2 \times h$	✓	✓		
$d_{\text{base}}^2 \times h$	✓	✓		
$d_{\text{base}}^2 \times h_{\text{crown}}$	✓	✓		
Slenderness ratio	✓	✓	✓	
Crown proportion	✓	✓	✓	
Crown form	✓	✓	✓	
Prominence index	✓	✓	✓	
Crown coverage index	✓	✓	✓	
Crown projection area (m^2)	✓	✓	✓	
g (m^2)	✓			

Notes: DBH (cm) = diameter at breast height (1.3 m above ground); h (m) = total height; d_{base} (cm) = diameter at 0.10 m above ground; d_{crown} (m) = crown diameter; h_{crown} (m) = crown height; g = cross-sectional area (m^2).

shaded trees (under *P. elliottii*) and full-sun trees. This stratification was used to examine differences in these parameters between light conditions.

All variables in table 3 met the homogeneity of variance assumption according to Levene's test, meaning that no transformations were necessary. ANOVA results indicated significant differences ($P < 0.05$) for most variables between shade and full sun, while h_{crown} , d_{crown} , SR, CP%, CF, CPA, number of branches per tree, and leaf width (LW) did not differ significantly.

Figure 2 displays boxplots of all dendrometric and morphometric variables, along with Tukey's 95% confidence comparisons, highlighting significant differences among the three conditions (Plot 55, Plot 50 Full Sun, and Plot 50 Shade).

Table 4 presents the models generated from the stepwise procedure for each plot and light condition, together with fit statistics. The R^2_{adjusted} (R^2_{adj}) indicates how well the model explains the observed data while accounting for the number of predictors, allowing comparisons across models with different predictor sets. The standard error of estimate (S_{yx}) shows that lower values correspond to better model performance.

Table 5 reports VIF values for the four models. Only in Model IV were all VIF values below the threshold, indicating minimal multicollinearity.

Figure 3 shows residual plots for all four models under each condition and overall, allowing visual assessment of potential trends in over- or underestimation of the predicted variable.

DISCUSSION

Trees growing under full sun in Plot 50 generally showed higher mean values than their shaded counterparts in Plots 50 and 55. However, VUADEN et al. (2009) emphasizes that although DBH is commonly used for biomass estimation in trees, this variable is not suitable for yerba mate plantations. The species is typically pruned at about one meter in height and often develops multiple stems, making breast-height measurements at 1.30 m impractical.

Basal diameter (d_{base}), measured at 0.10 above ground, averaged 7.6 cm in Plot 55, 4.3 cm in Plot 50 (full sun), and 10.5 cm in Plot 50 (shade). By contrast, FLEIG et al. (2003) and VUADEN et al. (2009) recommended measuring diameter at

Table 2 - Descriptive statistics of dendro-morphometric and biomass variables of *I. paraguariensis* trees in Plots 50 and 55 of the Três Barras National Forest (FLONA).

Variable	CV (%)	Minimum	Maximum	Mean
DBH (cm)	36.86	3.0	17.7	8.6
h (m)	21.46	5.1	13.5	8.6
d_{base} (cm)	37.35	3.5	23.9	9.4
h_{crown} (m)	37.93	1.2	9.2	3.6
d_{crown} (m)	30.39	0.9	5.2	3.1
SR	35.78	0.6	2.3	1.1
PI	44.41	0.1	1.1	0.4
CP (%)	36.55	13.3	81.4	43.1
CCI	32.69	0.1	0.7	0.4
CF	47.06	0.3	2.9	1.0
CPA (m ²)	56.98	0.7	20.9	8.2
MC%	39.89	2.8	74.2	43.3
No. of branches	42.42	5.0	39.0	14.6
Branch biomass (Kg)	92.33	1.3	37.9	4.5
Commercial biomass (Kg)	87.05	0.2	21.6	3.0
Leaf width (cm)	6.21	3.5	5.3	4.9
Leaf length (cm)	17.90	7.9	14.7	12.1

Notes: DBH (cm) = diameter at breast height (1.3 m above ground); h (m) = total height; d_{base} (cm) = diameter at 0.10 m above ground; d_{crown} (m) = crown diameter; h_{crown} (m) = crown height; SR = slenderness ratio; PI = prominence index; CP (%) = crown proportion; CCI = crown coverage index; CF = crown form; CPA (m²) = crown projection area; MC% = leaf moisture content; CV (%) = Coefficient of variation (%).

Table 3 - Mean biometric, morphometric, and biomass parameters of *I. paraguariensis* trees in Plots 50 and 55 of the Três Barras National Forest (FLONA) under full sun and understory/shade conditions.

Variable	-----Plot/Light condition-----			Levene (P-value)	ANOVA (P-value)
	55	50 Full Sun	50 Shade		
DBH (cm)	7.1	10.5	9.4	0.11	0.00
h (m)	7.9	9.6	9.0	0.18	0.00
d _{base} (cm)	7.6	11.3	10.5	0.13	0.00
h _{crown} (m)	3.5	3.3	3.8	0.58	0.54
d _{crown} (m)	3.1	2.8	3.1	0.13	0.47
SL	1	1	1	0.24	0.06
PI	0.5	0.3	0.3	0.26	0.00
CP (%)	45.4	35.0	43.4	0.17	0.11
CCI	0.4	0.3	0.4	0.77	0.00
CF	1	1	1	0.16	0.67
CPA (m ²)	8.1	7.1	8.7	0.18	0.59
MC%	57.3	40.4	29.22	0.12	0.00
No. of branches	14	14	16	0.97	0.29
Branch biomass (Kg)	3.5	3.9	5.8	0.11	0.05
Commercial biomass (Kg)	2.4	2.8	3.8	0.06	0.05
Leaf width (cm)	4.9	4.8	4.8	0.05	0.08
Leaf length (cm)	13	12	11.3	0.07	0.00

Notes: DBH (cm) = diameter at breast height (1.3 m above ground); h (m) = total height; d_{base} (cm) = diameter at 0.10 m above ground; d_{crown} (m) = crown diameter; h_{crown} (m) = crown height; SR = slenderness ratio; PI = prominence index; CP (%) = crown proportion; CCI = crown coverage index; CF = crown form; CPA (m²) = crown projection area; MC% = leaf moisture content; p-value = significance of Levene's test for variance homogeneity and ANOVA; 55 = trees in Plot 55; 50 Full Sun = trees in Plot 50 under full sun; 50 Shade = trees in Plot 50 in understory/shade conditions.

0.6 m above ground, noting that below this point, bifurcations at the base result in weak correlations between basal perimeter and crown biomass.

Tree height (h) varied from 5.1 to 11.3 m, with a mean of 7.9 m in Plot 55 (Table 2). Mean height under full sun and shade in Plot 50 was 9.6 and 9.0 m, respectively (Table 3). These values are far higher than those reported by FLEIG et al. (2003) for a homogeneous yerba mate stand in Santa Catarina (3.1 m), and by VUADEN et al. (2009) who recorded average 3.0 m. The greater tree heights observed here result from the heterogeneous planting and lack of pruning since establishment, which allowed stems to grow longer before crown insertion.

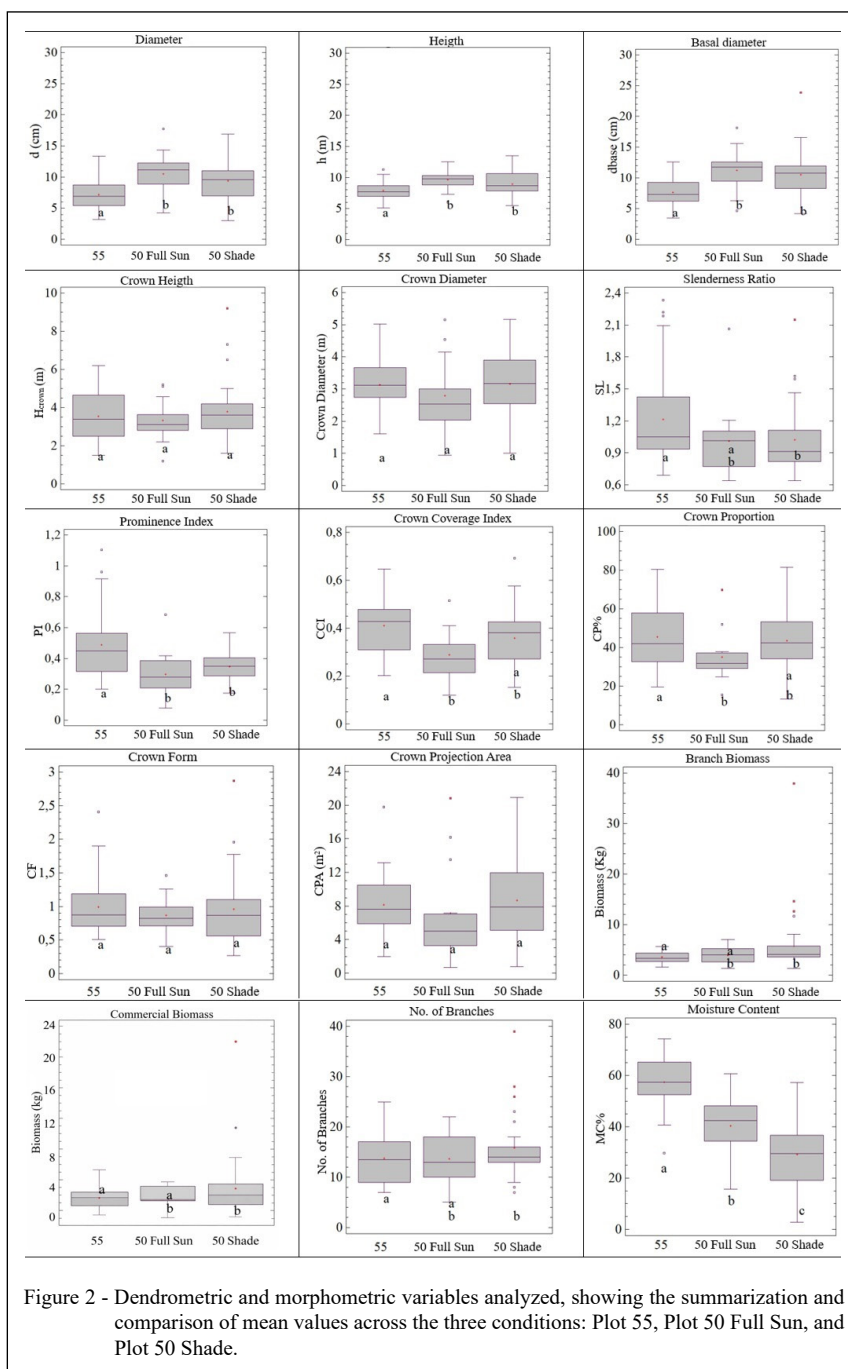
Across all trees, minimum, maximum, and total heights were 1.2, 9.2, and 3.6 m, respectively. Among light conditions, Plot 50 Shade obtained the highest mean, followed by Plot 55 and Plot 50 Full Sun. Notably, the crown height measurements in our study were close to the total heights reported by VUADEN et al. (2009). This reflects the difference in planting systems: commercial plantations consist almost entirely of crowns with short stems, whereas the trees in this study had never been pruned and

therefore had considerably longer stems, leading to greater total heights.

Crown diameter (d_{crown}) ranged from 0.9 to 5.2 m, with an overall mean of 3.1 m. Mean d_{crown} was smaller in Plot 50 Full Sun compared to the other conditions, which exhibited similar and higher values. Previous studies (FLEIG et al., 2003; BERGER et al., 2020; VUADEN et al., 2009) reported means between 1.5 and 2.2 m, considerably lower than those found here. The larger and more elongated crowns observed in this study may favor higher yields, since larger crowns are generally associated with greater commercial biomass.

The slenderness ratio (SR) averaged 1.0 m across all light conditions. This index is commonly used as an indicator of tree stability, with lower values reflecting a greater balance between diameter and height, which increases stability. BOSCHETTI et al. (2015) noted that tall stems combined with small diameters can result in instability.

Finally, the prominence index (PI) averaged 0.5 in Plot 55 overall and 0.3 under both full sun and shade within the same plot. This index represents the ratio of crown diameter to stem diameter at



breast height. The overall mean of 0.4 indicates that, on average, crowns were 40 times larger than stem diameters. Lower PI values suggested more efficient space use within a given crown projection area (CPA) (STERBA, 1992).

The crown proportion (CP%) reflects the proportion of total tree height occupied by the crown.

In this study, yerba mate crowns averaged 43.1% of tree height, while DURLO & DERNARDI (1998) reported a mean of 49.2% for *Cabralea canjerana*. Crown form (CF) averaged 1.0 across all conditions. Low values indicated slender crowns, high values flattened crowns, and values near 1 rounded crowns. Although, individual variation was wide, mean values suggested

Table 4 - Equations generated for estimating commercial biomass based on the four variable selection approaches.

	Equation	R ² adj	S _{yx} (%)	P-value
I	$Y = -8.65083 + 4.27539 \cdot \text{DBH} - 0.233925 \cdot d_{\text{base}} - 1.85042 \cdot h - 0.241991 \cdot h_{\text{crown}} - 1.22896 \cdot d_{\text{crown}} + 0.168916 \cdot \text{NB} - 1.36297 \cdot \text{LW} - 0.0452009 \cdot \text{LL} + 0.0113303 \cdot \text{DBH}^2 h + 0.00141145 \cdot d_{\text{base}}^2 h - 0.00148855 \cdot d_{\text{base}}^2 h_{\text{crown}} + 6.87271 \cdot \text{SR} + 0.13434 \cdot \text{CP} + 3.49204 \cdot \text{CF} + 1.33427 \cdot \text{PI} - 12.4868 \cdot \text{CCI} + 0.357753 \cdot \text{CPA} - 3481.66 \cdot g$	0.7775	36.12	0.0088
II	$Y = 4.02234 - 0.0795134 \cdot d_{\text{base}} + 0.689317 \cdot h - 2.02949 \cdot h_{\text{crown}} - 0.196164 \cdot d_{\text{crown}} - 1.97587 \cdot \text{LW} - 0.166197 \cdot \text{LL} + 0.00118474 \cdot \text{DBH}^2 h - 0.00141393 \cdot d_{\text{base}}^2 h + 0.00402045 \cdot d_{\text{base}}^2 h_{\text{crown}} - 0.50814 \cdot \text{SR} + 0.289712 \cdot \text{CP} + 6.13693 \cdot \text{CF} + 1.92842 \cdot \text{PI} - 22.6554 \cdot \text{CCI} + 0.258753 \cdot \text{CPA}$	0.6838	43.06	0.0012
III	$Y = 2.76439 + 0.0548173 \cdot d_{\text{base}} + 0.574402 \cdot h - 0.659753 \cdot h_{\text{crown}} - 1.06582 \cdot d_{\text{crown}} - 1.77993 \cdot \text{LW} - 0.208292 \cdot \text{LL} - 0.503455 \cdot \text{SR} + 0.224299 \cdot \text{CP} + 6.8024 \cdot \text{CF} + 1.39648 \cdot \text{PI} - 18.9885 \cdot \text{CCI} + 0.310473 \cdot \text{CPA}$	0.6722	43.64	0.0025
IV	$Y = -0.790795 + 0.0635957 \cdot d_{\text{base}} - 0.11486 \cdot h + 0.266669 \cdot h_{\text{crown}} - 0.00147815 \cdot d_{\text{crown}} + 0.543591 \cdot \text{BB} + 0.0562389 \cdot \text{NB}$	0.9352	19.36	0.7271

Notes: Y = commercial biomass (kg); DBH = diameter at breast height (cm); d_{crown} = crown diameter (cm); d_{base} = basal diameter (cm); BB = branch biomass (cm); NB = Number of branches per tree; h_{crown} = crown height (m); LL = leaf length (cm); LW = leaf width (cm); PI = prominence index ($d_{\text{crown}}/\text{DBH}$); CPA = crown projection area (m²); CCI = crown coverage index (d_{crown}/h); SR = slenderness ratio (h/d); CP = crown proportion (%); CF = crown form ($d_{\text{crown}}/h_{\text{crown}}$); R² adj = adjusted coefficient of determination; S_{yx} (%) = standard error of the estimate, in percent; P-value = Shapiro-Wilk test for residual normality.

that the yerba mate crowns assessed here were generally rounded (DURLO & DERNARDI, 1998).

CPA ranged from 0.7 to 20.9 m², with a mean of 8.2 m², reflecting the unmanaged and heterogeneous character of the stand. GREIG-SMITH (1983) defines this metric as the ground area covered by the vertical projection of tree crowns.

Leaves averaged 4.9 cm in width (range: 3.5-5.3 cm; CV: 6.21%) and 12.1 cm in length (range: 7.9-14.7 cm). Leaf moisture content (MC%) averaged 43.3% (range: 2.8-74.2%). In Plot 55, the number of branches per tree varied from 5 to 39 (mean: 14.6). As shown in tables 2 and 3, greater branch numbers were generally associated with higher commercial biomass. Branch biomass ranged from 1.3 to 37.9 kg (mean: 4.5 kg).

Minimum, maximum, and mean commercial biomass per tree were 0.2, 31.9, and 3.0 kg, respectively, with a CV of 87.05%. Plot 50 Shade produced higher mean values than the other conditions, followed by 50 Full Sun and Plot 55. Although, some trees produced exponentially high yields, these were rare and did not affect overall means. The wide variability in Plot 50 Shade aligns with previous reports: BERGER et al. (2020) recorded a mean commercial biomass of 7.8 kg per tree in a 12-year-old plantation, VUADEN et al. (2009) reported 1.6 kg in a 9-year-old stand, and BELTRÃO et al. (2000) 4.6 kg over 11 biennial harvests. ANDRADE (2002) noted that yerba mate yield stabilizes at 14-20 kg after 10-12 years, while large native trees may produce 80-

180 kg per harvest every 3-5 years. Although, the stand in this study was planted, its yields were closer to those of unmanaged native trees, likely because the plantation was abandoned after establishment.

Overall, Plot 50 Shade performed best, particularly for crown-related traits such as commercial biomass. This reflects the heterogeneous structure of the stand, where the highest individual biomass (21.6 kg) was found.

Of the models tested (Table 4), Model IV proved most reliable, with the highest R² adjusted, lowest S_{yx} %, normally distributed residuals, and VIF values below the cutoff, thus meeting the assumption of independence among predictor variables. Its performance closely matched the best model reported by SIGNOR et al. (2024), which had an R² adjusted of 0.9638 and S_{yx} (%) of 19.5%.

Although Model IV requires branch biomass as an output, a variable that can be difficult to measure, this limitation can be addressed through targeted sampling. As in forest inventory practices for estimating timber volume, a subset of trees could be harvested to measure branch biomass, supporting accurate estimates of commercial biomass for the broader stand.

CONCLUSION

Commercial biomass increases not with crown size, but with a higher number of branches and greater branch biomass per individual. Basal diameter, crown diameter, crown height, number of branches,

Table 5 - Variance inflation factor (VIF) for the selected models.

Model I		-----Model II-----		-----Model III-----		-----Model IV-----	
Variable	VIF	Variable	VIF	Variable	VIF	Variable	VIF
DBH	1340.0	d _{base}	50.87	d _{base}	6.52	d _{base}	1.76
d _{base}	120.3	h	33.12	h	18.31	h	1.78
h	146.0	h _{crown}	81.00	h _{crown}	22.73	h _{crown}	1.13
h _{crown}	95.0	d _{crown}	116.42	d _{crown}	109.05	d _{crown}	1.33
d _{crown}	121.1	LW	1.65	LW	1.60	BB	2.09
NB	2.4	LL	2.13	LL	1.98	NB	1.80
LW	1.7	DBH ² h	18.32	SR	12.63		
CF	2.3	d _{base} ² h	41.71	CP	23.79		
DBH ² h	379.9	d _{base} ² h _{crown}	25.45	CF	7.20		
d _{base} ² h	108.7	SR	21.97	PI	16.52		
d _{base} ² h _{crown}	31.7	CP	52.97	CCI	38.54		
SR	71.9	CF	8.85	CPA	44.99		
CP	66.2	PI	17.11				
CF	11.3	CCI	43.01				
PI	17.3	CPA	50,80				
CCI	49.4						
CPA	51.2						
g	1714.6						

Notes: DBH (cm) = diameter at breast height (1.3 m above ground); h (m) = total height; d_{base} (cm) = diameter at 0.10 m above ground; d_{crown} (m) = crown diameter; h_{crown} (m) = crown height; BB = branch biomass (cm); NB = number of branches per tree; LL = leaf length (cm); LW = leaf width (cm); SR = slenderness ratio; PI = prominence index; CP (%) = crown proportion; CCI = crown coverage index; CF = crown form; CPA (m²) = crown projection area; VIF = variance inflation factor.

and branch biomass were the most efficient variables for estimating commercial biomass, as indicated by Model IV. This model showed consistent and

robust statistics for estimating commercial biomass, particularly in unmanaged or native *I. paraguariensis* stands characterized by taller trees.

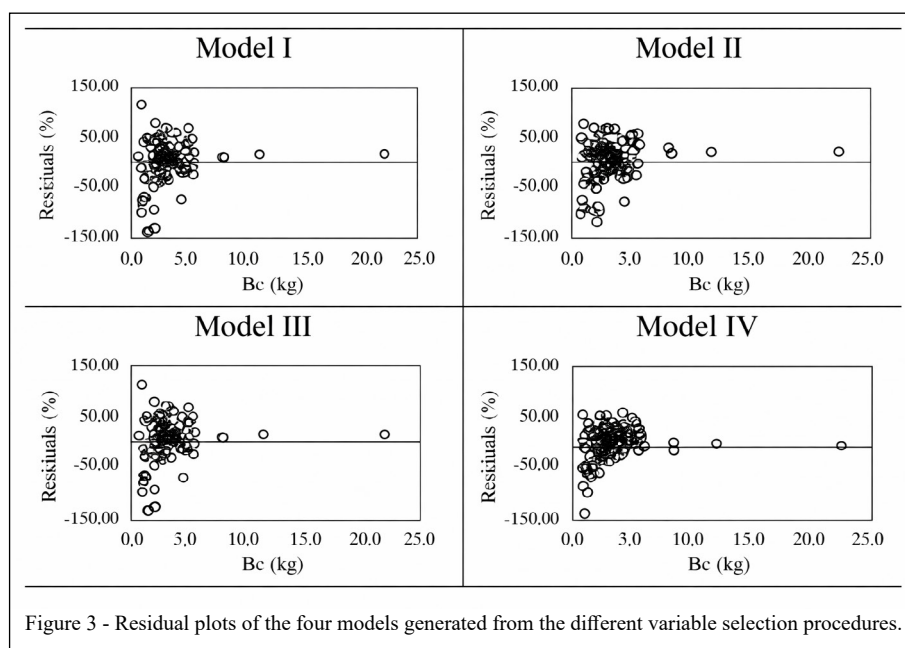


Figure 3 - Residual plots of the four models generated from the different variable selection procedures.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare no financial or personal conflicts of interest that could have influenced this work.

AUTHORS' CONTRIBUTIONS

All authors contributed equally to the manuscript.

DATA AVAILABILITY STATEMENT

The raw data supporting this study is available upon request from the corresponding author.

DECLARATION OF USE OF ARTIFICIAL INTELLIGENCE

The authors did not use artificial intelligence to develop this study.

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