Coeficiente mórfico de Apuleia leiocarpa (Vogel) J.F. Macbr. por tipo de bosque, Amazonía peruana

Morphic coefficient of Apuleia leiocarpa (Vogel) J.F. Macbr. according to forest type, Peruvian Amazon

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Abstract

The objective of the study was to determine and compare the morphic coefficient (*MC*) and allometric models in order to estimate the forest volume of *Apuleia leiocarpa* in two forest types in the *Madre de Dios* region of the Peruvian Amazonia. A sample size of 42 felled *A. leiocarpa* trees was used: 22 in low-hill forest, and 20 in low-terrace forest. The diameter at breast height (*DBH*) and the stem height of each individual were measured, and diameter measurements were taken along the stem every 2 m. The morphic coefficient was determined by forest type, and 11 nonlinear models were assessed for determining the merchantable forest volume. The *MC* in the low-ill forest is significantly higher than that calculated in the low-terrace forest (t-Student, *p*<0.01). The ANCOVA showed that the *MC* varied significantly between the two forest types. The *DBH* did not exert a significant influence on the *MC* (*p*>0.05); however, the interaction between the forest type and the DBH was significant (*p*<0.05). The best allometric model for estimating the merchantable forest volume was Takata's model for the low-hill forest, while Spurr's model with independent term was the best for the low-terrace forest.

Key words: Allometry, Amazonia, volume equations, shape factor, regression, timber volume.

Resumen

El objetivo del estudio fue determinar y comparar el coeficiente mórfico (*CM*) y modelos alométricos para estimar volumen fustal de *Apuleia leiocarpa* en dos tipos de bosque en la Amazonía de Madre de Dios, Perú. Se utilizó un tamaño de muestra de 42 árboles talados de *A. leiocarpa*: 22 en bosques de colina baja y 20 en bosque de terraza baja. De cada individuo se midió su diámetro a la altura del pecho (*DAP*) y la altura del fuste, y se realizaron mediciones de diámetro a lo largo del fuste cada 2 m. Por tipo de bosque se determinó el coeficiente mórfico y se evaluaron 11 modelos no lineales para el volumen fustal comercial. El *CM* en el bosque de colina baja es significativamente superior al calculado en el bosque de terraza baja (*t-Student*, *p*<0.01). El ANCOVA mostró que el *CM* varía significativamente entre los dos tipos bosque. El *DAP* no influyó de forma significativa en el *CM* (*p*>0.05), aunque sí la interacción entre bosque × *DAP* (*p*<0.05). El mejor modelo alométrico para estimar el volumen varía según el tipo de bosque, en el bosque de colina baja fue el modelo de *Takata* y en el bosque de terraza baja fue el modelo de *Spurr* con término independiente.

Palabras clave: Alometría, Amazonía, ecuaciones de volumen, factor de forma, regresión, volumen maderable.

Introduction

The tropical forests of the Amazonia are the most complex ecosystems on the planet because they support the greatest biodiversity and productivity in the world (Bowman *et al.*, 2022). These forests provide important services for the maintenance of ecosystems and the economic and social development of Peru, such as the forestry industry (Tito, 2022). With the increasing demand for timber, one of the ways to ensure sustainable forest management is the use of allometric models for timber volume estimation (Fan *et al.*, 2020; Zhang *et al.*, 2020).

Peru ranks ninth in the world in terms of forest area with 73.3 million hectares of tropical forests (Rojas *et al.*, 2020). Of the total Peruvian tropical forests, 10 % are considered timber-harvesting concessions (Minam, 2015). The *Madre de Dios* region is recognized as the biodiversity capital of Peru (Fuentes *et al.*, 2022) and is the second region in the country (85 301 km^2) with the highest roundwood production (>300 000 m^3 año^{-1}) (Pacheco *et al.*, 2016).

Apuleia leiocarpa (Vogel) J. F. Macbr. (*ana caspi*) is one of the most intensively harvested species with the highest volume extracted (4 300 m^3 year^{-1}) (Pacheco *et al.*, 2016), due to the high density of its wood (0.70 g cm^{-3}) and the high extractive value; therefore, a correct and precise evaluation of the calculation of its volume, at individual tree level, would allow its sustainable use (García *et al.*, 2016).

The morphic coefficient (*MC*) is a factor of reduction of a reference solid to the actual shape of an aggregate (Ikonen *et al.*, 2006); the cylindrical shape is the most commonly used (Tlaxcala-Méndez *et al.*, 2016). It is obtained by dividing the real

volume of the stem by the volume of a conventional geometric body with the same diameter and height as the normal section of a tree (Furlan *et al.*, 2010). The *MC* has been used for several decades in many Latin American countries dedicated to timber forestry in the absence of specific volume models for harvested species (Costa *et al.*, 2016; Fan *et al.*, 2020).

Accurate estimation of the commercial volume of standing trees is essential for sustainable forest management (Tamarit *et al.*, 2014; Mendes *et al*., 2020; Zhang *et al*., 2020). The *MC* of trees is considered an important alternative for volume estimation (Colgan *et al.*, 2014; García *et al.*, 2016) because the *DBH*, the merchantable height, and the *MC* of the species are used to determine it in standing trees (García *et al.,* 2016).

In Peru, general allometric models are currently used to estimate timber volume, in which a single *MC* is used for all species (Malata *et al.*, 2017). For tropical taxa, an *MC* or form factor of 0.75 is applied (Guzmán-Santiago *et al.*, 2020). The Peruvian national forest authority establishes an *MC* of 0.65 (Del Mar, 2021); however, having a general *MC* for all species could overestimate or underestimate the timber volume (Azevêdo *et al.*, 2014).

Another way of estimating the merchantable volume is by means of specific allometric models (Malata *et al.*, 2017). Allometric equations derived from linear or nonlinear regression models allow estimation of the stem volume based on diameter and height measurements (Gúzman-Santiago *et al.*, 2020; Zhang *et al.*, 2020). Previous studies have shown that nonlinear equations can better describe volume trends; therefore, they are more effective than linear models (Gúzman-Santiago *et al.*, 2020). The Spurr, Schumacher-Hall and Husch models are the most widely used in Amazonia (Costa *et al.*, 2016; Mendes *et al.*, 2020; Souza *et al.*, 2021). However, due to the high diversity of ecosystems and species in Amazonian forests, it is

necessary to develop taxon-specific allometric models that include different site conditions (Aguilar *et al.*, 2017; Miranda *et al.*, 2021).

On the other hand, bark thickness is a fundamental variable in forestry measurements (Reis *et al.*, 2020). During timber forest management, it is important to estimate the merchantable volume without the bark (Berrill *et al.*, 2020); therefore, determining the bark thickness is relevant for accurate estimation of the volume without the bark. Meanwhile, estimates of the sapwood and heartwood of trees are important both in the timber industry and for dynamic vegetation models because they determine the biomechanical stability, as well as the nutrient and water transport (Aye *et al.*, 2022). In this regard, studies on the formation of heartwood and its proportions along the stem are still scarce, which is why there is little solid information for the development of silvicultural practices, especially since heartwood is the most valuable part of tropical species, as it has a determining influence on the price of wood (Meupong *et al.*, 2021).

Moreover, for the estimation of the merchantable volume, it is vital to consider that species have different growth response to different site conditions (Molina-Valero *et al.*, 2019; Mendes *et al.*, 2020), yet another factor that influences the variation of the *MC*. Within this context, the present study aimed to determine and compare both the *MC* and 11 allometric models for calculating the tree crown volume of *A. leiocarpa* in two forest types in the *Madre de Dios* region of the Peruvian Amazonia. Furthermore, differences in the variables height, *DBH*, stem volume, sapwood thickness, heartwood thickness, and bark thickness were assessed and compared between the two forest types, and the influence of forest type on the *MC* was analyzed.

Materials and Methods

Study area

The research was conducted in two forest concessions for the management and harvesting of products other than timber (Brazil nut collection), located in the *Tambopata* district, *Tambopata* province, *Madre de Dios* region, Peru. Based on the National Land Cover Map of the Peruvian Ministry of Environment (Minam, 2015), a low-hill forest (12°6'31.16" S and 69°33'17.96" W) and a low-terrace forest (12°11'18.85" S and 69°23'5.94" W) were identified in the study area. The two concessions were Fredy Turpo's and Maritza Callo's; the former has an area of 634 ha and is located in a low-hill forest; of the latter concession, only the part of the low-terrace forest was considered, with an area of 550 ha (Figure 1).
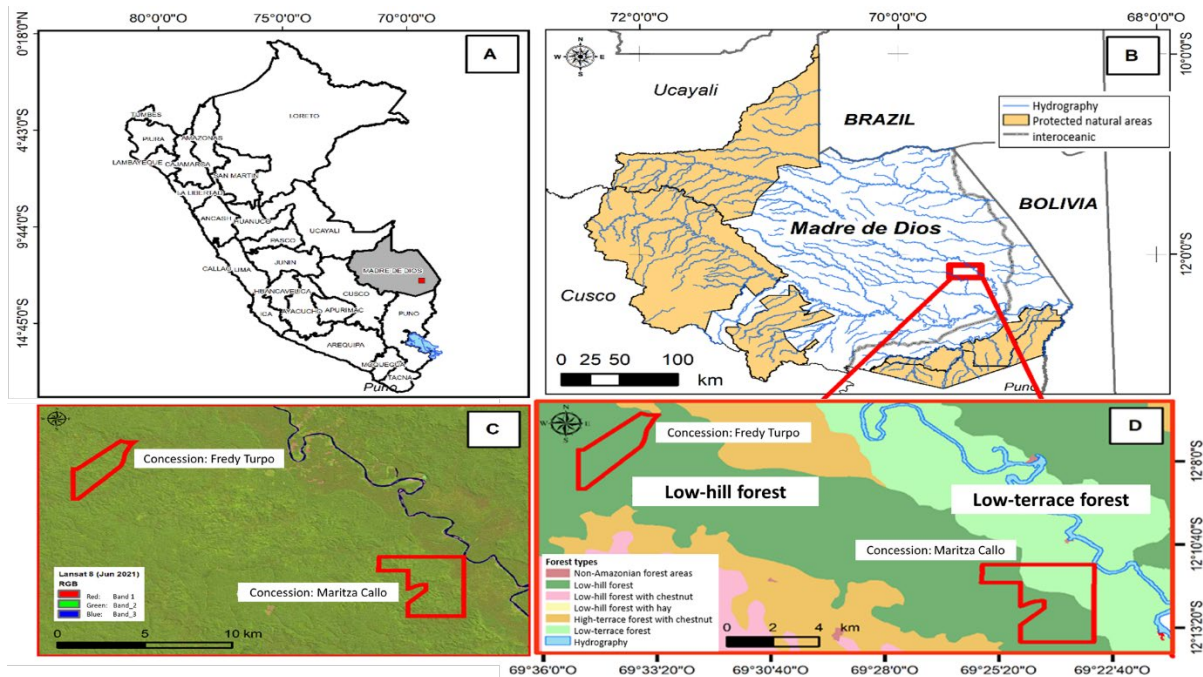
Figure 1. Location of the study area in the *Tambopata* province, *Madre de Dios* region, Peru (A and B), in the areas corresponding to Fredy Turpo's and Maritza Callo's concessions (C and D).

Data collection

A sample of 42 *A. leiocarpa* trees of the following species was collected: 22 in low-hill forest, and 20 in low-terrace forest. Only trees with a diameter at breast height (*DBH*) above 41 cm were included; this length is equivalent to the minimum cutting diameter established in the Peruvian forest regulations for merchantable timber harvesting (Del Mar, 2021); therefore, only information from merchantable specimens was analyzed. Each individual was felled, and the length of the stem

(height of the stem) was measured with a model Pro-FMHT33100-0 Stanley FatMax®
flexometer, the diameter, with a Haglöf® (Mantax Blue) caliper every 2 m along the
stem (Aguilar *et al.*, 2017), without sectioning it into logs. At the base of the stem,
two bark measurements were taken with the flexometer; the thickness of sapwood
and heartwood was also recorded in centimeters to calculate the percentage of
sapwood and heartwood, whose reference was the diameter of the stem. The volume
of each section was estimated with the Smalian equation (Guzmán-Santiago *et al.*,
2020; Souza *et al.*, 2021), the volume of the forest was obtained from the sum of all
the sections.

Data analysis

Based on the shape of the stem of *A. leiocarpa* observed in the field, the cylinder
was used to calculate the morphic coefficient (Guzmán-Santiago *et al.*, 2020); for
this purpose, the following expression was used:

$$MC = \frac{V_R}{V} \quad (1)$$

Where:

MC = Morphic coefficient

V_R = Real stem volume

V = Volume of cylinder solid with base area equal to the base area of the tree and equal in height.

Differences in height, *DBH*, stem volume, sapwood thickness, heartwood thickness and bark thickness between forest types were evaluated using the two-tailed t-Student test when the parametric assumptions (normality and homoscedasticity) were met, and the Mann-Whitney test when not (Berger *et al.*, 2018); a significance level of 5 % was used in both cases. On the other hand, the t-Student test was applied to a sample in order to compare the estimated *MC* values with respect to the *MC* established by the Peruvian national authority and to the one cited in previous research (Del Mar, 2021; Lozano and Bonilla 2022) for cylindrical *Dipteryx odorata* (Aubl.) Forsyth f. stems, whose shape is similar to that of *A. leiocarpa* stems (Lozano and Bonilla, 2022).

For the purpose of analyzing the relationship between *DBH*, height, bark thickness, thickness of the sapwood and the heartwood, and sapwood/heartwood ratio, a correlation analysis was carried out for each forest type; these were represented in a correlation matrix using Pearson's and Spearman's (non-parametric) correlation coefficients. Simple linear regression models were fitted to the variables that were significantly correlated. An analysis of covariance (ANCOVA) was also applied to analyze the influence of the forest type on the *MC*, in which the *DBH* was the covariate, as well as the forest type-diameter interaction.

11 nonlinear allometric models were assessed for volume estimation (Table 1), considering the volume functions suggested by Guzmán-Santiago *et al.* (2020), Ogana *et al.* (2020) y Reis *et al.* (2020).

Table 1. Nonlinear allometric models adjusted to estimate the volume of *Apuleia leiocarpa* (Vogel) J. F. Macbr. stems.

Expression of the model	Name	Label
$V_s = \beta_0 DBH^{\beta_1} \times H^{\beta_2} + \varepsilon$	Schumacher-Hall	M1
$V_s = \beta_0 DBH^2 \times H + \varepsilon$	Spurr	M2
$V_s = \beta_0 (DBH^2 \times H)^{\beta_1} + \varepsilon$	Spurr potential	M3
$V_s = \beta_0 + \beta_1 DBH^2 \times H + \varepsilon$	Spurr with independent term	M4
$V_s = \beta_0 + \beta_1 H + \beta_2 DBH^2 \times H + \varepsilon$	Composite variable	M5
$V_s = (DBH^2 / (\beta_0 + (\frac{\beta_1}{H})) + \varepsilon$	Honer	M6
$V_s = (DBH^2 \times \frac{H}{(\beta_0 + \beta_1 \times DBH)} + \varepsilon$	Takata	M7
$V_s = \beta_0 + \beta_1 (DBH^2) + \beta_2 (DBH^2 \times H) + \beta_3 H + \varepsilon$	Stoate	M8
$V_s = DBH^2 \times (\beta_0 + \beta_1) + \varepsilon$	Ogaya	M9
$V_s = \beta_0 DBH^2 + \beta_1 DBH^2 \times H + \beta_2 (DBH \times H) + \beta_3 H^2 + \varepsilon$	Näslund	M10
$V_s = \beta_0 DBH^{\beta_1} + (\beta_1 DBH^2 \times H)^{\beta_2} + \varepsilon$	Meyer	M11

V_s = Volume of the stem; *DBH* = Diameter at breast height (cm); *H* = Height of the stem (m); β_i = Coefficients of the model; ε = Error of the model.

The following fit statistics criteria were used to discriminate between the best nonlinear models: root mean square error (*RMSE*), mean square error (*MSE*), Akaike information criterion (*AIC*), and Bayesian information criterion (*BIC*) (Ogana *et al.*, 2020; Reis *et al.*, 2020). The best models were selected using the model ranking method (Tamarit *et al.*, 2014; Ogana *et al.*, 2020), in which values from 1 to 11 were assigned to each model by fit statistic, in descending order, with 1 being the lowest and best value. For the final rating, all the values obtained were added

together, and the model with the lowest value was considered the best (Ogana *et al.*, 2020; Reis *et al.*, 2020).

All analyses and figures were performed with the R v4.2.2.2 statistical software in the environment of R-Studio v12 (R Core Team, 2022), InfoStat (InfoStat, 2022), and SigmaPlot v14 (Inpixon, 2022). In R, the packages ggplot2, AICcmodavg, HH, and PerformanceAnalytics were used.

Results and Discussion

The descriptive statistics of the variables corresponding to the sample of trees analyzed by concession are presented in Table 2; significant differences are also shown when applying the Student's t-test and the Mann-Whitney test.

Table 2. Descriptive statistics of the variables measured in *Apuleia leiocarpa* (Vogel) J. F. Macbr. trees by forest type and Student's t and Mann-Whitney tests for the average values.

Variable	Forest type	Minimum	Maximum	Average	Median	*SD*	*CV*
Height of the stem (m)†	LHF	8.15	21.17	14.97 b	15.14	2.83	18.93
	LTF	11.84	24.86	17.58 a	18.60	2.95	16.81
DBH (cm)†	LHF	56.00	151.00	86.55 a	80.00	22.10	25.53
	LTF	54.00	133.00	87.85 a	85.00	20.36	23.17
Sapwood thickness (cm)‡	LHF	2.00	7.00	3.45 a	3.00	1.22	35.43
	LTF	2.00	6.00	3.85 a	4.00	0.99	25.66
Sapwood proportion (%)†	LHF	3.80	17.10	8.00 a	7.90	3.13	39.13
	LTF	5.00	16.70	9.22 a	8.10	2.89	31.32

Heartwood thickness (cm)‡	LHF	26.00	77.00	41.59 a	40.00	11.63	27.96
	LTF	25.00	57.00	39.05 a	38.00	8.00	20.49
Heartwood proportion (%)†	LHF	82.90	96.30	92.01 a	92.10	3.14	3.41
	LTF	83.30	95.00	90.78 a	91.90	2.89	3.18
Bark thickness (mm)†	LHF	0.50	2.55	1.38 a	1.51	0.50	35.89
	LTF	0.70	2.20	1.28 a	1.19	0.44	34.58
Volume of the stem (m^3)‡	LHF	2.48	16.36	7.47 a	6.09	3.82	51.12
	LTF	3.59	16.88	7.76 a	6.45	3.48	44.84

LHF = Low hill forest; LTF = Low-terrace forest; *DBH* = Diameter at breast height; *SD* = Standard deviation; *CV* = Coefficient of variation (%). Different letters show significant differences with the Student's t-test (†) and the Mann-Whitney test (‡).

Morphic coefficient by forest type

A. leiocarpa trees in the low-terrace forest had greater *DBH*, stem height, and sapwood thickness than in the low-hill forest. Although only the stem height was statistically significant (Student's t, $p<0.01$). On the other hand, trees from the low-hill forest had a slightly greater bark and heartwood thickness than those from the low-terrace forest, although this difference was not statistically significant (Student's t, $p>0.05$) (Table 2).

Trees in the low hill forest had a significantly higher *MC*, of 0.88±0.07 (Student's t, $p<0.01$), than those in the low terrace forest, whose *MC* was 0.79±0.10, i.e., 11.4 % higher. In the low-hill forest, none of the tree variables analyzed were significantly correlated with the *MC* (Pearson, $p>0.05$). However, in the low-terrace forest, trees of smaller diameter showed a tendency to a higher *MC* because a

significant, inverse relationship between *MC* and stem diameter was found ($r=-0.47$, $p<0.05$) (Figure 2).
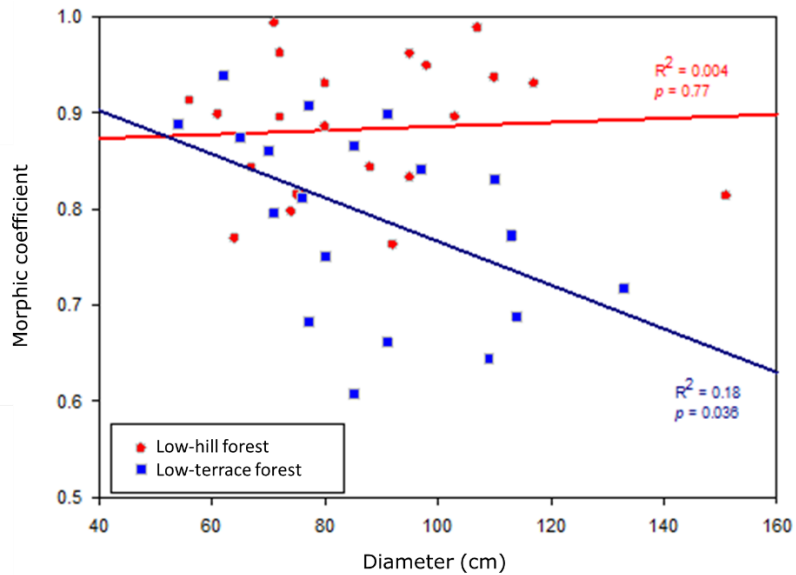

Figure 2. Scatter plot and simple linear regression line fitted to the model between tree diameter and morphic coefficient by forest type.

The ANCOVA showed that the *MC* varies significantly between the two forest types, which explains 22 % of the variability of the *MC* ($p<0.001$, Table 3). The *DBH* had no influence on the *MC* ($p>0.05$), unlike the interaction between the forest type and the diameter ($p=0.046$). This suggests that the relationship between the diameter and the *MC* varies according to the forest type, which is direct and non-significant in low-hill forest and inverse and significant in low-terrace forest (Table 3, Figure 2). The fitted regression model expressed as *MC=0.993-0.00227×DAP* was only significant for the low-terrace forest ($R^2=0.18$ y $p<0.05$).

Table 3. ANCOVA results: morphic coefficient as dependent variable, forest type as factor, and diameter at breast height (*DBH*) as covariate.

Variable	Coefficients	Sum of squares	*F*	*p*
Intercept	0.8649			
Forest type	0.1283	0.084	12.99	<0.001
DBH	0.0002	0.014	2.12	0.153
Forest type×Diameter	-0.0025	0.027	4.26	0.046

The Student' t test for one sample and $p<0.01$ showed that the *MC* averages obtained of 0.79 to 0.88, were significantly higher than the 0.65 established by the Peruvian forestry authority (Del Mar, 2021) (Figure 3), as well as to the average cited for species with cylindrical stems (Lozano and Bonilla, 2022). Compared to the *MC* of 0.82 registered for *D. odorata* —a species with similar characteristics in terms of straight cylindrical stem and with a detachment of the bark in the form of irregular plates (Lozano and Bonilla, 2022)—, this value was found to be slightly higher than that determined in the low-terrace forest ($p>0.05$) and significantly lower than that estimated in the low-hill forest ($p<0.01$) (Figure 3). Aguilar *et al.* (2017) report that variations in stem characteristics in different species influence the *MC*; in the present study, the high *MC* values are due to the fact that *A. leiocarpa* has a straight, cylindrical, irregular stem with a low reduction in diameter along the length of the stem. In addition, the growth and shape of the stem is similar to *D. odorata* which also has a high *MC*.
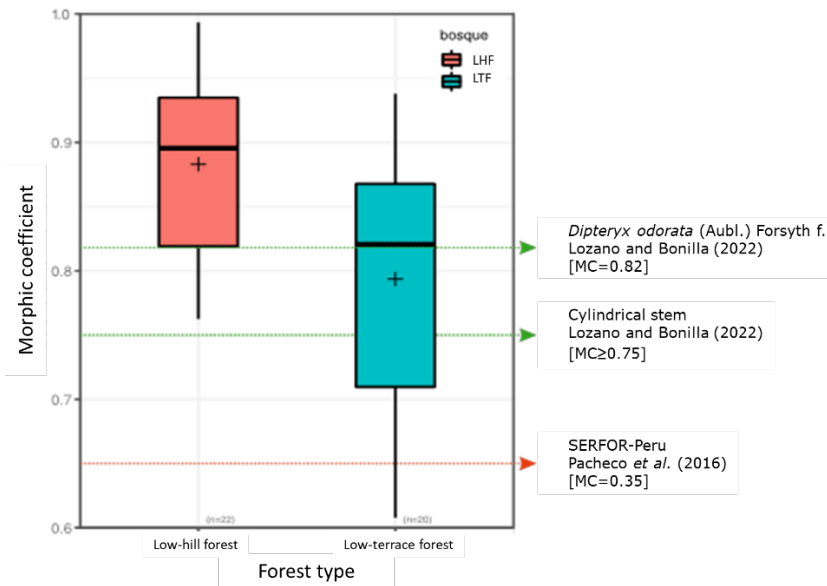
Figure 3. Comparison of the morphic coefficient of *Apuleia leiocarpa* (Vogel) J. F. Macbr. between two forest types and with reference values.

Sapwood to heartwood ratio

Non-significant differences in sapwood and heartwood thickness or sapwood to heartwood ratio were observed based on the forest type ($p<0.05$, Table 4). Stem height and bark thickness did not correlate significantly with the thickness of sapwood and heartwood or with their proportions ($p<0.05$). However, the *DBH* was significantly correlated with the proportion of sapwood, with heartwood, and with the proportion of heartwood, although this varied according to the type of forest (Table 4).

Table 4. Correlation matrix between dasometric characteristics and the thickness and proportion of sapwood and heartwood of *Apuleia leiocarpa* (Vogel) J. F. Macbr. trees by forest type.

Forest type	Height (m)	Diameter	Bark thickness (mm)	Sapwood (cm)	Sapwood ratio (%)	Heartwood (cm)
(a) Low-hill						
Diameter	-0.14¥					
Bark thickness (mm)	0.11¥	0.00¥				
Sapwood thickness (cm)	-0.13†	0.25†	0.08†			
Sapwood proportion (%)	-0.06¥	-0.40¥	0.09¥	0.78†*		
Heartwood thickness (cm)	0.04†	0.93†*	-0.14†	0.15†	-0.49†*	
Heartwood proportion (%)	0.06¥	0.40¥	-0.09¥	-0.78†	-1.00¥*	0.47†*
(b) Low-terrace						
Diameter	-0.09¥					
Bark thickness (mm)	-0.31¥	0.03¥				
Sapwood thickness (cm)	-0.03†	-0.22†	-0.03†			
Sapwood proportion (%)	0.00¥	-0.66¥*	0.10¥	0.80†*		
Heartwood thickness (cm)	-0.05¥	0.83¥*	-0.10¥	0.03†	-0.59¥*	
Heartwood ratio (%)	0.00¥	0.66¥*	-0.10¥	-0.80†*	-1.00¥*	0.59¥*

¥ = Pearson's coefficient of correlation; † = Spearman's coefficient of correlation. * = $p<0.05$.

In the low-hill forest, only a significant relationship between *DBH* and heartwood thickness was obtained (*rho*=0.93, *p*<0.05). Whereas, in the low-terrace forest, *DBH* was significantly correlated with the sapwood proportion (*r*=-0.66, *p*<0.05), the heartwood thickness (*r*= 0.83, *p*<0.05), and the proportion of heartwood (*r*=0.66, *p*<0.05). This has implications for the quality of the wood of *A. leiocarpa* according to the type of forest because, since there is a significant relationship between *DBH* and sapwood in the low-terrace forest, a greater thickness and a

higher proportion of sapwood is expected there than in the low-hill forest (Aye *et al.*, 2022).

Figure 4 shows the trend in both sapwood and heartwood thickness, as well as in the sapwood/heartwood ratio in relation to the *DBH*. It was determined that sapwood thickness is not related to *DBH* in any forest type; it was observed that heartwood thickness in both forest types increases as a function of the *DBH*, although the coefficient of determination is higher in the low-hill forest (R^2=0.86) than in the low-terrace forest (R^2=0.69). Likewise, the proportion of heartwood has a linear and direct relationship, while the proportion of sapwood has an inverse relationship. This is because the heartwood is directly related to the age and diameter of the trees, and its formation can be affected by exogenous and endogenous factors such as the density or number of trees (spacing), the crown diameter, and the content of extractive chemical compounds, among others (Kang *et al.*, 2001; Piqueras *et al.*, 2020).
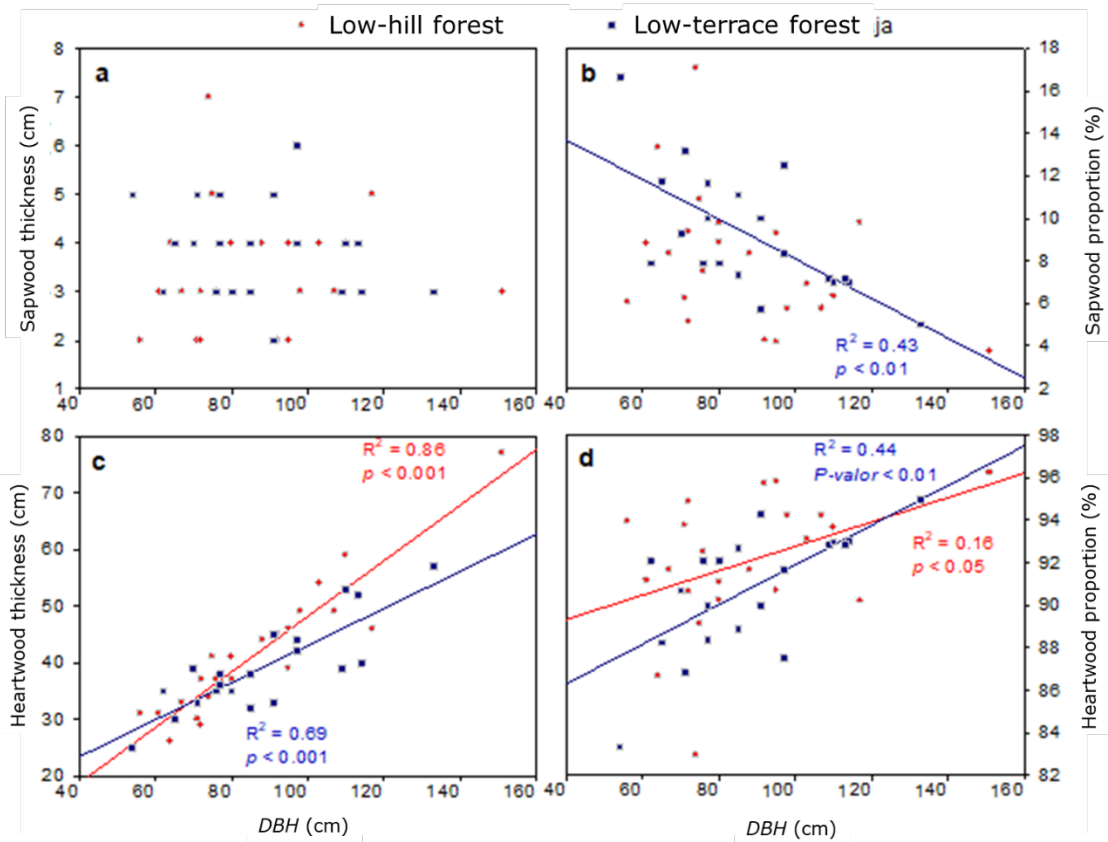
(a) = Between *DBH* with sapwood thickness; (b) = Between *DBH* with sapwood ratio; (c) = Between *DBH* with heartwood thickness; (d) = Between *DBH* with and heartwood ratio. *P-valor* <0.01 = *P*-value <0.01.

Figure 4. Scatterplot and trend by forest type.

Heartwood determines the economic value of the wood, and the sapwood is closely related to the physiological functions of the trees (Meunpong *et al.*, 2021). Therefore, it will be important for forest harvesting to estimate heartwood thickness based on easily measured variables, such as the *DBH* (Yang *et al.*, 2020). In the present study, heartwood thickness (*HT*) was found to be directly related to the *DBH*; therefore, the models generated could be used to estimate heartwood

thickness. The linear model for estimating heartwood thickness in the low-hill forest was:

$$HT = -0.86477 + 0.49056(DBH) \quad (2)$$

Where:

HT = Heartwood thickness

DBH = Diameter at breast height (m)

In the low-terrace forest, it was:

$$HT = 10.28 + 0.32749(DBH) \quad (3)$$

Where:

HT = Heartwood thickness

DBH = Diameter at breast height (m)

Forest volume estimation models

In both forest types, the 11 models fitted to estimate volume were significant ($p<0.05$) with low values for the root mean square error (of up to 0.88 in the low hill forest, and of up to <1.088 in the low-terrace forest). In the two forest types, the models that generated the lowest values of *RMSE* were Takata, Spurr, Spurr potential, and Spurr with independent term (Table 5).

Table 5. Fit, comparison, and ranking statistics of the fitted volume models for *Apuleia leiocarpa* (Vogel) J. F. Macbr. by forest type.

Model		β_0	β_1	β_2	β_3	RMSE	MSE	AIC	BIC	Rating total
				Coefficient				**Fit statistics**		
				(a) Low-hill forest						
M1	Schumacher-Hall	0.835	1.897	0.916		0.858	0.855	63.763	68.127	6
M2	Spurr	0.665				0.879	0.81	60.785	62.967	2
M3	Spurr potential	0.76	0.951			0.861	0.815	61.829	65.102	3
M4	Spurr with independent term	0.255	0.647			0.872	0.837	62.41	65.683	4
M5	Generalized composite variable	0.637	-0.029	0.649		0.868	0.873	64.23	68.594	11
M6	Honer	0.001	1.483			0.88	0.851	62.774	66.047	7
M7	Takata	1.366	0.129			0.857	0.808	61.636	64.909	1
M8	Stoate	3	-3.337	0.903	-0.207	0.846	0.875	65.083	70.538	10
M9	Ogaya	-0.0028	0.665			0.88	0.851	62.785	66.058	8
M10	Näslund	-1.469	0.58	0.344	-0.01	0.824	0.832	63.962	69.417	5
M11	Meyer	0.835	0.066	0.916		0.858	0.855	63.763	68.127	9
				(b) Low-terrace forest						
M1	Schumacher-Hall	0.608	1.706	0.973		0.965	1.095	63.323	67.306	6
M2	Spurr	0.558				1.088	1.248	64.155	66.147	7
M3	Spurr potential	0.826	0.865			0.975	1.057	61.763	64.75	3
M4	Spurr with independent term	1.144	0.49			0.964	1.034	61.317	64.304	1
M5	Generalized composite variable	0.563	0.039	0.485		0.958	1.081	63.063	67.046	4
M6	Honer	-0.009	1.94			1.085	1.308	66.015	69.002	10
M7	Takata	1.244	0.525			0.97	1.045	61.527	64.515	2
M8	Stoate	0.358	0.258	0.47	0.051	0.958	1.148	65.061	70.04	9
M9	Ogaya	0.584	0.524			1.086	1.309	66.041	69.028	11

M10 Näslund	5.428	0.393	-0.42	0.015	0.913	1.043	63.139	68.117	5
M11 Meyer	0.608	-0.24	0.973		0.965	1.095	63.323	67.306	8

RMSE = Root of the mean square error; *MSE* = Mean square error; *AIC* = Akaike information criterion; *BIC* = Bayesian information criterion.

Based on the ranking of models, it was determined that the best model for estimating forest volume in the low-hill forest was the Takata model expressed in the following form:

$$V_s = \left(DBH^2 \times \frac{H}{(1.366 + 0.129 \times DBH)}\right) \quad (4)$$

Where:

V_s = Volume of the stem

DBH = Diameter at breast height (cm)

This had the lowest total score (8 points), followed by the Spurr model (13 points) and the Spurr potential model (15 points). For the case of the low terrace forest, the best model was the Spurr model with independent term expressed as:

$$V_s = 1.144 + 0.490 DBH^2 \times H \quad (5)$$

Where:

V_s = Volume of the stem

DBH = Diameter at breast height (cm)

H = Height (m)

The same that presented the lowest value of the total rating (7 points), followed by Takata (14 points) and Spurr's potential model (18 points). These models exhibited the lowest values for *RMSE*, *AIC*, and *BIC*. The *AIC* and *BIC* criteria are widely used to select the simplest model with the greatest explanatory power in which balance is sought between the predictive capacity and the number of parameters it must have to achieve an optimal fit; these statistics reward the models as the explained variance increases but at the same time penalize them as the number of parameters increases (Nikita *et al*., 2022).

Several authors agree that the Schumacher-Hall function guarantees accurate estimates for several tropical species (Costa *et al.*, 2016; García *et al*., 2016; Tlaxcala-Méndez *et al.*, 2016; Guzmán-Santiago *et al.,* 2020). However, for *A. leiocarpa* in the two forest types analyzed, the best models for estimating forest volume were Takata and Spurr with independent terms. However, the Schumacher-Hall equation at the evaluated sites was among the six best models, in agreement with the findings of several studies (Costa *et al.*, 2016; Tlaxcala-Méndez *et al.*, 2016; Guzmán-Santiago *et al.*, 2020).

Research on specific allometric equations for volume of *A. leiocarpa* yielded similar results to that obtained in the present study. For example, Midsma (2001) in Argentina indicates that the model with the best fit was the Spurr model; in the study on the low-hill forest, it was the second best, while in the one on the low-terrace forest, the Spurr model with independent term was the best. However, Souza *et al.* (2021) determined that the Husch model was the best for the Brazilian Amazonia. These differences could be due to the fact that the study by Souza *et al.*

(2021) used models with log-transformed variables and that the *Guadua* genus is predominant in the forests where they collected their information.

When comparing the *RMSE* and *MSE* values generated by the models in each forest type, they were found to be lower in the low-hill forest. These differences are due to the different site conditions to which *A. leiocarpa* trees are subjected. In particular, for the estimation of the merchantable volume, it is important to consider that the same species has a different growth response as the site's conditions change (Molina-Valero *et al.*, 2019; Mendes *et al.*, 2020). This is reflected in the dimensions reached by the stems in each forest condition. For example, although the average *DBH* of *A. leiocarpa* stems was similar in both forests (86.55 cm in the low-hill forest, and 87.85 cm in the low-terrace forest), trees in the low-terrace forest had a higher canopy height than those in the low-hill forest. This difference is related to variations in physiography, in addition to the fact that low-hill forests are more irregular and tend to occur on steeper slopes, as opposed to low-terrace forests (Velioğlu *et al.*, 2023), potentially affecting the availability of water, a key element for growth (Rachid-Casnati *et al.*, 2019).

As for the comparison between the volume estimation carried out with the best allometric models and that obtained based on the shape factors by forest type, it was observed that, in the low-hill forest, the *RMSE* value calculated with the Takata equation, of 16.15, was lower by 16.6 % than the one estimated with the shape factor, of 19.37. While in the low-terrace forest the volume values estimated with the *MC* yielded an *RMSE* of 41.11, which is 54.7 % higher than the one obtained with the Spurr model with independent term, of 18.61. This analysis suggests that specific equations are better for calculating the volume of the stem than the use of the *MC*; furthermore, in order to minimize errors in estimating the volume of timber in each forest type, the variations in bark thickness and the thickness and proportion of sapwood and heartwood should be considered.

Among the limitations of this study, its results are restricted to only two forest conditions in the *Madre de Dios* region of Peru, affecting the generalizability of its application to other ecoregions. On the other hand, a small sample was analyzed in each forest condition due to a low density of individuals per unit area. In addition, we did not have information on a complete range of diameter categories or heights, because we only measured merchantable specimens of *A. leiocarpa*, for which forestry regulations of the Government of Peru have established a minimum cutting diameter of 41 cm for timber harvesting. These aspects, while restricting the applicability of the results, also provide insights for a deeper understanding of the form factor and promote the use of allometric models for volume estimation in the Peruvian Amazonia. In future studies, it is recommended to include more forest types in the analysis, to increase the sample size, and to use non-destructive methods in order to include individuals with *DBH* less than 40 cm.

Conclusions

The morphic coefficient of *Apuleia leiocarpa* trees growing in the *Tambopata* province, in the *Madre de Dios* region of Peru, is significantly higher in the low-hill forest (*MC*=0.88) than in the low-terrace forest (*MC*=0.79). There are no significant differences in the thickness and proportion of sapwood and heartwood between the two forest types. In the low-hill forest, there is a significant relationship only between heartwood diameter and heartwood thickness. Whereas, in the low-terrace forest, the diameter correlates significantly with the proportion of sapwood, the heartwood thickness, and the proportion of heartwood. The best allometric model

for estimating the volume varies according to the forest type, in the low-hill forest it is Takata's model, and in the low-terrace forest, Spurr's model with independent term.

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Conflict of interest

The authors declare that they have no conflict of interest.

Contribution by author

Jorge Garate-Quispe: conceptualization-ideas, data curation, formal analysis, supervision, drafting of original manuscript; Lili Florez-Castillo: conceptualization-ideas, research, methodology, visualization, drafting, revising, and proofreading the manuscript.

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