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Ecological zone-based volume estimation of *Calycophyllum spruceanum* and *Cedrelinga cateniformis* in the Northeastern Peruvian Amazon

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A B S T R A C T

Forest volume modeling plays a fundamental role in forest inventory, biomass estimation, and the sustainable management of timber resources. In the Amazon region of Peru, native species such as *Calycophyllum spruceanum* and *Cedrelinga cateniformis* hold high ecological and commercial value, yet remain understudied in terms of volumetric estimation. This study aimed to develop and evaluate volumetric models for both species across three ecological zones—humid forest, very humid forest, and dry forest—representing the environmental diversity of the northeastern Peruvian Amazon. A total of 18 volumetric models were fitted for each species and site condition using linear regression techniques. Model performance was assessed through adjusted coefficient of determination (R^2adj), root mean square error (RMSE), mean absolute error (MAE), Akaike Information Criterion (AIC), and diagnostic analyses including residual plots and relative error histograms. The results revealed that model performance varied by ecological zone, with the dry forest models showing the highest precision and lowest residual dispersion. Models M3 (Spurr), M4 (Schumacher & Hall), and M9 (Meyer) consistently achieved strong predictive accuracy. Prediction errors were higher in small-volume classes, suggesting the need for caution when applying models to young or small-diameter trees. The developed models are statistically reliable, requiring minimal input variables for the accurate estimation of the timber volume of the two species across various Amazonian environments. It is recommended to adopt zone-specific models for operational use and to continue expanding regional forest databases to improve future model calibration and validation.

1. Introduction

In recent decades, forest plantations have gained increasing importance, playing a significant role in land use and continuing to expand with the aim of producing timber for industrial purposes, restoring degraded soils, combating desertification, and capturing carbon (Prado, 2019). At present, plantations surpass native forests in global industrial wood production and offer multiple economic and social advantages. However, plantations often involve significant ecological trade-offs; for example, they tend to sustain substantially lower biodiversity compared to mature or secondary forests. Studies report that tree plantations harbor only about 66.7 % of the insect species and between 30 % and 39 % of the dung beetle species found in mature forests (Tito et al., 2022). From the perspective of the sustainable use of native forest products, it is therefore essential to promote proper management of both plantations and natural forests in the Peruvian Amazon (Pedroso, 2015; Dourojeanni, 2019; Rojas et al., 2020), thereby reducing pressure on the resources of natural forests (Mejía and Pacheco, 2013; Peirano et al.,

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2023). Volume quantification in plantations is a key indicator for forest planning, management, and valuation. However, due to the great diversity of forest species and their morphological characteristics, volume calculation remains one of the most costly and complex tasks in forest management (Hernández-Ramos et al., 2017; Vargas-Larreta et al., 2021). Therefore, the accurate determination of volume constitutes a fundamental challenge in precision forestry, which, in this context, refers to the use of species-specific models, localized data, and adapted forest management strategies to improve estimation accuracy and decision-making efficiency (De Lima et al., 2021; Sharma, 2021;Wang et al., 2022).

Over time, volume estimation in standing trees has evolved from destructive methods with high operational costs to non-invasive instruments complemented by mathematical models (García-Espinoza et al., 2019). The actual tree stem volume can be directly determined using the water displacement method, although this is largely impractical (Burkhart and Tomé, 2012). Alternatively, rigorous scaling can be employed through mathematical expressions that approximate tree shape (Soares et al., 2011), commonly using Smalian's, Huber's, and Newton's formulas (Campos and Leite, 2013), although their field application is limited.

Other scaling methods such as form factor, taper functions, and volume models have been widely used (Machado et al., 2005; Martins et al., 2017). The form factor adjusts cylindrical volume based on diameter and total height and is considered simple and illustrative (Romanh and Ramírez, 2010), although site-dependent (Chapagain and Sharma, 2021). Taper functions simplify calculations and reduce biases in diameter estimation (Cancino, 2006), but present challenges for parameter estimation and the use of commercial formulas (Kozak, 1988). Volume models offer flexibility by integrating multiple variables for more accurate and adaptable estimates across various scenarios (Picard et al., 2012; Schröder et al., 2013; Diéguez Aranda et al., 2023).

Implementing more precise production diagnostics using tools like volume models is essential for improving forest inventories and optimizing sustainable forest management (De Lima et al., 2014; Pedroso, 2015; Fernandes et al., 2017; Ramirez-Martínez et al., 2018; J.M. Revilla et al., 2021). Worldwide, allometric volume functions have shown significant advances over the past decades. Pioneering studies by Schumacher and Hall (1933) and Spurr (1952) laid the mathematical foundations for relating individual-tree variables to volume (Benavides et al., 2018; Imaña-Encinas et al., 2019; Pompa García and Solis Moreno, 2008). In regions like Europe and America, specific equations are used according to forest type and species (Fang et al., 2000; Graciano-Ávila et al., 2019; Návar et al., 2001; Tamarit Urías et al., 2013; Trincado et al., 1997).

Recent advances in forest mensuration highlight the potential of Terrestrial Laser Scanning (TLS) as a non-destructive and precise tool for estimating tree volume and biomass. Its combination with technologies such as LiDAR has demonstrated good accuracy in estimating stem volume (Kankare et al., 2013), although it presents limitations related to the overestimation of small branches due to occlusions and noise in point clouds (Demol et al., 2022). Recent studies have expanded its application in tropical and temperate forests, using TLS together with open-source software to estimate volume and biomass (Hernández-Moreno et al., 2025) and developing hybrid approaches that integrate quantitative structural models with Poisson surface reconstruction techniques to improve volume estimation in complex geometries (Ali et al., 2025).

In parallel, artificial intelligence and computer vision methods are increasingly being incorporated into forestry operations, particularly in the assessment of stacked timber. YOLOv8 models have been successfully applied to detect and count stacked eucalyptus logs (Casas et al., 2023), while hybrid approaches combining deep learning-based detection with diameter distribution models have achieved accurate estimates of solid wood volume (Casas et al., 2024). Together, these advances demonstrate a growing synergy between TLS and artificial intelligence approaches, offering practical and scalable tools to strengthen precision forestry and improve forest volume modeling in tropical regions such as the Amazon.

In Peru, research on forest modeling in the Amazon has mainly focused on the estimation of growth, biomass, and carbon capture (J.M. Revilla-Chávez et al., 2021; Revilla-Chávez et al., 2024; Chave et al., 2014; Baluarte-Vásquez and Alvarez-Gonzales, 2015), while studies specifically dedicated to tree volume remain scarce. The few existing contributions are limited to localized areas and a small number of species, such as *Cedrelinga cateniformis* (Otárola-Acevedo and Linares-Bensimón, 2002), *Guazuma crinita* (Guerra et al., 2008), and *Swietenia macrophylla* (Romero, 2017; Escobar, 2018). More recently, models have been developed for *Guazuma crinita* and *Apuleia leiocarpa* (J.M. Revilla et al., 2021). However, an integrated effort to calibrate volume models across different ecological zones and to establish species-specific equations for other Amazonian trees of commercial and ecological importance has not yet been undertaken, leaving a critical gap for forest management in Peru.

Calycophyllum spruceanum (Benth.) Hook.f. ex and *Cedrelinga cateniformis* (Ducke) Ducke are Amazonian species locally known as “capirona” and “tornillo,” respectively. These species are notable for their high wood quality, adaptability, and productivity (Otárola-Acevedo and Linares-Bensimón, 2002; Lombard et al., 2008; Ugarte and Domínguez, 2010; Baluarte-Vásquez and Alvarez-Gonzales, 2015; Cruz et al., 2020; Haag et al., 2020; Cardenas-Rengifo et al., 2024; Murga-Orrillo et al., 2024). *Calycophyllum spruceanum* is a pioneer species that colonizes alluvial plains and disturbed forests, reaching heights of up to 35 m and breast height diameters of up to 1.8 m at maturity (Guerra-Arévalo et al., 2025; Saldaña et al., 2021; Weber and Montes, 2005). In turn, *Cedrelinga cateniformis* is a promising species for Amazonian reforestation, growing between 25 and 40 m tall with diameters of up to 2 m (Baluarte-Vásquez and Alvarez-Gonzales, 2015; Cardenas-Rengifo et al., 2024).

In recent years, the production of roundwood from natural forests in Peru has significantly declined. For *Calycophyllum spruceanum*, production dropped by 72.51 %, from 93,896 m^3 to 25,816 m^3, while for *Cedrelinga cateniformis*, the reduction was 37.02 %, falling from 183,106 m^3 to 115,318 m^3 over the same period (DGFFS, 2014; SERFOR, 2024). This downturn reflects the impact of excessive reliance on natural forests and underscores the need to strengthen sustainable management strategies such as the establishment of forest plantations (CEPLAN, 2023). However, national demand for wood products continues to grow and is primarily met through imports (FAO, 2018; SERFOR, 2024).

The use of allometric volume functions is a valuable tool in countries with vast forest resources like Peru, where the economic potential of native species represents a strategic asset for the development of the forestry sector and the growing demand for wood products (Cuellar and Reyes, 2016). The absence of species-specific equations can lead to inaccurate volume estimates, highlighting the need to develop ecological zone-specific models with broad applicability and precise estimations that ensure sustainable use (Segura and Kanninen, 2005; Fearnside et al., 2020; Aryal et al., 2023).

This study was conducted with the aim of modeling commercial timber volume for two ecologically and economically important Amazonian species—*Calycophyllum spruceanum* and *Cedrelinga cateniformis*—by developing and validating volumetric equations across representative ecological zones of the northeastern Peruvian Amazon, including very humid forest, humid forest and dry forest environments.

2. Materials and methods

2.1. Study area

The study was conducted in 18 plots established in the northeastern Amazon region of Peru, these plots are distributed across the departments of Loreto, San Martín, and Ucayali, belonging to the National Institute for Agricultural Innovation (Agricultural Experimental Stations of San Roque, El Porvenir, and Pucallpa), as well as private forestry producers. These plots span multiples life zones, representative sampling of Amazonian Forest types (Holdridge, 1967).

In Loreto, the plots are located primarily within the very humid forest (bmh) life zones (Fig. 1), characterized by a mean annual biotemperature between 22 and 24 °C and high annual precipitation ranging from 4500 to 5500 mm. Soil in this region is typically deep, acidic, and low in fertility (Fig. 1). The vegetation is classified as evergreen rainforest. Additionally, some plots are in humid forest (bh) life zones, where the mean annual biotemperature ranges from 23.2 to 25.7 °C and precipitation varies between 1916 and 3419.5 mm. The terrain is predominantly undulating to hilly with deep, acidic soils composed of kaolinitic clays, and the characteristic vegetation is tall forest (Aybar and Lavado, 2017; ONERN, 1994).

In San Martín, the plots were established in both very humid forest (bmh) and dry forest (bs) life zones (Fig. 1). These areas exhibit a where the mean annual biotemperature ranges from 23.9 to 25.1 °C, with annual precipitation between 1020 and 1391 mm. The topography terrain varies from gently sloping to steep hills, with deep, clayey, and calcareous soils. The typical vegetation includes tall forest species, both evergreen and deciduous (Aybar and Lavado, 2017; ONERN, 1994).

In Ucayali, the plots are situated in the humid forest (bh) life zone (Aybar and Lavado, 2017; ONERN, 1994) (Fig. 1). The area exhibits a diverse relief, comprising three main landscapes units: alluvial plains, hilly terrain and mountain regions (Mateo et al., 2006).

The plantations varied both in spacing and establishment method, encompassing three modalities: forest stand, agroforestry system, and living fence, with areas ranging from 0.09 to 1.26 ha (Table 1). The plantations were established at different times using botanical seed material collected from trees located in surrounding natural forests (Cruz et al., 2020).

The *Calycophyllum spruceanum* individuals ranged in age from 3.2 to 19.0 years, while *Cedrelinga cateniformis* specimens showed an age range of 9.4 to 35.1 years. Plantation density exhibited wide variation between species and systems, fluctuating between 73 and 1250 individuals ha^{-1} for *Calycophyllum spruceanum* and between 46 and 892 individuals ha^{-1} for *Cedrelinga cateniformis*. Likewise, basal area showed marked heterogeneity, with values ranging from 0.9311 to 8.9179 m^2 ha^{-1} for *Calycophyllum spruceanum* and from 1.9353 to 51.0460 m^2 ha^{-1} for *Cedrelinga cateniformis*. These differences reflect the influence of factors such as plantation age, initial spacing, and the edaphic and environmental conditions of the evaluated sites.

2.2. Data collection

A 100 % forest inventory was conducted to ensure the representativeness of diverse site conditions, including variations in site quality, age, and plantation density (Ercanli et al., 2014). The study encompassed a total of 902 trees, of which 369 corresponded to *Calycophyllum spruceanum* and 533 to *Cedrelinga cateniformis* (Table 1).

Field measurements were carried out between October 2022 and October 2024, following the methodology proposed by Basely-Villanueva et al. (2025). The diameter at breast height (DBH; 1.3 m above the ground) was measured using a diameter tape. Additionally, diameters were recorded at 0.3 m, 0.5 m, and 1.0 m above ground level using the same device. For diameters above DBH, a laser dendrometer (Criterion™ RD1000, laser technology, USA) was used (Kim and Lee, 2016; Martins et al., 2017; García-Espinoza et al., 2019; Flores Morales

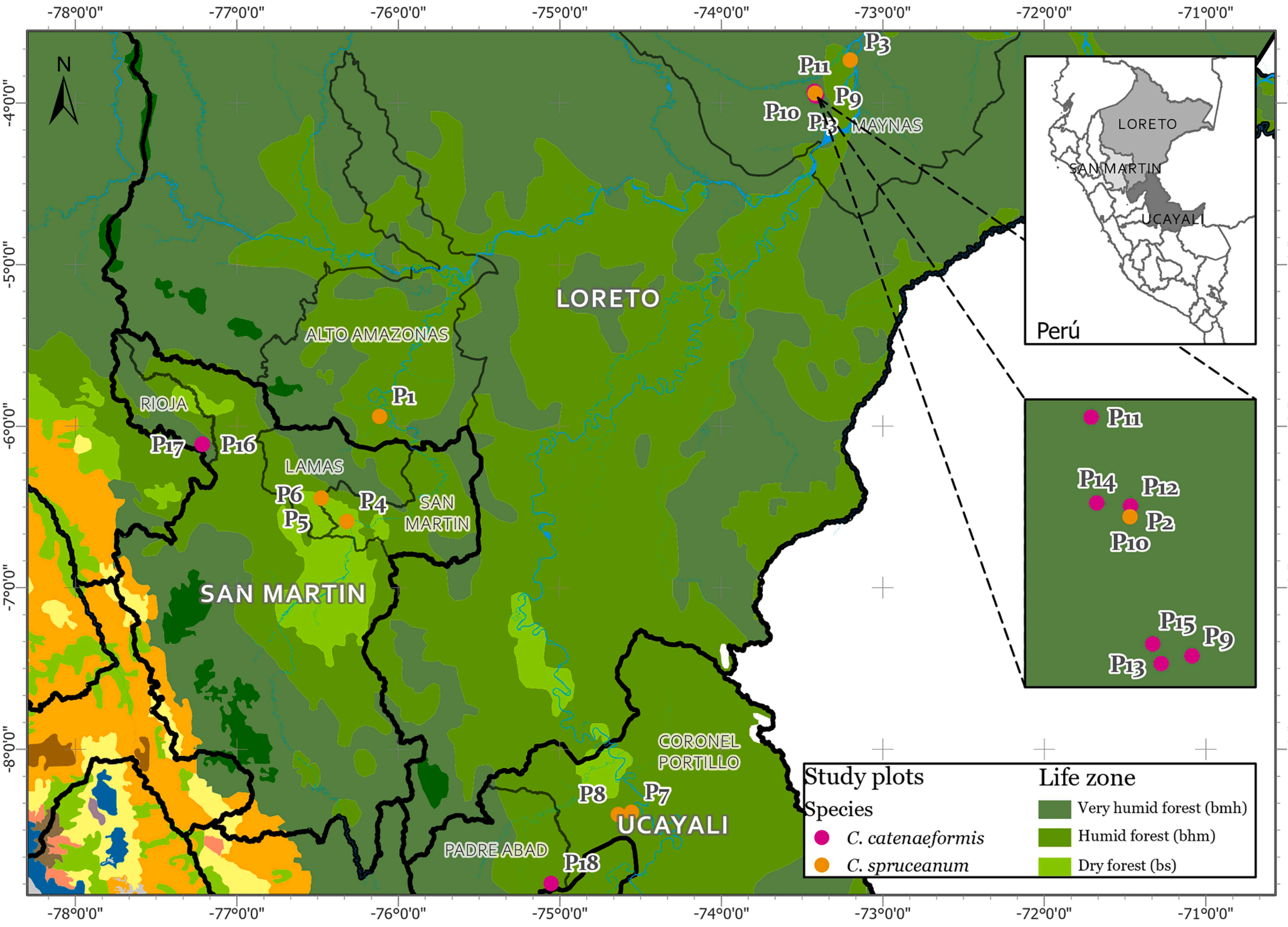

Fig. 1. Geographic location of the 18 study plots in the northeastern Peruvian Amazon.

Table 1
Description of the study plots located in the departments of Loreto, San Martín, and Ucayali.

Plot	Species	Type of plantation (spacing)	Associated with crops	Plantation area (ha)	Age (years)	Density (individuals ha^{-1})	Individuals evaluated (N)	Basal area (m^2 ha^{-1})	DBH range (cm)	Commercial height range (m)	Life zone
P1	*Calycophyllum spruceanum*	Forest massif (4 × 4 m)	-	0.40	5,1	625	60	2.0326	9–16,8	3–8	bh
P2	*Calycophyllum spruceanum*	Agroforestry System (15 × 5 m)	*C. cateniformis*-*Virola* sp-*Theobroma cacao*	1.00	10,6	73	67	1.4285	8,1–28,6	4–16	bmh
P3	*Calycophyllum spruceanum*	Forest massif (3.5 × 3.5 m)	-	0.30	3,2	816	26	0.9311	8–18,5	4–10	bh
P4	*Calycophyllum spruceanum*	Agroforestry System (5 × 5 m)	*Theobroma cacao*	0.25	10,7	400	60	4.0893	9,5–20,5	5–11,3	bs
P5	*Calycophyllum spruceanum*	Forest massif (2.9 × 3 m)	-	0.50	10,8	1150	80	3.6594	12,4–23,8	6–14	bs
P6	*Calycophyllum spruceanum*	Agroforestry System (2 × 6 m)	*Theobroma cacao*	0.50	10,8	833	30	1.3311	12,7–19,6	8–14	bs
P7	*Calycophyllum spruceanum*	Forest massif (3 × 3 m)	-	0.37	15,0	1111	24	1.5743	8,5–25,5	3–12	bh
P8	*Calycophyllum spruceanum*	Forest massif (3 × 3 m)	-	0.09	19,0	1111	22	8.9179	13–31,9	5–9	bh
P9	*Cedrelinga cateniformis*	Living Fence (5 m)	-	0.35	28,3	84	62	41.3520	15,5–109,6	8–24	bmh
P10	*Cedrelinga cateniformis*	Agroforestry System (15 × 5 m)	*C. spruceanum*-*Virola* sp-*Theobroma cacao*	1.00	10,6	97	96	4.4201	8,7–39,6	3,5–14,5	bmh
P11	*Cedrelinga cateniformis*	Agroforestry System (12 × 8 m)	*Bertholletia excelsa*	0.54	24,4	78	40	15.2692	21,9–85,6	10,5–26,9	bmh
P12	*Cedrelinga cateniformis*	Forest massif (5 × 5 m)	*Centrosema macrocarpum*	0.09	9,6	480	44	14.5478	8,4–29,8	3,5–10,3	bmh
P13	*Cedrelinga cateniformis*	Agroforestry System (10 × 10 m)	*Theobroma grandiflorum*	0.40	28,4	162	40	11.5169	17,1–68,3	7–16	bmh
P14	*Cedrelinga cateniformis*	Agroforestry System (35 × 5 m)	*Citrus* sp	1.26	19,3	46	50	7.0695	19,6–72,3	9–21	bmh
P15	*Cedrelinga cateniformis*	Agroforestry System (2.7 × 2.7 m)	*Piper nigrum*	0.27	35,1	330	88	51.0460	12,4–96,9	6–24	bmh
P16	*Cedrelinga cateniformis*	Forest massif (4 × 4 m)	-	1.00	35,0	454	24	2.7362	30,2–52,2	12–18	bmh
P17	*Cedrelinga cateniformis*	Forest massif (3.5 × 3.5 m)	-	0.50	9,4	892	43	1.9353	13,2–21,3	6–12	bh
P18	*Cedrelinga cateniformis*	Agroforestry System (10 × 10 m)	*Theobroma cacao*	0.57	25	100	46	12.1841	18,6–68,8	4–12	bmh

Note: Plots 1, 2, 3, 9, 10, 11, 12, 13, 14 and 15 are located in the department of Loreto; plots 4, 5, 6, 16, and 17 are located in the department of San Martín; and plots 7, 8 and 18 are situated in the department of Ucayali.

et al., 2021; Aryal et al., 2024).

The spacing of remote measurements along the stem varied according to tree size:

- For trees with DBH < 15 cm, measurements were taken every 1 m
- For trees with DBH between 15 and 30 cm, every 2 m
- For trees with DBH > 30 cm, every 3 m

Measurements continued up to a section with a diameter equal to or greater than 5 cm, a threshold commonly adopted in tropical dendrometry to define the commercial wood volume and exclude fine branches with minimal yield (Cysneiros et al., 2020). Reports from tropical forests have shown that volume estimates tend to stabilize in branches with diameters greater than 5 cm, whereas smaller segments introduce greater variability and error (Takoudjou et al., 2017). The commercial height (H) was defined as the height of the last measurable stem section, while total height (TH) corresponds to the top of the tree.

The individual stem volume was estimated by applying Smalian's formula to each section. The commercial volume (V) of each tree was calculated as the sum of all partial volumes along the stem up to the minimum usable diameter (Schröder et al., 2013; Pedroso, 2015; Ramos et al., 2018; Monárrez-González et al., 2024).

The sampled individuals of *Calycophyllum spruceanum* exhibited DBH values ranging from 8.00 to 31.90 cm, H ranging from 3.00 to 16.00 m, and TH between 6.70 and 25.54 m; likewise, V fluctuated between 0.0150 and 0.9730 m^3 (Table 1). In turn, the individuals of *Cedrelinga cateniformis* showed DBH values ranging from 8.40 to 109.60 cm, H between 3.50 and 26.87 m, and TH varying from 5.20 to 42.10 m; similarly, V ranged from 0.0180 to 10.9670 m^3.

Structurally, *Calycophyllum spruceanum* exhibited relatively uniform growth, characteristic of young plantations, with a homogeneous distribution of sizes and heights. In contrast, *Cedrelinga cateniformis* displayed greater structural heterogeneity, reflected in the wide variability of its dendrometric dimensions; this pattern suggests the presence of individuals at different stages of development.

2.3. Models analyzed

To estimate the commercial volume of trees (V), allometric volume functions were employed using (DBH), commercial height (H), and total height (TH) as potential explanatory variables. These variables have been widely used in previous studies due to their strong correlation with stem volume. Linear and multiple models, recognized for their effectiveness in various forestry contexts, were considered. (Table 2)

2.5. Statistical analysis

Data verification was carried out through an exploratory graphical analysis (Supplementary 1), following the recommendations of Zuur et al. (2010) and Fonsêca et al. (2021). The behavior of accumulated commercial volume in relation to different commercial heights was analyzed, as well as the relationship between relative diameter (d/DBH) and relative height (h/H), according to the approaches proposed by Özçelik & Göçeri (2015), Tang et al. (2016), Gómez-García et al. (2016), Martins et al. (2017), and Flores Morales et al. (2021). The data showed no evidence of outliers in either of the two analyzed species and presented consistent and expected trends in both relationships.

The volume prediction models were fitted using linear regressions with the "*lm*" function of R Project v4.4.1 (R Core Team, 2024), implemented through the caret package (Kuhn et al., 2024). To ensure model robustness, stability, and generalization, a 10-fold cross-validation scheme ($k = 10$) was applied, defined using the "*trainControl()*" function of the same package with the option method = "cv", which allowed the dataset to be randomly divided into ten subsets of equal size. In each iteration, nine subsets were used for model training and the remaining one for validation, rotating this process until all subsets had been used as test data (Gonzalez-Benecke et al., 2022; Da Rocha et al., 2023).

The application of this method allowed for a more objective evaluation of the model's predictive capacity, reducing dependence on a single validation set and minimizing the risk of overfitting. This approach is consistent with recent studies in forest modeling, where cross-validation has been established as a fundamental tool for estimating the accuracy and stability of allometric volume functions (Aló et al., 2024; Diamantopoulou et al., 2025). Thus, a more reliable estimation of the average prediction error was obtained, reinforcing the statistical consistency of the generated models (Tian et al., 2022).

The correct division of data into the different cross-validation subsets (folds) was verified using scatter plots (Supplementary 2), which represent the relationship between CV and the variables DBH, TH and slenderness index (TH/DBH). The observed patterns show a homogeneous distribution of the folds, with no evidence of bias or irregular clustering, confirming an appropriate random allocation of observations among partitions. This proper stratification of the data supports the reliability of the cross-validation process and ensures an objective and reproducible evaluation of model performance.

The overall significance of each model was assessed using the F-test ($p \leq 0.05$), while the individual significance of the parameters was determined using *t*-tests ($p \leq 0.05$). Model performance was evaluated using the adjusted coefficient of determination (R^2adj), the root mean square error (RMSE), the mean absolute error (MAE), the Akaike information criterion (AIC) and relative error (RE (%)) (Table 3). Additionally, residual plot analysis was conducted to verify the homogeneity of variances and detect any systematic patterns (Ercanli et al., 2014; Kora et al., 2018; Xu et al., 2022; Mulatu et al., 2024). All graphs were generated in R using the *ggplot2* package (Wickham, 2016).

Table 2
Allometric volume functions fitted for estimating the commercial tree volume of *C. spruceanum* and *C. cateniformis*.

Model	Functions	Reference	Structure
M1	$V = \beta_0 + \beta_1 DBH + \varepsilon$	Berkhout (1920)	Linear
M2	$\ln(V) = \beta_0 + \beta_1 \ln(DBH) + \varepsilon$	Husch et al.(1972)	Logarithmic
M3	$\ln(V) = \beta_0 + \beta_1 \ln(DBH^2 \cdot H) + \varepsilon$	Spurr (1952)	Logarithmic
M4	$\ln(V) = \beta_0 + \beta_1 \ln(DBH) + \beta_2 \ln(H) + \varepsilon$	Schumacher & Hall (1933)	Logarithmic
M5	$V = \beta_0 + \beta_1 DBH^2 + \varepsilon$	Kopezky- Gehrhardt	Quadratic linear
M6	$V = \beta_0 + \beta_1 DBH + \beta_2 DBH^2 + \varepsilon$	Hohenald-Krenn	Quadratic
M7	$V = \beta_0 + \beta_1 (DBH^2 \cdot H) + \varepsilon$	Spurr (1952)	Quadratic
M8	$V = \beta_0 + \beta_1 DBH^2 + \beta_2 H + \beta3(DBH^2 \cdot H) + \varepsilon$	Stoate (1945)	Cubic
M9	$V = \beta_0 + \beta_1 DBH^2 + \beta_2 (DBH \cdot H) + \beta3(DBH^2 \cdot H) + \varepsilon$	Meyer (1938)	Cubic
M10	$V/DBH^2 = \beta_0 + \beta_1 (1/DBH^2) + \varepsilon$	Otárola-Acevedo y Linares-Bensimón (2002)	Inverse
M11	$V/DBH^2 = \beta_0 + \beta_1 (1/DBH^2) + \beta_2 (1/DBH) + \varepsilon$	Otárola-Acevedo y Linares-Bensimón (2002)	Inverse
M12	$V/DBH^2 \cdot H = \beta_0 + \beta_1 (1/DBH^2 \cdot H) + \beta_2 (1/H) + \beta_3 (1/DBH^2) + \varepsilon$	Otárola-Acevedo y Linares-Bensimón (2002)	Inverse
M13	$V/DBH^2 \cdot H = \beta_0 + \beta_1 (1/DBH^2 \cdot H) + \beta_2 (1/H) + \beta_3 (1/DBH) + \varepsilon$	Otárola-Acevedo y Linares-Bensimón (2002)	Inverse
M14	$V/DBH^2 = \beta0 + \beta1(1/DBH^2) + \beta2(H/DBH^2) + \beta3H + \varepsilon$	Otárola-Acevedo y Linares-Bensimón (2002)	Inverse
M15	$V/DBH^2 = \beta_0 + \beta_1 (1/DBH^2) + \beta_2 (H/DBH) + \beta_3 H + \varepsilon$	Otárola-Acevedo y Linares-Bensimón (2002)	Inverse
M16	$V/DBH^2 H = \beta_0 + \beta_1 (1/DBH^2 H)$	Otárola-Acevedo y Linares-Bensimón (2002)	Inverse
M17	$V = \beta_0 + \beta_1 DBH + \beta_2 \cdot DBH^2 + \beta_3 DBH \cdot TH + \varepsilon$	Meyer (1941)	Quadratic polynomial
M18	$V = \beta_0 + \beta_1 DBH^2 \cdot TH + \beta_2 DBH^2 + \varepsilon$	Prodan et al.(1997)	Quadratic polynomial

Where: β₀, β₁, β₂, and β₃ are the model parameters, V is the commercial volume (m^3), DBH is the diameter at breast height (cm), H is the commercial height (m), and TH is the total height (m), "ln" denotes the natural logarithm, and ε is the random error.

3. Results

The parameter estimates and statistical performance of 18 volumetric models fitted for *Calycophyllum spruceanum* and *Cedrelinga cateniformis* across different ecological zones of the northeastern Peruvian Amazon are presented in the appendix (Supplementary 3 and Supplementary 4).

In the Very Humid Forest, for *Calycophyllum spruceanum*, models M1, M2, M3, M4, M5, M7, M10, M11, M16, and M17 showed statistically significant parameters ($p < 0.05$), while M6, M8, M9, M12, M13, M14, M15, and M18 exhibited one or more non-significant parameters,

Table 3
Statistical indicators for evaluating the goodness-of-fit of the allometric volume functions.

Number	Description	Equation
1	Adjusted coefficient of determination (R^2adj)	$\mathrm{Radj}^2 = 1 - \left[\left(\frac{n-1}{n-k-1}\right)\right] * \left[1 - \frac{\sum_{t=1}^{T} (\widehat{Y}_t - \overline{Y})^2}{\sum_{t=1}^{T} (Y_t - \overline{Y})^2}\right]$
2	Root mean square error (RMSE)	$\mathrm{RMSE} = \left[\frac{\sum_{i=1}^{n} (y_i - \widehat{y})^2}{n-p}\right]^{0.5}$
3	Mean Absolute Error (MAE)	$\mathrm{MAE} = \frac{1}{n} \sum_{i=1}^{n} \lvert Y_i - \widehat{Y_l} \rvert$
4	Akaike Information Criterion (AIC)	$\mathrm{AIC} = n\ln\left[\sum_{i=1}^{n} (Y_i - \widehat{Y_l})^2 / n\right] + 2p$
5	Relative Error (%)	$\mathrm{RE} = \frac{(\widehat{Y}_i - Y_i)}{Y_i} \times 100$

Where: Y_i are the observed values, $\widehat{Y}_i$ are the predicted values, n is the number of observations, p is the number of model parameters, and ln denotes the natural logarithm.

indicating lower statistical robustness (Supplementary 3). Among the models with significant parameters, M3, M7, and M16 stood out for their superior performance, with adjusted R^2 values between 0.970 and 0.973, low RMSE (0.016–0.017 m^3), reduced MAE (0.010–0.011 m^3), and minimal AIC (–356.300 to –350.391).

These models incorporate DBH and H, either through their product or implicitly via logarithmic and inverse transformations, which notably enhance the predictive capacity of volume. In contrast, models M1, M5, and M10, although with significant parameters, showed lower fit (adjusted R^2 between 0.869 and 0.924) and higher errors (RMSE from 0.027 to 0.036 m^3). These results indicate that simple models based solely on DBH underestimate volume variability compared to those that include height. In summary, for *Calycophyllum spruceanum*, models M3, M7, and M16 are the most accurate and stable in very humid forest conditions.

In the case of *Cedrelinga cateniformis*, models M1, M2, M3, M4, M5, M6, M7, M10, M11, M16, and M17 were statistically significant ($p < 0.05$), while M8, M9, M12, M13, M14, M15, and M18 did not show complete significance in their parameters (Supplementary 4). Among the significant models, the best-performing ones were M3, M4, and M16, with adjusted R^2 values between 0.959 and 0.968, RMSE ranging from 0.241 to 0.273 m^3, MAE from 0.130 to 0.156 m^3, and low AIC values (0.305 to 131.222). These models also simultaneously incorporate DBH and H, which increases their accuracy by capturing the structural variability of the trees. Conversely, models M1, M5, and M10 showed the lowest performance (adjusted R^2 from 0.827 to 0.929), exhibiting high residual dispersion and low predictive capacity due to their reliance solely on DBH. Overall, for *Cedrelinga cateniformis*, models M3, M4, and M16 stand out as the most accurate and parsimonious for volume estimation in very humid forests.

In the case of humid forests, for *Calycophyllum spruceanum*, models M1, M2, M3, M4, M5, M6, M7, M10, M11, M16, and M17 showed statistically significant parameters ($p < 0.05$). Among these, models M4, M6, and M17 presented the best indicators, with adjusted R^2 values ranging from 0.952 to 0.971, low RMSE (0.029–0.038 m^3), MAE between 0.018 and 0.023 m^3, and the lowest AIC values (–484.434 to –550.591). These models exhibit logarithmic, quadratic, and polynomial structures that integrate both DBH and H, which enhances their predictive capacity by more comprehensively representing tree structure. In contrast, models M1, M7, and M16, although statistically significant, showed the lowest performance, with adjusted R^2 values between 0.880 and 0.916 and higher RMSE (0.050–0.060 m^3). These models have linear or inverse structures, based solely on DBH or partial combinations of this parameter.

For *Cedrelinga cateniformis*, models M1, M2, M3, M4, M7, M9, and M16 presented statistically significant parameters ($p < 0.05$), while the remaining models included one or more non-significant coefficients (Supplementary 4). Among the models with significant parameters, the best-performing ones were M3, M4, and M9, with adjusted R^2 values of 0.884, 0.881, and 0.905, respectively. These models also showed low RMSE (0.011–0.012 m^3), MAE between 0.008 and 0.009 m^3, and reduced AIC values (–263.113 to –253.361). On the other hand, models M1, M2, and M16, which included DBH as the sole predictor variable, showed the lowest fit, with adjusted R^2 ranging from 0.624 to 0.878 and higher AIC values (–252.497 to –203.980).

In summary, the models that incorporate DBH and H as predictor variables and exhibit non-linear structures (logarithmic, quadratic, or polynomial) provided the best indicators of fit and accuracy. Therefore, models M4, M6, and M17 are recommended for estimating the volume of *Calycophyllum spruceanum*, while M3, M4, and M9 are the most suitable for *Cedrelinga cateniformis* under humid forest conditions. These models combine statistical robustness, biological consistency, and parsimony.

In the Amazonian dry forests, for *Calycophyllum spruceanum*, models M1, M2, M3, M4, M5, M7, M10, M11, M16, M17, and M18 showed statistically significant parameters ($p < 0.05$), while the remaining models included one or more non-significant coefficients (Supplementary 3). Among the models with significant parameters, the best-performing ones were M3, M4, and M7, which achieved the highest adjusted R^2 values (0.985–0.986), along with the lowest RMSE (0.008 m^3), MAE (0.005–0.006 m^3), and AIC (–1146.91 to –1136.03). Similarly, these models integrate both DBH and total height (TH), either through their product or via logarithmic transformations. In contrast, models M1, M2, and M11 showed inferior performance.

Overall, the results indicate that under Amazonian dry forest conditions, models M3, M4, and M7 provide the most accurate and consistent volume estimates for *Calycophyllum spruceanum*, standing out for their high statistical significance, low error, and appropriate balance between complexity and parsimony.

At the scale of the entire Northeastern Peruvian Amazon, for *Calycophyllum spruceanum*, models M1, M2, M3, M4, M5, M6, M10, M11, and M17 presented highly significant coefficients ($p < 0.05$). Additionally, some models such as M8, M9, and M18 showed acceptable statistical performance, although they included at least one non-significant parameter (Supplementary 3). Model M4 showed the best statistical performance, with an adjusted R^2 of 0.915, the lowest RMSE (0.036 m^3), and an AIC of –1407.342, indicating excellent predictive capacity. It was followed by models M3 and M17, which also showed strong fits (adjusted R^2 of 0.864) and low RMSE values (0.045 m^3 in both cases). On the other hand, models M1, M6, and M11 showed more modest performance, with lower adjusted R^2 values (0.791, 0.756, and 0.821, respectively) and higher prediction errors (RMSE between 0.052 and 0.060 m^3).

For *Cedrelinga cateniformis*, models M1, M2, M3, M4, M5, M6, M7, M10, M11, M16, and M17 presented highly significant coefficients ($p < 0.05$). Among them, model M4 stood out, with the highest adjusted R^2 (0.969), the lowest RMSE (0.231 m^3), and an AIC of –45.748, indicating excellent fitting capacity (Supplementary 4). Models M3 and M16 also showed excellent performance (adjusted R^2 of 0.961 and 0.960, respectively; RMSE of 0.262 and 0.263 m^3), consolidating themselves as robust options for volume estimation. In contrast, models M1, M5, and M10 obtained moderate results, with adjusted R^2 between 0.826 and 0.930, high RMSE values (0.348 to 0.551 m^3), and positive AIC values (between 425.366 and 952.779), reflecting lower accuracy in the estimates.

In summary, the models with the best statistical performance varied by species. For *Calycophyllum spruceanum*, models M3, M4, M6, M7, M16, and M17 show great potential for volume estimation. On the other hand, for *Cedrelinga cateniformis*, models M3, M4, M9, and M16 were the most robust. These differences in performance reflect the structural variability between species and highlight the importance of selecting species-specific allometric volume functions according to the morphological and ecological characteristics of each species within the northeastern Peruvian Amazon.

Fig. 2 shows the distribution of relative errors (RE %) between the observed and predicted volumes of *Calycophyllum spruceanum* across the three evaluated ecological zones: very humid forest, humid forest, dry forest, and the northeastern Peruvian Amazon.

In the very humid forest, models M3, M7, and M16 showed error distributions centered around zero; however, model M3 exhibited the least dispersion and the narrowest clustering of residuals, indicating an almost negligible bias and excellent statistical calibration. In models M7 and M16, a slight positive dispersion was observed in smaller volumes, suggesting a mild overestimation in trees of smaller dimensions.

In the humid forest, models M4, M6, and M17 exhibited more variable residual behavior (Fig. 2). Model M4 showed a more homogeneous distribution of errors, with residuals evenly spread across almost the entire prediction range. Model M6 showed a slight tendency to underestimate at lower volumes and a mild overestimation at higher volumes, whereas model M17 was characterized by a stronger overestimation in trees of smaller volume and a wider spread of residuals.

In the dry forest, models M3, M4, and M7 showed the best residual

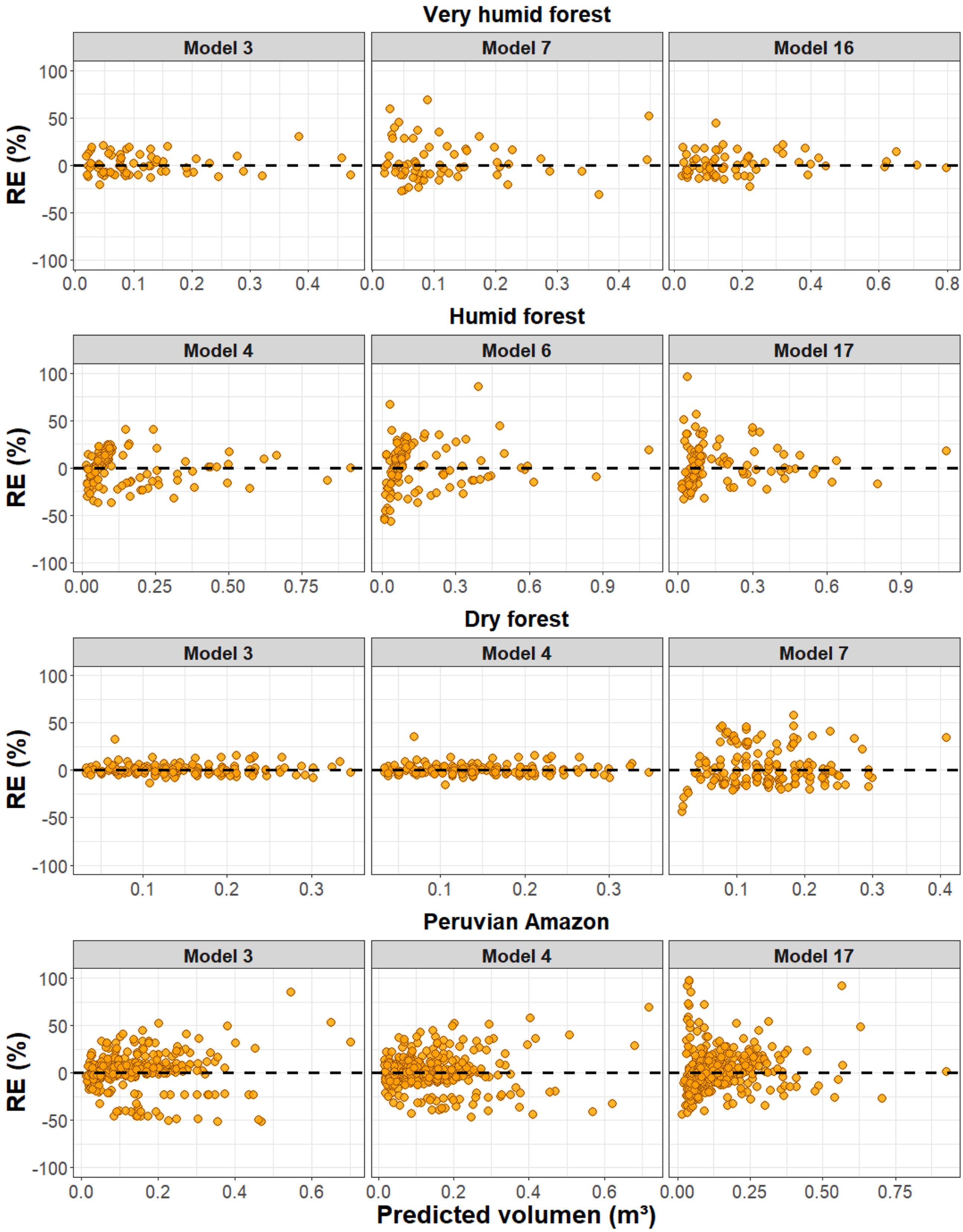

Fig. 2. Relative error (%) of the predicted commercial volume for *Calycophyllum spruceanum* using selected volumetric models across the ecological zones of the northeastern Peruvian Amazon. The black dashed line indicates the zero-error reference.

performance among all life zones (Fig. 4). The residuals clustered tightly around the zero line, with no apparent bias and minimal dispersion, indicating precise calibration and the absence of heteroscedasticity. However, models M3 and M4 demonstrated the best residual performance across all analyzed ecological zones; both presented residuals tightly grouped around the zero line, with minimal dispersion and no systematic bias.

In the northeastern Peruvian Amazon (Fig. 4), models M3, M4, and M17 showed differences in the distribution of relative errors (RE %). Model M4 exhibited the best residual dispersion, evidencing homoscedasticity. Model M3 also displayed balanced behavior, with low variability and absence of systematic bias. In contrast, model M17 showed greater error dispersion, mainly in trees with smaller volumes, with a slight tendency toward overestimation.

Fig. 3 shows the distribution of relative error classes (RE %) for the predicted commercial volume of *Calycophyllum spruceanum*, grouped by volumetric model and life zone. Each histogram allows the evaluation of model accuracy and bias by analyzing the concentration, symmetry, and spread of error classes around the zero value.

In the very humid forest, models M3, M7, and M16 exhibited relatively symmetrical error distributions centered around zero. Model M16 showed the most concentrated and narrow distribution, while model M3 also performed well, with most errors clustered around zero and a slight dispersion toward negative values, suggesting a mild tendency to underestimation. In contrast, model M7 showed a wider spread in error classes.

In the humid forest, models M4, M6, and M17 displayed well-concentrated and predominantly symmetrical distributions. Model M4 stood out for its narrower distribution around zero, although it showed a slight tendency toward underestimation. Meanwhile, model M6 exhibited slightly greater dispersion, with a tail extending toward negative values, indicating a tendency to underestimate. Model M17, on the other hand, showed greater variability and a more pronounced trend toward overestimation.

In the dry forest, models M3 and M4 showed highly concentrated and symmetrical distributions, with mean RE values very close to zero, reflecting excellent predictive precision and the absence of systematic bias under dry conditions. In contrast, model M7 presented a slight right-skewed asymmetry, indicating a tendency to overestimate volumes.

Across the entire Amazonian region, models M3, M4, and M17 exhibited concentrated and symmetrical error distributions, with mean RE values close to zero. Model M3 was the most consistent, showing the narrowest and most centered distribution, indicating excellent predictive capacity and the absence of systematic bias. Model M4 also maintained strong performance, with high accuracy and a slight tendency toward overestimation. Finally, model M17 showed a greater number of error classes and a tendency toward overestimation, suggesting lower relative accuracy and wider variability in predictions under Peruvian Amazon conditions.

Overall, the residual analysis confirms that models M3 (Spurr, 1952), M4 (Schumacher and Hall, 1933), and M16 (Otárola-Acevedo and Linares-Bensimón, 2002) exhibited the best residual distribution (Figs. 2 and 3), demonstrating high precision, statistical consistency, and the absence of systematic bias across the evaluated life zones.

Fig. 4 shows the distribution of relative errors (RE %) between the observed and predicted commercial volumes of *Cedrelinga cateniformis* in two ecological zones (very humid forest and humid forest) and across the Peruvian Amazon as a whole.

In the very humid forest, models M3, M4, and M16 showed moderate dispersion of RE %, with ranges reflecting appreciable variability in the predictions (Fig. 4). Model M4 stood out for presenting a more symmetrical and compact distribution of residuals around the zero line, suggesting greater stability and lower systematic bias. In contrast, models M3 and M16 showed slightly higher dispersion, with alternating tendencies of overestimation and underestimation in smaller volumes, probably associated with stem morphological heterogeneity and the architecture of smaller individuals.

In the humid forest, models M3, M4, and M9 showed errors tightly clustered around zero, reflecting consistent and balanced predictions (Fig. 4). However, model M9 showed the best residual dispersion, with a more compact and uniform error distribution. The generally low level of dispersion suggests that these models are properly calibrated for humid forest conditions, maintaining minimal bias across the full range of predicted volumes.

Across the Peruvian Amazon, models M3, M4, and M16 showed residual amplitudes reaching approximately ±50 % (Fig. 4). Model M4 stood out for its best overall performance, with lower dispersion and greater uniformity of errors. Models M3 and M16 showed similar behavior, although with a slight tendency toward both overestimation and underestimation in smaller volumes.

Fig. 5 shows the distribution of relative error classes (RE %) for the predicted commercial volume of *Calycophyllum spruceanum*, grouped by volumetric model and life zone. The histograms allow the evaluation of model accuracy, dispersion, and bias through the concentration and symmetry of errors relative to the zero value.

In the very humid forest, models M3, M4, and M16 presented narrow error distributions centered around zero, reflecting good predictive performance under high-humidity conditions (Fig. 5). Model M4 stood out for having the fewest error classes, with a strongly concentrated distribution around zero, indicating high precision and minimal systematic bias.

Model M3 showed similar behavior, although with slight asymmetry toward negative values, suggesting a mild tendency toward underestimation. Meanwhile, model M16 showed somewhat greater dispersion and fewer observations in the central error classes.

In the humid forest, models M3, M4, and M9 exhibited concentrated and symmetrical error distributions, with mean RE values close to zero (Fig. 5). Model M9 stood out for having the largest proportion of errors grouped around zero, demonstrating very high precision and making it the most accurate model under humid forest conditions. Model M4 also showed a narrow and concentrated distribution around zero, with a reduced number of error classes, while model M3 exhibited slight dispersion toward negative values.

Across the Amazonian region as a whole, models M3, M4, and M16 showed narrow and centered distributions, with mean RE values very close to zero (Fig. 5). Model M4 exhibited the highest overall precision, with the most concentrated distribution around zero, indicating high predictive stability and the absence of systematic bias. Model M3 maintained a slight tendency toward underestimation but preserved good symmetry and concentration. In contrast, model M16 showed greater dispersion and a lower concentration of observations in the central classes.

Overall, the residual analysis confirms that models M4 (Schumacher and Hall, 1933) and M9 (Meyer, 1938) presented the best distributions of relative errors (RE %) (Figs. 4 and 5), demonstrating high precision, statistical stability, and the absence of systematic bias across the evaluated ecological zones. Both models showed residuals centered around the zero-error line, with reduced dispersion and adequate symmetry, reflecting robust calibration and consistent predictive behavior under contrasting environmental conditions.

Table 4 presents a comprehensive selection of the optimal allometric volume functions used to estimate the commercial wood volume of *Calycophyllum spruceanum* and *Cedrelinga cateniformis* across the main ecological zones of the northeastern Peruvian Amazon: very humid, humid, and dry forests. In addition, general models applicable to all ecological zones are included. The selection of models was based on validation performance criteria—adjusted R^2, RMSE, MAE, AIC, and graphical validation of model fit and error distribution—ensuring both statistical rigor and biological consistency.

The selected models reflect the distinctive allometric behavior of each species under different site conditions, highlighting the importance

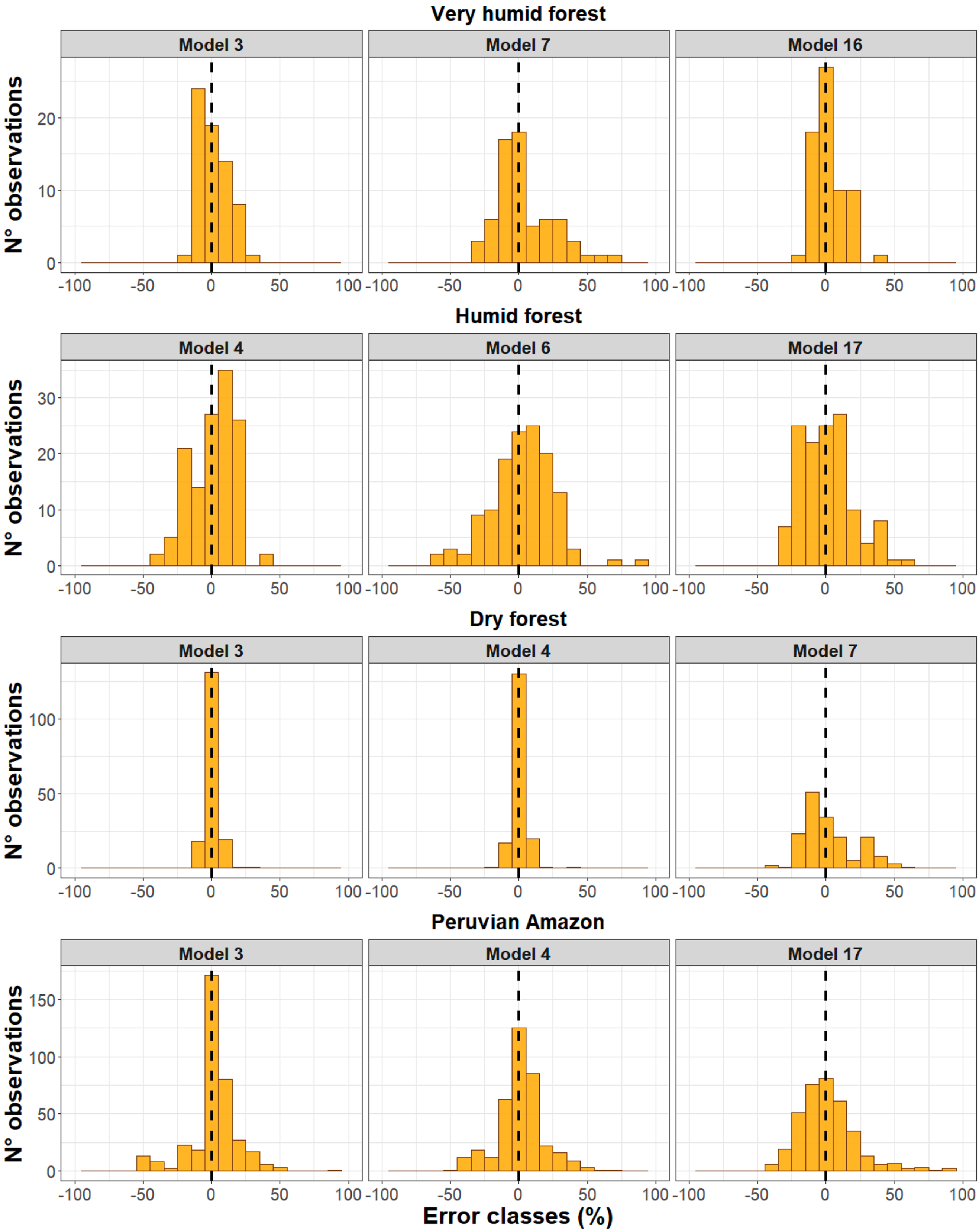

Fig. 3. Histogram of relative error (%) classes for *Calycophyllum spruceanum* across selected volumetric models across the ecological zones of the northeastern Peruvian Amazon. The black dashed line represents the mean error for each model-zone combination, allowing for the evaluation of bias direction (overestimation or underestimation).

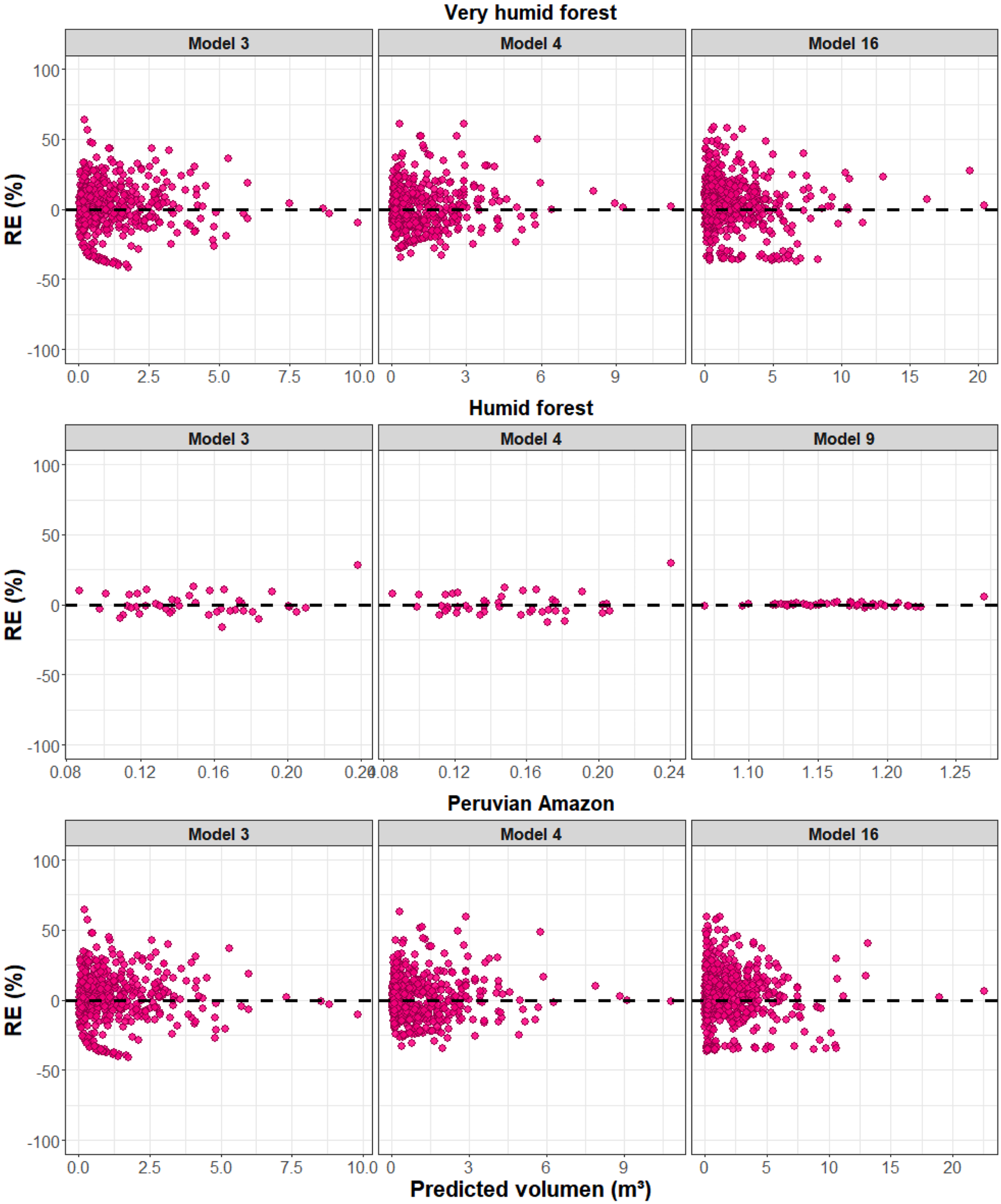

Fig. 4. Relative error (%) of predicted commercial volume for *Cedrelinga cateniformis* using selected volumetric models across the ecological zones of the northeastern Peruvian Amazon. The black dashed line represents the zero-error reference.

of applying zone-specific models to improve accuracy in operational forest inventories. These results reaffirm the efficiency and robustness of equations that jointly integrate DBH and H as explanatory variables in the estimation of commercial volume for both species. Likewise, the stability observed in logarithmic and polynomial models suggests an optimal balance between parsimony, biological coherence, and predictive capacity, supporting their practical applicability across different ecological conditions of the northeastern Peruvian Amazon. Overall,

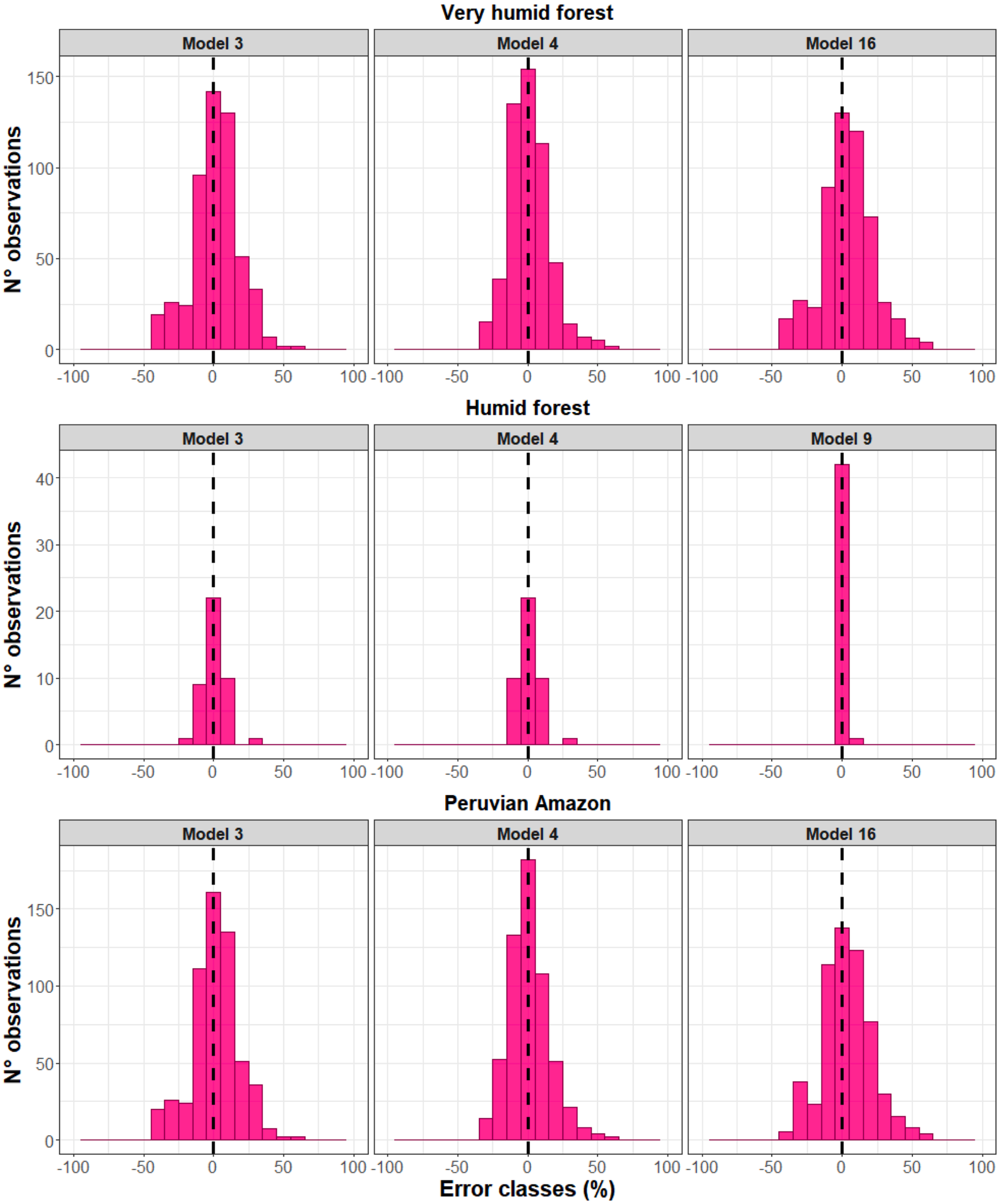

Fig. 5. Histogram of relative error classes (%) for *Cedrelinga cateniformis* across selected volumetric models across the ecological zones of the northeastern Peruvian Amazon. Each histogram represents the frequency of error classes, with the black dashed line indicating the mean relative error.

these models are consolidated as the most reliable tools for volumetric estimation and sustainable forest planning for both species in the Amazon region.

4. Discussion

The modeling results show clear variations in the accuracy of volume prediction across different ecological zones and between the two

Table 4
Optimal Volume Prediction Models for *Calycophyllum spruceanum* and *Cedrelinga cateniformis* Across Ecological Zones in the Northeastern Peruvian Amazon.

Ecological Zones	Species	Selected Model	Autor	Equation	R^2adj	RMSE (m^3)	MAE (m^3)	AIC	Comments
Very humid forest	*Calycophyllum spruceanum*	M3	Spurr (1952)	$\ln(V) = -9.032069 + 0.880930 \ln(DBH^2 \cdot H)$	0.973	0.016	0.010	−356.300	High accuracy, minimal dispersion.
	Cedrelinga cateniformis	M4	Schumacher & Hall (1933)	$\ln(V) = -9.460639 + 2.133552 \ln(DBH) + 0.608036 \ln(H)$	0.968	0.241	0.13	0.305	Robust across diameters and heights.
Humid forest	*Calycophyllum spruceanum*	M4	Schumacher & Hall (1933)	$\ln(V) = -10.871691 + 2.732059 \ln(DBH) + 0.643270 \ln(H)$	0.967	0.031	0.020	−534.923	Excellent fit, minimal bias.
	Cedrelinga cateniformis	M9	Meyer (1938)	$V = -0.163979 + 0.000660\ DBH^2 + 0.002349\ (DBH \cdot H) - 0.000092\ (DBH^2 \cdot H)$	0.905	0.011	0.008	−263.113	Consistently accurate for humid zones.
Dry forest	*Calycophyllum spruceanum*	M4	Schumacher & Hall (1933)	$\ln(V) = -9.331172 + 1.865511 \ln(DBH) + 0.964244 \ln(H)$	0.986	0.008	0.005	−1146.906	Exceptional precision in dry zones.
Northeastern Peruvian Amazon	*Calycophyllum spruceanum*	M3	Spurr (1952)	$\ln(V) = -9.716166 + 0.995075 \ln(DBH^2 \cdot H)$	0.864	0.045	0.026	−1234.546	Generalized robust model.
	Cedrelinga cateniformis	M4	Schumacher & Hall (1933)	$\ln(V) = -9.352060 + 2.084338 \ln(DBH) + 0.637998 \ln(H)$	0.969	0.231	0.12	−45.748	Highly reliable for general use.

R^2adj = Adjusted coefficient of determination; RMSE= Root mean square error; MAE = Mean Absolute Error; AIC = Akaike Information Criterion.

analyzed species. In general terms, the models achieved their best performance in the dry forest, where the highest precision and the narrowest residual distribution were obtained. In this more arid zone, several models—particularly M3, M4, and M7—achieved almost identical and outstanding fits (adjusted R^2 ~0.986; RMSE ~0.008 m^3; MAE ~0.005 m^3) for *Calycophyllum spruceanum*. These results reflect a very high predictive capacity under more homogeneous and water-limited conditions, where an allometric relationship based on the product D^2H or on the logarithmic combination of DBH and H captures stem volume with great accuracy (Chave et al., 2005; Schumacher and Hall, 1933).

By contrast, in humid and very humid forests, prediction errors were slightly higher and more variable, especially in smaller trees, suggesting greater heterogeneity in growth forms in resource-rich environments. Even so, the best models in these zones maintained high precision. In the very humid forest for *Calycophyllum spruceanum*, for example, models M3, M7, and M16 achieved adjusted R^2 values between 0.970 and 0.973, with low RMSE (0.016–0.017 m^3) and reduced MAE (0.010–0.011 m^3), reflecting robust performance despite ecological complexity (Segura and Kanninen, 2005; van der Sande et al., 2024).

Regarding the species, clearly differentiated modeling behaviors were observed. *Calycophyllum spruceanum* consistently showed higher R^2 values and lower errors than *Cedrelinga cateniformis* under similar ecological conditions. In the very humid forest, the most accurate equation for *Calycophyllum spruceanum* explained 97.3 % (M3) of the variance in volume, while for *Cedrelinga cateniformis* the best model explained 96.8 % (M4). In the humid forest, *Calycophyllum spruceanum* maintained an equally solid performance (adjusted R^2 = 96.7 %, M4), compared to 90.5 % obtained by *Cedrelinga cateniformis* (M9). These differences reflect intrinsic allometric divergences between both species (Henry et al., 2011; Chave et al., 2014). The straighter and more cylindrical stem of *Calycophyllum spruceanum*, characteristic of fast-growing pioneer species (Finegan et al., 2015; Lombardi et al., 2008), favors the prediction of volume based on diameter and height. In contrast, the greater morphological variability of *Cedrelinga cateniformis* introduces higher residual dispersion. Previous studies in Loreto reported an adjusted R^2 close to 81 % for *Cedrelinga cateniformis* (Otárola-Acevedo and Linares-Bensimón, 2002), a value comparable to that observed in this study, confirming its more variable volumetric structure. Meanwhile, *Calycophyllum spruceanum* maintains statistical superiority attributable to its regular morphology and high form factor (Lombardi et al., 2008), which explains the high accuracy of its volumetric models.

Several studies on tropical forest species have confirmed the outstanding performance of the classical models of Spurr (1952), Schumacher & Hall (1933), and Meyer (1938) in estimating commercial volume, corroborating the findings of this study. The M3 (Spurr) model has shown a high explanatory capacity across various timber species. Research has reported adjusted R^2 values ranging from 0.81 to 0.98 when applying this function (Corral-Rivas and Návar-Cháidez, 2009; Imaña-Encinas et al., 2019), results very similar to those obtained for *Calycophyllum spruceanum* (adjusted R^2 = 0.973). The strength of the Spurr model lies in its functional simplicity: the inclusion of the $DBH^2 \cdot H$ product in a general logarithmic form efficiently summarizes stem volume by integrating both the cross-sectional area and the vertical dimension of the tree.

The M4 (Schumacher & Hall) model, which employs separate logarithmic variables for DBH and H, also showed robust performance in the present study. Several works have demonstrated that this function outperforms other volumetric models, providing reliable and precise estimates of stem volume, with adjusted R^2 values between 0.96 and 0.99 (Ramos-Uvilla et al., 2014; Monárrez-González et al., 2024). These results are comparable to those obtained here for both species, whose models reached adjusted R^2 values between 0.967 and 0.986. Conceptually more flexible, the Schumacher & Hall model allows capturing the independent influence of diameter and height on volume, reducing heteroscedasticity and improving the stability of errors.

The M9 model (Meyer, 1938), a multiple polynomial model, incorporates quadratic terms and interactions between DBH and H, making it more adaptable to species with irregular stems. Studies conducted in Brazil reported adjusted R^2 values between 0.94 and 0.99 (Medeiros, 2018), results close to those obtained for *Cedrelinga cateniformis* in the humid forest (adjusted R^2 = 0.905). Although polynomial models generally present greater residual dispersion, they are particularly useful for representing nonlinear curvature in the relationship between diameter and height. In this context, the Meyer model complements the predictive efficiency of logarithmic equations, providing a more detailed description of volumetric variability in species with diverse morphology.

The inclusion of DBH together with H substantially improves accuracy in the estimation of merchantable volume. This combination has a clear ecological basis: height reflects growth strategies, competition for light, and site conditions, integrating variation in stem form and taper—factors that DBH alone cannot represent (Picard et al., 2012). In this study, models based solely on DBH showed lower coefficients of determination, while those incorporating both DBH and H achieved higher values across most zones and species, confirming that the inclusion of height reduces residual variability and enhances the stability of volumetric predictions.

These results are consistent with previous findings in various tropical regions. In the Peruvian Amazon, Otárola-Acevedo and Linares-Bensimón (2002) identified the $DBH^2 \cdot H$ model as the most accurate for estimating the volume of *Cedrelinga cateniformis*. Similarly, Segura and Kanninen (2005) demonstrated in the rainforests of Costa Rica that the inclusion of total height significantly increases the R^2 of volume and biomass models. Likewise, Picard et al. (2012) emphasized that the combined use of diameter and height improves the flexibility and accuracy of allometric equations by better capturing the geometric relationships that determine stem volume. At the pantropical level, Feldpausch et al. (2012) and Chave et al. (2014) showed that explicitly modeling height reduces uncertainty in estimating tree size and volume. More recently, Peña et al. (2025) demonstrated that stem taper, and consequently total volume, is predicted more accurately when height and forest type are incorporated along with DBH. Taken together, both the results of this study and those reported in the literature agree that models combining diameter and total height offer greater accuracy, biological consistency, and statistical robustness, establishing themselves as the most reliable basis for volumetric modeling in Amazonian species.

On the other hand, the slight decrease in adjusted R^2 from zone-specific models (average 0.960) to the general model for the entire Amazon (average 0.917) reinforces the advantage of local calibration (Henry et al., 2011; Molto et al., 2013): a universal equation sacrifices part of its precision in favor of generality. This pattern was evident in *Calycophyllum spruceanum*, which reached the highest values in the dry forest (adjusted $R^2 = 0.986$) and the very humid forest (adjusted $R^2 = 0.973$), while the lowest fits were recorded for the entire northeastern Amazon (adjusted $R^2 = 0.864$). Overall, the average of the specific models confirms a high predictive power and excellent fit among ecological zones, in contrast with the slight loss of precision in the general model.

From a biological perspective, these findings suggest that trees of the same species follow slightly different allometric trajectories under varying climatic and edaphic conditions. In dry forests, trees tend to allocate their growth toward more robust diameters relative to height, making volume estimation more predictable; whereas in humid forests, greater height growth and resource abundance introduce higher variability in form. This result has direct practical implications, as it validates the strategy of employing zone-specific models to improve the accuracy of merchantable volume estimation, an essential aspect in sustainable forest management planning (Feldpausch et al., 2012).

Our models, particularly the best-performing ones, such as M3, M4, and M9, offer statistically robust and cost-effective tools for forest inventories across different Amazonian environments. Consequently, the operational use of equations specific to both ecological zone and species is recommended rather than a single generic model. Thus, for *Calycophyllum spruceanum*, model M3 is suggested for very humid zones, and model M4 for humid and dry forests; while for *Cedrelinga cateniformis*, model M4 is recommended for the very humid forest and model M9 for the humid forest. This differentiated application ensures that volume estimates reflect the local allometry of each species and zone, improving inventory precision and the reliability of forest growth and yield assessments. This adapted approach aligns with broader calls to develop zone-specific allometric volume functions in support of sustainable forest management.

Finally, the evaluated models demonstrated strong statistical performance and biological consistency, and their successful calibration across different Amazonian ecoregions represents a step forward toward precision forestry in Peru. Nevertheless, several limitations must be acknowledged. First, crown parameters were not included, which could improve model accuracy in future studies. Second, the sampled trees come exclusively from plantations, meaning that natural forest populations, which display greater morphological variability, have not yet been assessed. Third, although rigorous field protocols were applied, the possibility of species identification errors or silvicultural inconsistencies cannot be completely ruled out, introducing additional sources of uncertainty. Therefore, future research should expand the regional database by incorporating more sites, a wider range of diameters and ages (including larger trees), and greater ecological diversity. Moreover, emerging techniques such as artificial intelligence—for example, recent advances in total height estimation for *Guazuma crinita* (Casas et al., 2022; De Oliveira et al., 2021)—could complement these efforts, opening new opportunities to enhance the precision and applicability of forest volume modeling.

5. Conclusions

This study successfully established robust volumetric models specifically calibrated for *Calycophyllum spruceanum* and *Cedrelinga cateniformis* across distinct ecological zones within the northeastern Peruvian Amazon, highlighting important ecological and species-specific variations:

1. Very humid forest: The models developed for this zone showed high accuracy and low residual variability. In *Calycophyllum spruceanum*, model M3 (Spurr, 1952) achieved an adjusted R^2 of 0.973, while in *Cedrelinga cateniformis*, model M4 (Schumacher and Hall, 1933) obtained an adjusted R^2 of 0.968, confirming their excellent performance under high-humidity conditions.
2. Humid forest: Models M4 and M9 were the most accurate for *Calycophyllum spruceanum* and *Cedrelinga cateniformis*, respectively. In the first species, model M4 (Schumacher and Hall, 1933) explained 96.7 % of the variance, while the M9 model, a multiple polynomial type, achieved an adjusted R^2 of 0.905 in *Cedrelinga cateniformis*, reflecting greater structural variability in this species.
3. Dry forest: Model M4 (Schumacher and Hall, 1933) for *Calycophyllum spruceanum* showed an outstanding fit (R^2adj = 0.986), demonstrating the high stability of allometric relationships in environments with lower structural heterogeneity
4. Models M3 and M4 proved to be remarkably robust across a variety of ecological conditions, presenting stable and consistent predictions for both species. The inclusion of log-squared terms effectively accounted for variability in tree shape, making it suitable for broader applications, particularly in developing generalized regional allometric volume functions.
5. Models based solely on diameter (e.g., M1 and M2) consistently underperformed compared to more complex equations. Although simpler and operationally convenient, these models showed increased error dispersion and reduced predictive precision, particularly evident in very humid and Amazon-wide analyses.
6. Significant prediction errors were consistently observed in smaller volume classes, especially for trees with predicted volumes below 0.1 m^3. This highlights a critical limitation and suggests caution when applying these models to young or small-diameter trees, indicating the need for further refinement or separate modeling for early developmental stages.
7. *Calycophyllum spruceanum* exhibited consistently better models fit compared to *Cedrelinga cateniformis*, likely due to its more uniform and cylindrical stem morphology. *Cedrelinga cateniformis* showed greater variability in stem form, reinforcing the necessity of species-specific equations to achieve accurate volume estimations.
8. For practical and accurate forest inventory applications, zone- and species-specific models are recommended. Specifically, the use of models M3 and M4 for *Calycophyllum spruceanum* and models M4 or M9 for *Cedrelinga cateniformis*, depending on ecological zones, will significantly improve the precision of commercial volume estimations.

CRediT authorship contribution statement

Christian Koch Duarte: Writing – original draft, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization. **Carlos Francisco del Aguila Piña:** Writing – review & editing, Visualization, Formal analysis, Data curation. **Andrés-Fernández Sandoval:** Writing – review & editing, Investigation, Data curation. **Gloria Patricia Cárdenas-Rengifo:** Writing – review & editing, Visualization, Data curation. **Manuel Dante Santillán Gonzales:** Writing – review & editing, Resources, Project administration, Investigation, Funding acquisition. **Evelin Judith Salazar Hinostroza:** Writing – review & editing, Visualization, Project administration, Investigation, Data curation. **Fernando Castedo-Dorado:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Pedro Álvarez-Álvarez:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Gianmarco Goycochea Casas:** Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Juan Rodrigo Baselly-Villanueva:** Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2025.101085.

Data availability

Data will be made available on request.

References

Ali, M., Lohani, B., Hollaus, M., Pfeifer, N., 2025. A hybrid approach for enhanced tree volume estimation of complex trees using terrestrial LiDAR. GIsci Remote Sens. 62 (1). https://doi.org/10.1080/15481603.2025.2474836.

Aló, L.L., le Maire, G., Thiersch, C.R., et al., 2024. Mapping stem volume in fast-growing eucalypt plantations: integrating spectral, textural, and temporal remote sensing information with forest inventories and spatial models. Ann. For. Sci. 81, 43. https://doi.org/10.1186/s13595-024-01255-6.

Aryal, K.R., Chapagain, T.R., Basukala, R.K., Khadka, S., Chaudhary, G., Budha, R.K., Adhikari, H., Khatri, D.J., Aryal, U., Sharma, R.P., 2023. Allometric tree volume models for *Pinus roxberghii* and *Cedrus deodara* in Karnali Province, Nepal. For. Ecol. Manag. 546, 121364. https://doi.org/10.1016/j.foreco.2023.121364.

Aryal, K.R., Mahatara, D., Basukala, R.K., Khadka, S., Dhakal, S., Bhattarai, S., Adhikari, H., Khatri, D.J., Sharma, R.P., 2024. Modeling tree stem volume for hill *shorea robusta* gaertn. Forests in Karnali Province, Nepal. Trees For. People 18, 100675. https://doi.org/10.1016/j.tfp.2024.100675.

Aybar, C., & Lavado, W. (2017). *Atlas de zonas de vida del Perú - Guía explicativa*. SENAMHI Recuper de https://idesep.senamhi.gob.pe/geonetwork/srv/spa/catalog.search#/metadata/8266683e-dc79-413e-bbd2-aca640b1f1e8.

Baluarte-Vásquez, J.R., & Alvarez-Gonzales, J.G. (2015). Modelamiento del crecimiento de tornillo *Cedrelinga cateniformis* Ducke en plantaciones en Jenaro Herrera, departamento de Loreto, Perú 24 (1): 21–32. https://doi.org/10.24841/fa.v24i1.57.

Baselly-Villanueva, J.R., Fernández-Sandoval, A., Salazar-Hinostroza, E.J., Cárdenas-Rengifo, G.P., Puerta, R., Trigoso, T.S.C., Rufasto-Peralta, Y.L., Vallejos-Torres, G., Casas, G.G., Araújo Junior, C.A., Quiñónez-Barraza, G., Álvarez-Álvarez, P., Leite, H. G., 2025. MultiProduct optimization of *cedrelinga cateniformis* (Ducke) ducke in different plantation systems in the Peruvian Amazon. Forests 16 (1), 164. https://doi.org/10.3390/f16010164.

Benavides, J.de D., Rueda, A., Flores, J., Orozco, G., Goméz, D., 2018. Ecuaciones De Volumen para Plantaciones Forestales Ecuaciones De Volumen Para Plantaciones Forestales Comerciales De Teca (tectona grandis L.F), 1st ed., 2. en Jalisco y Nayarit (A. y P. Instituto Nacional de Investigaciones Forestales.

Berkhout, A.H., 1920. Het meten der boomen in verband met hun aanwas. Meded Landbouwhogesch Wagening 17, 109–225. https://library.wur.nl/WebQuery/wurpubs/fulltext/298143.

Burkhart, H.E., Tomé, M., 2012. Modeling Forest Trees and Stands. Springer, Berlin, p. 457. https://doi.org/10.1007/978-90-481-3170-9.

Campos, J.C.C., Leite, H.G., 2013. Mensuração florestal: Perguntas e Respostas. UFV, p. 605, 4 ed.

Cancino, J.O.C., 2006. Dendrometría Básica. Universidad de Concepción, p. 171.

Cardenas-Rengifo, G.P., Baselly-Villanueva, J.R., Chumbimune-Vivanco, S.Y., Macedo-Ramírez, A.T., Salazar, E., Minaya, B., Quintana, S., Cabudivo, A., Palma, S.A.S., Álvarez-Álvarez, P., Ocaña-Reyes, J.A., 2024. Using acoustic tomography to model wood deterioration in *Cedrelinga cateniformis* Ducke in the Peruvian Amazon. Forests 15 (5), 778. https://doi.org/10.3390/f15050778.

Casas, G.G., Ismail, Z.H., Limeira, M.M.C., da Silva, A.A.L., Leite, H.G., 2023. Automatic detection and counting of stacked eucalypt timber using the YOLOv8 model. Forests 14 (12), 2369. https://doi.org/10.3390/f14122369.

Casas, G.G., Ismail, Z.H., Limeira, M.M.C., Soares, C.P.B., Gleriani, J.M., Binoti, D.H.B., Araújo Júnior, C.A., Shapiai, M.I., Rodrigues, L.I., Araújo, T.M., Leite, H.G., 2024. Quantifying solid volume of stacked eucalypt timber using detection-segmentation and diameter distribution models. Smart Agric. Technol. 9, 100653. https://doi.org/10.1016/j.atech.2024.100653.

Casas, G.G., Gonzáles, D.G.E., Villanueva, J.R.B., Fardin, L.P., Leite, H.G., 2022. Configuration of the deep neural network hyperparameters for the hypsometric modeling of the Guazuma crinita Mart. in the Peruvian Amazon. Forests 13, 697. https://doi.org/10.3390/f13050697.

Centro Nacional de Planeamiento Estratégico (CEPLAN). (2023). El Sector Forestal En El Perú: Propuestas Estratégicas Para Fortalecer su Desarrollo. Recuperado de https://cdn.www.gob.pe/uploads/document/file/5605664/4973838-ceplan-el-sector-forestal-en-el-peru.pdf.

Chapagain, T.R., Sharma, R.P., 2021. Modeling form factors for sal (Shorea robusta Gaertn.) using tree and stand measures, and random effects. For. Ecol. Manage. 482, 118807. https://doi.org/10.1016/j.foreco.2020.118807.

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.-P, Nelson, B.W., Ogawa, H., Puig, H., Riéra, B., Yamakura, T., 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145 (1), 87–99. https://doi.org/10.1007/s00442-005-0100-x.

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B.C., Duque, A., Eid, T., Fearnside, P.M., Goodman, R.C., Henry, M., Martínez-Yrízar, A., Mugasha, W.A., Muller-Landau, H.C., Mencuccini, M., Nelson, B.W., Ngomanda, A., Nogueira, E.M., Ortiz-Malavassi, E., Pélissier, R., Ploton, P., Ryan, C.M., Saldarriaga, J.G., Vieilledent, G., 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. Glob. Chang. Biol. 20 (10), 3177–3190. https://doi.org/10.1111/gcb.12629.

Corral-Rivas, S., Návar-Cháidez, J.de J., 2009. Comparación de técnicas de estimación de volumen fustal total para cinco especies de pino de durango, México. Rev. Chapingo ser cienc for ambiente 15 (1), 5–13.

Cruz, W., Saldaña, C., Ramos, H., Baselly, R., Loli, J.C., Cuellar, E., 2020. Estructura y diversidad genética de poblaciones naturales de *Cedrelinga cateniformis* "tornillo" en la región oriental del Perú. Sci. Agropecu 11 (4), 521–528. https://doi.org/10.17268/sci.agropecu.2020.04.07.

Cuellar, B.J.E., & Reyes, I.P. (2016). ¿Es la capirona *Calicophyllum spruceanum* una opción rentable para la promoción de plantaciones forestales en la Amazonia? Artículo Aprobado En El Congreso Nacional Forestal CONAFOR (2016) Lima – Perú. https://repositorio.inia.gob.pe/bitstream/20.500.12955/364/1/Cuellar-capirona.pdf.

Cysneiros, V.C., Gaui, T.D., Silveira Filho, T.B., Pelissari, A.L., Machado, S.D.A., de Carvalho, D.C., Moura, T.A., Amorim, H.B., 2020. Tree volume modeling for forest types in the Atlantic Forest: generic and specific models. iForest Biogeosciences For. 13 (1), 417–425. https://doi.org/10.3832/ifor3495-013.

Da Rocha, S.J.S.S., Romero, F.M.B., Torres, C.M.M.E., Jacovine, L.A.G., Ribeiro, S.C., Villanova, P.H., Schettini, B.L.S., De Morais Junior, V.T.M., Reis, L.P., Rufino, M.P. M.X., Comini, I.B., Da Silva Tavares Júnior, I., Viana, Á.B.T, 2023. Machine learning: volume and biomass estimates of commercial trees in the Amazon forest. Sustainability 15 (12), 9452. https://doi.org/10.3390/su15129452.

De Lima, R.B., Rutishauser, E., da Silva, J.A.A., Guedes, M.C., Herault, B., de Oliveira, C. P., Aparício, da S.P., Sotta, E.D., da Silva, D.A.S., Ferreira, R.L.C, 2021. Accurate estimation of commercial volume in tropical forests. For. Sci. 67 (1), 14–21. https://doi.org/10.1093/forsci/fxaa032.

De Lima, R.D., Aparício, P.S., Ferreira, R.L.C., Silva, W.C., Guedes, M.C., Oliveira, C.P., Silva, D.A.S., Batista, A.P.B., 2014. Volumetry and classification of production capacity for *Mora paraensis* (Ducke) in Amapa estuary. Sci. Florest 42 (101), 141–154. http://www.bibliotecaflorestal.ufv.br:80/handle/123456789/14845.

De Oliveira, C.P., Ferreira, R.L.C., Da Silva, J.A.A., Lima, R.B., Silva, E., Alves Júnior, F. T., Souto-Maior Sales De Melo, C.L., 2021. Prediction of biomass in dry tropical forests: an approach on the importance of total height in the development of local and pan-tropical models. J. Sustain. For. 41 (10), 983–998. https://doi.org/10.1080/10549811.2021.1891940.

Demol, M., Wilkes, P., Raumonen, P., Sruthi, M., Calders, K., Gielen, B., Verbeeck, H., 2022. Volumetric overestimation of small branches in 3D reconstructions of *Fraxinus excelsior*. Silva Fenn. 56 (4). https://doi.org/10.14214/sf.10550. Article 10550.

Diamantopoulou, M.J., Georgakis, A., Progios, M., 2025. Optimizing pine tree stem volume models using artificial neural networks with minimal input variables. Oper Res. Int. J. 25, 42. https://doi.org/10.1007/s12351-025-00926-0.

Diéguez Aranda, U., Barrio Anta, M., Castedo Dorado, F., Ruiz González, A. D., Álvarez Taboada, M. F., Álvarez González, J. G. y Rojo Alboreca, A. (2023). Dendometría (2ª ed.).

Dirección General Forestal y de Fauna Silvestre (DGFFS). (2014). Perú Forestal en Números 2013. https://repositorio.serfor.gob.pe/handle/SERFOR/408.

Dourojeanni, M.J. (2019). Esbozo de una nueva política forestal peruana. 34(1): 4–20. https://doi.org/10.21704/rfp.v34i1.1244.

Ercanli, I., Gunlu, A., Başkent, E.Z., 2014. Mixed effect models for predicting breast height diameter from stump diameter of oriental beech in Göldağ. Sci Agric 72 (3), 245–251. https://doi.org/10.1590/0103-9016-2014-0225.

Escobar Cadillo, M.L., 2018. Volumetría De árboles en Pie De Caoba (Swietenia Macrophylla King) En El Departamento De Madre de Dios. Perú.

Fang, Z., Borders, B.E., Bailey, R.L., 2000. Compatible volume-taper models for loblolly and slash pine based on a system with segmented-stem form factors. For Sci. https://academic.oup.com/forestscience/article/46/1/1/4617337.

Fearnside, P.M., Romero, F.M.B., Jacovine, L.A.G., Ribeiro, S.C., Torres, C.M.M.E., da Silva, L.F., Gaspar, R.O., Rocha, S.J.S.S., Staudhammer, C.L., 2020. Allometric equations for volume, biomass, and carbon in commercial stems harvested in a managed forest in the southwestern amazon: a case study. Forests 11 (8), 1–17. https://doi.org/10.3390/f11080874.

Feldpausch, T.R., Lloyd, J., Lewis, S.L., Brienen, R.J.W., Gloor, M., Monteagudo Mendoza, A., Lopez-Gonzalez, G., Banin, L., Abu Salim, K., Affum-Baffoe, K., Alexiades, M., Almeida, S., Amaral, I., Andrade, A., Aragão, L.E.O.C., Araujo Murakami, A., Arets, E.J.M.M., Arroyo, L., Aymard, C., G, A., Baker, T.R., Bánki, O. S., Berry, N.J., Cardozo, N., Chave, J., Comiskey, J.A., Alvarez, E., de Oliveira, A., Di Fiore, A., Djagbletey, G., Domingues, T.F., Erwin, T.L., Fearnside, P.M., França, M.B., Freitas, M.A., Higuchi, N., Honorio, C.E., Iida, Y., Jiménez, E., Kassim, A.R., Killeen, T.J., Laurance, W.F., Lovett, J.C., Malhi, Y., Marimon, B.S., Marimon-Junior, B.H., Lenza, E., Marshall, A.R., Mendoza, C., Metcalfe, D.J., Mitchard, E.T.A., Neill, D.A., Nelson, B.W., Nilus, R., Nogueira, E.M., Parada, A., Peh, K.S.-H., Pena Cruz, A., Peñuela, M.C., Pitman, N.C.A., Prieto, A., Quesada, C.A., Ramírez, F., Ramírez-Angulo, H., Reitsma, J.M., Rudas, A., Saiz, G., Salomão, R.P., Schwarz, M., Silva, N., Silva-Espejo, J.E., Silveira, M., Sonké, B., Stropp, J., Taedoumg, H.E., Tan, S., ter Steege, H., Terborgh, J., Torello-Raventos, M., van der Heijden, G.M.F., Vásquez, R., Vilanova, E., Vos, V.A., White, L., Willcock, S., Woell, H., Phillips, O.L, 2012. Tree height integrated into pantropical forest biomass estimates. Biogeosciences 9 (8), 3381–3403. https://doi.org/10.5194/bg-9-3381-2012.

Fernandes, A.M.V., Gama, J.R.V., Rode, R., de Oliveira Melo, L., 2017. Equações volumétricas para Carapa guianensis Aubl. E Swietenia macrophylla King em sistema silvipastoril na Amazônia. Nativa 5 (1), 73–77. https://doi.org/10.31413/nativa.v5i1.4069.

Finegan, B., Peña-Claros, M., de Oliveira, A., Ascarrunz, N., Bret-Harte, M.S., Carreño-Rocabado, G., Casanoves, F., Díaz, S., Eguiguren Velepucha, P., Fernández, F., Licona, J.C., Lorenzo, L., Salgado Negret, B., Vaz, M.y, Poorter, L., 2015. ¿La diversidad de rasgos funcionales predice la biomasa aérea y la productividad de los bosques tropicales? Probando tres hipótesis alternativas. J. Ecol. 103, 191–201. https://doi.org/10.1111/1365-2745.12346.

Flores Morales, E.A., Rodríguez Alemán, A.C., Aguirre Calderón, O.A., Alanís Rodríguez, E., & Quiñonez Barraza, G. (2021). Compatible taper-volume system for *Pinus pseudostrobus* Lindl. in the Corona del Rosal ejido, Nuevo León, Mexico *Madera y bosques*, 27(2), e2722130. https://doi.org/10.21829/myb.2021.2722130.

Fonsêca, N.C., Cunha, J.S.A., Santos da Cunha, J.A., Santos, J.N.B., dos Santos Rodrigues, L., Lins-e-Silva, A.C.B., 2021. Tree diametric relationships and their implications for estimation of above-ground biomass in a tropical rainforest. J. Sustain. For. 41 (10), 999–1013. https://doi.org/10.1080/10549811.2021.1894451.

Food and Agriculture Organization (FAO). (2018). La Industria de la Madera en el Perú. 178 p.

García-Espinoza, G.G., Aguirre-Calderón, O.A., Vargas-Larreta, B., Martínez-Ángel, L., García-Magaña, J.J., Hernández-Ramos, J., 2019. Sistema compatible de ahusamiento y volumen comercial *De pinus* pseudostrobus Lindl. En Nuevo San Juan Parangaricutiro, Michoacán, México. In: Agrociencia, 53, pp. 115–131.

Gómez-García, E., Diéguez-Aranda, U., Ózcelik, R., Sal-Cando, M., Castedo-Dorado, F., Crecente-Campo, F., Corral-Rivas, J.J., Arias-Rodil, M., 2016. Desarrollo de una función de perfil mediante modelos mixtos para *Pinus sylvestris* en Turquía: selección de parámetros fijos a expandir. Bosque 37 (1), 159–167. https://doi.org/10.4067/S0717-92002016000100015.

Gonzalez-Benecke, C.A., Fernández, M.P., Gayoso, J., Pincheira, M., Wightman, M.G., 2022. Using tree height, crown area and stand-level parameters to estimate tree diameter, volume, and biomass of Pinus radiata, eucalyptus globulus and eucalyptus nitens. Forests 13 (12), 2043. https://doi.org/10.3390/f13122043.

Graciano-Ávila, G., Alanís-Rodríguez, E., Aguirre-Calderon, O.A., Gonzáles-Tagle, M.A., Treviño-Garza, E., Mora-Olivo, A., Buendía-Rodríguez, E., 2019. Estimación de volumen, biomasa y contenido de carbono en un Bosque de clima templado-frío de Durango, Mexico. Fitotec Mex 42 (2), 119–127.

Guerra, W., Soudre-Zambrano, M., Chota, M., 2008. Tabla de volumen comercial de bolaina blanca (Guazuma crinita Mart.) de las plantaciones experimentales de Alexander Von Humboldt, Ucayali. Perú 17 (1–2), 47–58. https://doi.org/10.24841/fa.v17i1-2.266.

Guerra-Arévalo, W.F., Cercado-Delgado, J.R., Espinoza-García, H.F., Ucañay-Ayllon, T. M., García-Soria, D.G., Abanto-Rodríguez, C., Castillo-Torres, D.del, Freitas-Alvarado, L.E., Díaz-Soria, R., Guerra-Arévalo, H., 2025. Emergence, growth, and quality of calycophyllum spruceanum plants produced in different containers and substrates. Agrosystems Geosci. Environ. 8 (1). https://doi.org/10.1002/agg2.70002.

Haag, V., Koch, G., Melcher, E., & Welling, J. (2020). Characterization of the wood properties of *Cedrelinga cateniformis* as substitute for timbers used for window manufacturing and outdoor applications. 22(1), 23–36. https://doi.org/10.4067/S0718-221×2020005000103.

Henry, M., Picard, N., Trotta, C., Manlay, R.J., Valentini, R., Bernoux, M., Saint-André, L., 2011. Estimating tree biomass of sub-Saharan African forests: a review of available allometric equations. Silva Fenn. 45 (3), 477–569. https://doi.org/10.14214/sf.38.

Hernández-Moreno, J.A., Velázquez-Martínez, A., Pérez-Salicrup, D.R., Bravo, F., MacFarlane, D.W., Reyes-Hernández, V.J., 2025. Terrestrial laser scanning for estimating the volume and biomass of coniferous stems in the Mariposa Monarca Biosphere Reserve, Mexico. Forests 16 (2), 334. https://doi.org/10.3390/f16020334.

Hernández-Ramos, J., De Los Santos-Posadas, H.M., Valdéz-Lazalde, J.R., Tamarit-Urias, J.C., Ángeles-Pérez, G., Hernández-Ramos, A., Méndez-Lopez, B., Peduzzi, A., 2017. Estimación del volumen comercial en plantaciones de Eucalypto urophylla con modelos de volumen total y de razón. Agrociencia 1 (5), 561–580.

Holdridge L.R. (1967). Life Zone Ecol Trop Sci Cent.

Husch, B., Miller, C.I., Beers, T.W., 1972. Forest Mensuration, 2nd ed. The Ronald.

Imaña-Encinas, J., Antunes-Santana, O., & Riesco-Muñoz, G. (2019). Selección de una ecuación volumétrica para Eucalyptus urophylla s.t. Blake en la región central del estado de Goiás, 16(39), 02–09. https://doi.org/10.18845/rfmk.v16i39.4406.

Kankare, V., Holopainen, M., Vastaranta, M., Puttonen, E., Yu, X., Hyyppä, J., Vaaja, M., Hyyppä, H., Alho, P., 2013. Individual tree biomass estimation using terrestrial laser scanning. ISPRS J. Photogramm. Remote Sens. 75, 64–75. https://doi.org/10.1016/j.isprsjprs.2012.10.003.

Kim, H.J., Lee, S.H., 2016. Developing the volume models for 5 major species of street trees in Gwangju metropolitan city of Korea. Urban For. Urban Green 18, 53–58. https://doi.org/10.1016/j.ufug.2016.05.004.

Kora, S.H., Guendehou, G.S., Goussanou, C.A., Assogbadjo, A.E., Sinsin, B., 2018. Allometric equations from a non-destructive approach for biomass prediction in natural forest and plantation in West Africa. South For. J. For. Sci. 81 (2), 111–122. https://doi.org/10.2989/20702620.2018.1512795.

Kozak, A., 1988. A variable-exponent taper equation. Can. J. For. Res. 18 (11), 1363–1368. https://doi.org/10.1139/x88-213.

Kuhn, M., Wing, J., Weston, S., Williams, A., Keefer, C., Engelhardt, A., Cooper, T., Mayer, Z., Kenkel, B., Benesty, M., Lescarbeau, R., Ziem, A., Scrucca, L., Tang, Y., Candan, C., & Hunt, T. (2024). *caret: Classification and Regression Training (Version 7.0-1)* [R package]. CRAN. Disponible en: https://CRAN.R-project.org/package=caret.

Lombard, L., Bogale, M., Montenegro, F., Wingfield, B.D., Wingfield, M.J., 2008. A new bark canker disease of the tropical hardwood tree *Cedrelinga cateniformis* in Ecuador. Fungal Divers 31, 81, 73.

Machado, S do.A., Urbano, M.E., da Conceição, M.B., 2005. Comparação de métodos de estimativa de volume para *Pinus oocarpa* em diferentes idades e diferente regimenes de desbastes. Bol. Pesqui. Florest Bras. 50, 81. -81. https://pfb.sede.embrapa.br/pfb/article/view/242.

Martins, A.P.M., Machado, S do A., Filho, A.F., Corte, A.P.D., Gorenstein, M.R., 2017. Efeito da idade na forma do fuste de *Araucaria angustifolia* na região Centro-Sul do Paraná. Pesqui Florest. Bras. 37 (90), 109–117. https://doi.org/10.4336/2017.pfb.37.90.1329.

Mateo, S., Cornejo, C., Tello, H., Salo, J., 2006. Estrategia Regional de Diversidad Biológica de Ucayali. In Comisión Ambiental Regional de Ucayali. Gobierno Regional de Ucayali, Instituto de Investigaciones de la Amazonía Peruana – IIAP, Proyecto BIODAMAZ, Consejo Nacional del Ambiente – secretaria ejecutiva Regional de Ucayali. In: Convenio De Cooperación Técnica, 12. Instituto de Investigación de la Amazonia Peruana - IIAP.

Medeiros, P.C.A. (2018).

Mejía, E., & Pacheco, P. (2013). Aprovechamiento forestal y mercados de la madera en la Amazonía. Ecuatoriana. Centro para la Investigación Forestal Internacional. https://doi.org/10.17528/cifor/004290.

Meyer, H.A. (1941). correct syst error occur appl logarithmic vol equ.

Meyer, W.H. (1938). Yield of even-aged stands of ponderosa pine. Department.

Molto, Q., Rossi, V., Blanc, L., 2013. Error propagation in biomass estimation in tropical forests. Methods Ecol. Evol. 4 (2), 175–183. https://doi.org/10.1111/j.2041-210x.2012.00266.x.

Monárrez-González, J.C., Márquez-Linares, M.A., López Hernández, J.A., Pérez Verdín, G., Quiñonez Barraza, G., García Cuevas, X., 2024. Ecuaciones de volumen fustal-total y ahusamiento para especies maderables del ecosistema templado en Puebla, México. Rev. Mex. Cienc. For. 15 (84), 4–28. https://doi.org/10.29298/rmcf.v15i84.1440.

Mulatu, A., Negash, M., Asrat, Z., 2024. Species-specific allometric models for reducing uncertainty in estimating above ground biomass at Moist Evergreen Afromontane Forest of Ethiopia. Sci. Rep. 14, 1147. https://doi.org/10.1038/s41598-023-51002-6.

Murga-Orrillo, H., Pashanasi, A.B., Arévalo, L.L.A., Chujutalli, I.M., Abanto-Rodríguez, C., 2024. *Cedrelinga cateniformis* (Tornillo) in natural and agroforestry systems: dendrometry, soil and macrofauna. Trees For. People 16 (2024), 100577. https://doi.org/10.1016/j.tfp.2024.100577.

Návar, J., González, N., & Graciano, J. (2001). Ecuaciones Para Estimar El Rendimiento e Incremento En Biomasa Total En Plantaciones Forestales De Durango, México.

Oficina Nacional de Evaluación de Recursos Naturales (ONERN) (1994). Mapa Ecológico del Perú.https://hdl.handle.net/20.500.12543/1052.

Otárola-Acevedo, E., & Linares-Bensimón, C. (2002). Tablas de volumen total y comercial de *Cedrelinga cateniformis* Ducke "tornillo" para plantaciones en Loreto, Perú. 13(1–2), 151–174. https://doi.org/10.24841/fa.v13i1-2.314.

Özçelik, R., Göçeri, M.F., 2015. Compatible merchantable stem volume and taper equations for eucalyptusplantations in the Eastern Mediterranean Region of Turkey. Turk J. Agric. For. 39 (6), 851–863. https://doi.org/10.3906/tar-1501-27.

Pedroso, de A.B.E., 2015. Modelagem da altura, volume e afilamento do fuste de *Calycophyllum spruceanum* Benth. Empregando Regressão e Redes Neurais Artificiais. Instituto Nacional De Pesquisas da Amazônia - INPA, Dissertação (Mestrado). https://repositorio.inpa.gov.br/bitstream/1/5093/1/Breno_Araujo.pdf.

Peirano, T.G.D., de la Flor, S.L.E., Vilchez, A.J., 2023. El Sector Forestal En El Perú: Propuestas estratégicas Para Fortalecer Su Desarrollo. Centro Nacional de Planeamiento Estratégico.

Peña, M.A., Castaño, N., Chave, J., González-Caro, S., Saatchi, S., Zuleta, D., Duque, A., 2025. Stem taper and volume across biogeographic regions of Colombia. For. Ecol. Manage. 595, 123046. https://doi.org/10.1016/j.foreco.2025.123046.

Picard, N., Saint-André, L., Henry, M., 2012. Manual For Building Tree Volume and Biomass Allometric equations: From field Measurement to Prediction. FAO & CIRAD, Rome.

Pompa García, M., & Solis Moreno, R. (2008). Ecuación de volumen para el género Quercus en la región noroeste de Chihuahua, 16, 84–93.

Prado, José Antonio, 2019. Plantaciones Forestales (Más Allá De Los Árboles). Chile.

Prodan, M., Peters, R., Cox, F., & Real, P. (1997). Mensura forestal. Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH: instituto Interamericano de Cooperación para la Agricultura (IICA).

R Core Team. (2024). R: Lang Environ Stat Comput. https://www.R-project.org.

Ramirez-Martínez, A., Santiago-García, W., Quiñonez-Barraza, G., Ruiz-Aquino, F., Antúnez, P., 2018. Taper and total volume model for *Pinus ayacahuite* Ehren. Madera Bosques. 24 (2), 1–14. https://doi.org/10.21829/myb.2018.2421496.

Ramos-Uvilla, J.A., García-Magaña, J.J., Hernández-Ramoz, J., García-Cuevas, X., Velarde-Ramirez, J.C., Muñoz-Flores, H.J., García Espinoza, G.G., 2014. Equations and volume tables for two Pinus species of la Sierra Purhépecha, Michoacán. Rev. Mex. Cienc For. 5 (23), 92–109.

Revilla - Chávez, J.M., López - Galán, E.E., Guerra - Arevalo, W.F., García - Soria, D.G., Rojas - Mego, K.C., Domínguez - Torrejón, G., Abanto - Rodríguez, C., 2021. Allometric model of biomass of white bolaina (*Guazuma crinita* Mart.) trees in forest plantations of Ucayali, Peru. Sci. Agropecu. 12 (4), 579–587. https://doi.org/10.17268/sci.agropecu.2021.062.

Revilla Chávez, J.M., Abanto-Rodríguez, C., Guerra Arévalo, W.F., García Soria, D., Guerra Arévalo, H., Domínguez Torrejón, G., Gabriel da Silva Carmo, I.L., 2021. Allometric models to estimate the volume of Guazuma crinita in forest plantations. Sci. Agropecu. 12 (1). https://doi.org/10.17268/sci.agropecu.2021.003.

Revilla-Chávez, J.M., Sáenz-Ramírez, L.H., Gonzales-Alvarado, A.C., García-Soria, D.G., Sebbenn, A.M., 2024. Allometric models of biomass and essential oils of *Aniba rosaeodora* Ducke in a tropical middle terrace soil forest of Masisea, Ucayali. Peru Trees For. People, 100594. https://doi.org/10.1016/j.tfp.2024.100594.

Rojas, B.N.B., Cotrina, S.D.A., Barboza, C.E., Barrena, G.M.Á., Sarmiento, F.O., Sotomayor, D.A., Oliva, M., Salas, L.R, 2020. Current and future distribution of five timber forest species in Amazonas, Northeast Peru: contributions towards a restoration strategy. Diversions 12 (305). https://doi.org/10.3390/d12080305.

Romanh, de la V C.F. & Ramírez, M.H. (2010). Dendrometría. Universidad Autónoma Chapingo. 312 pp.

Romero Saavedra, C.N. (2017). Estimación del volumen de árboles en pie de caoba (Swietenia macrophylla King) en el departamento de Ucayali,https://hdl.handle.net/20.500.12996/2694.

Saldaña, C.L., Cancan, J.D., Cruz, W., Correa, M.Y., Ramos, M., Cuellar, E., Arbizu, C.I., 2021. Genetic diversity and population structure of capirona (Calycophyllum spruceanum benth.) from the peruvian amazon revealed by rapd markers. Forests 12 (8). https://doi.org/10.3390/f12081125.

Schröder, T., Hofiço, N.D.S., Zimmermann, A.P.L., Pereira, L.D., Rocha Junior, D.S., Meyer, E.A., Fleig, F.D., 2013. Methods for commercial volume estimation of *Eucalyptus grandis*: characteristics and recommendations. Pesqui Florest Bras. 33 (73), 01–07. https://doi.org/10.4336/2013.pfb.33.73.446.

Schumacher, F.X., Hall, F.S., 1933. Logarithmic expression of timber-tree volume. J. Agric. Res. 47 (9), 719–734.

Segura, M., Kanninen, M., 2005. Allometric models for tree volume and total aboveground biomass in a tropical humid forest in Costa Rica 1. Biotropica 37 (1), 2–8.

Servicio Nacional Forestal y de Fauna Silvestre (SERFOR). (2024). Anuario Forestal y de Fauna Silvestre 2023. https://repositorio.serfor.gob.pe/handle/SERFOR/408.

Sharma, M., 2021. Total and merchantable volume equations for 25 commercial tree species grown in Canada and the northeastern United States. Forests 12 (9), 1270. https://doi.org/10.3390/f12091270.

Soares, C.P.B., de Paula, N.F., de Souza, A.L., 2011. Dendrometria e Inventário Florestal. Viçosa. Minas Gerais, Brasil. Universidad Federal de Viçosa, p. 272, 2. edp.

Spurr, S.H., 1952. Forest Inventory, 1952. Ronald Press Company, New York, p. 476p.

Stoate, T.N., 1945. The use of a volume equation in pine stands. Aust. For. 9, 48–52.

Takoudjou, S.M., Ploton, P., Sonké, B., Hackenberg, J., Griffon, S., De Coligny, F., Kamdem, N.G., Libalah, M., Mofack, G.I., Moguédec, G.L., Pélissier, R., Barbier, N., 2017. Using terrestrial laser scanning data to estimate large tropical trees biomass and calibrate allometric models: a comparison with traditional destructive approach. Methods Ecol. Evol. 9 (4), 905–916. https://doi.org/10.1111/2041-210x.12933.

Tamarit Urías, J.carlos, De los santos Posada, H.M., Aldrete, A., Valdez Lazalde, René., Ramírez Maldonado, H., Guerra de la Cruz, V., 2013. Sistema de cubicación para árboles individuales de Tectona grandis L.f. mediante funciones compatibles de ahusamiento-volumen. Rev. Mex Cienc. For. 5, 58–76.

Tang, X., Pérez-Cruzado, C., Fehrmann, L., Álvarez-González, J.G., Lu, Y., Kleinn, C., 2016. Development of a compatible taper function and stand-level merchantable volume model for Chinese fir plantations. PLoS One 11 (1), e0147610. https://doi.org/10.1371/journal.pone.0147610.

Tian, H., Zhu, J., He, X., Chen, X., Jian, Z., Li, C., Ou, Q., Li, Q., Huang, G., Liu, C., Xiao, W., 2022. Using machine learning algorithms to estimate stand volume growth of Larix and Quercus forests based on national-scale Forest Inventory data in China. For. Ecosyst. 9, 100037. https://doi.org/10.1016/j.fecs.2022.100037.

Tito, R., Salinas, N., Cosio, E.G., Boza Espinoza, T.E., Muñiz, J.G., Aragón, S., Nina, A., Roman-Cuesta, R.M., 2022. Secondary forests in Peru: differential provision of ecosystem services compared to other post-deforestation forest transitions. Ecol. Soc. 27 (3), 12. https://doi.org/10.5751/ES-13446-270312.

Trincado, G., Von Gadow, K., Sandoval, V., 1997. Estimación de volumen comercial en latifoliadas. BOSQUE 18 (1).

Ugarte-Guerra, L.J., & Domínguez-Torrejón, G. (2010). Site index of *Calycophyllum Spruceanum* Benth. In relation with the dominant height of essay plantations in the Aguaytía basin, Ucayali, 9(2), 2010. https://doi.org/10.21704/rea.v9i1-2.400.

van der Sande, M.T., Poorter, L., Derroire, G., do Espirito Santo, M.M., Lohbeck, M., Müller, S.C., Bhaskar, R., van Breugel, M., Dupuy-Rada, J.M., Durán, S.M., Jakovac, C.C., Paz, H., Rozendaal, D.M.A., Brancalion, P., Craven, D., Mora Ardilla, F., Almeida, J.S., Balvanera, P., Becknell, J., Bongers, F., 2024. Tropical forest succession increases tree taxonomic and functional richness but decreases evenness. Glob. Ecol. Biogeogr. 33, e13856. https://doi.org/10.1111/geb.13856.

Vargas-Larreta, B., Aguirre-Calderón, C.E., Aguirre-Calderón, C.G., & Hernández, F.J. (2021). Factores de forma y ecuaciones de volumen comercial para cinco especies de pino en el estado de Durango, México 84. https://doi.org/10.33064/iycuaa2021842815.

Wang, C., Zhang, W., Li, X., Wu, J., 2022. A global meta-analysis of the impacts of tree plantations on biodiversity. Glob. Ecol. Biogeogr. 31, 576–587. https://doi.org/10.1111/geb.13440.

Weber, J.C., Montes, C.S., 2005. Variation and correlations among stem growth and wood traits of calycophyllum spruceanum benth. From the Peruvian Amazon. Silvae Genet. 54 (1), 31–41. https://doi.org/10.1515/sg-2005-0005.

Wickham, H., 2016. ggplot2: Elegant Graphics For Data Analysis. Springer-Verlag, New York. https://ggplot2.tidyverse.org.

Xu, Q., Lei, X., Zang, H., Zeng, W., 2022. Climate change effects on height–Diameter allometric relationship vary with tree species and size for larch plantations in Northern and northeastern China. Forests 13 (3), 468. https://doi.org/10.3390/f13030468.

Zuur, A.F., Ieno, E.N., Elphick, C.S., 2010. A protocol for data exploration to avoid common statistical problems. Methods Ecol. Evol. 1 (1), 3–14. https://doi.org/10.1111/j.2041-210X.2009.00001.x.