Almada Gomes, K.M., Woycikievicz, A.P.F., Carvalho, D.S.V., Pertille, C.T., Santos, L.E., Ribeiro, R.B.S., Protásio, T.P., Figueiredo Filho, A. (2026). Modeling latex and cernambi production in Amazonian Hevea guianensis Aubl. plantations. Agriculture and Forestry, 72 (2): 351-378. https://doi:10.17707/AgricultForest.72.2.22

DOI: 10.17707/AgricultForest.72.2.22

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MODELING LATEX AND CERNAMBI PRODUCTION IN AMAZONIAN *Hevea guianensis* Aubl. PLANTATIONS

SUMMARY

The sustainable management of native and planted rubber tree stands is essential to optimize natural rubber production and conserve this forest resource. This study assessed the productive performance of rubber tree plantations in the Tapajós National Forest and developed statistical models to estimate latex and cernambi (coagulated natural rubber) production, considering the ecological and structural characteristics of Amazonian stands. A full inventory of all trees was conducted in both areas, recording diameter at breast height (*DBH*), total height and commercial height. Latex and cernambi production were measured weekly over one year in sampled trees distributed across all observed *DBH* classes. Additional dendrometric and morphometric variables were also measured in these trees. Correlations were analyzed between dendrometric variables, morphometric indices and combined variables. Statistical modelling included: (1) Spearman correlation, (2) stepwise selection using Variance Inflation Factor and (3) stepwise selection based on Akaike Information Criterion. High structural variability was observed. Trees with $DBH \geq 60$ cm showed the highest latex production, while those with $DBH \geq 40$ cm showed higher cernambi production. *DBH* and the composite variable D^2h were the strongest predictors, with significant positive correlations. The selected models showed moderate explanatory capacity, with R^2_{adj} values of 0.309 for latex and 0.291 for cernambi, and relative standard errors of 26.24% and

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Notes: The authors declare that they have no conflicts of interest. Authorship Form signed online.
Recieved:04/03/2026 *Accepted:11/06/2026*

23.69%, respectively, which is consistent with the high structural and environmental heterogeneity characteristic of Amazonian forest-based rubber systems. Cross-validation results confirmed stable predictive performance, with R^2_{cv} values of 0.294 and 0.259 for latex and cernambi, respectively. The proposed models provide quantitative support for estimating latex and cernambi production in Amazonian rubber plantations, with potential application in community-based management systems for non-timber product extraction.

Keywords: non-timber forest products; Amazonian rubber plantations; statistical modelling; latex production; cernambi production; *Hevea guianensis*

INTRODUCTION

The rubber tree, belonging to the genus *Hevea* (Euphorbiaceae), is native to South America and cultivated in Brazil for the extraction of latex, a plant exudate used as raw material for natural rubber (Sterling *et al.*, 2019; Faria *et al.*, 2021). These trees show vigorous growth, a wide crown and high productive capacity (Gonçalves *et al.*, 2011). After collection, latex may coagulate naturally or during processing, producing cernambi, a solid natural rubber product traditionally commercialized in Amazonian extractive systems. Together, latex and cernambi form one of the main non-timber forest product value chains in the Brazilian Amazon (Gama *et al.*, 2017).

The extraction of latex and cernambi is a traditional activity in the Amazon region, ensuring subsistence for riverside populations and traditional peoples (Gomes *et al.*, 2019). A relevant example of this activity takes place in the Tapajós National Forest (FLONA Tapajós), a Federal Conservation Unit located in the state of Pará, northern Brazil. With approximately 600 000 hectares, FLONA Tapajós hosts rich biodiversity and traditional communities that develop agroforestry systems based on the cultivation and extraction of non-timber forest products (Gomes *et al.*, 2019). In this region, native and planted rubber plantations have been managed for over a century, often intercropped with fruit and timber species, promoting sustainable practices that reconcile conservation and income generation (Shanley and Medina, 2005).

Despite the economic importance of natural rubber, with production estimated at 463 401 tonnes (Brazilian Institute of Geography and Statistics – IBGE, 2023), its yield varies significantly due to factors such as environmental conditions, disease susceptibility and genetic material (Mesquita *et al.*, 2006). To address these variations and optimize production, genetic improvement research has been conducted to develop more productive and resistant cultivars (Gonçalves *et al.*, 2021). However, in addition to genetics, the application of mathematical models can contribute to accurate yield estimates in rubber plantations, supporting sustainable management planning.

Although the modelling of dendrometric variables and the prediction of growth and wood volume are widely studied in planted forests, providing a consistent methodological basis for predictive approaches, the application of such models to non-timber forest products remains limited, especially in regions of high ecological and socioeconomic importance, such as the Amazon (Jaramillo-Giraldo *et al.,* 2017). In the context of *Hevea brasiliensis*, several studies have explored relationships between latex yield and dendrometric or morphological traits such as girth, bark thickness and leaf architecture, indicating the potential for developing predictive models based on structural variables (De Castro Sant'Anna *et al*., 2020; Suwanchana *et al.,* 2020).

These studies, although conducted primarily with *Hevea brasiliensis*, provide an important methodological and physiological reference framework due to the functional similarities among species of the genus *Hevea*, particularly regarding latex production and structural development. Other factors such as tree age, tapping time and environmental conditions also significantly affect latex production and have been integrated into empirical assessments of yield variation (Li *et al*., 2014; Sugiarto *et al*., 2024).

However, most of these approaches are predominantly based on *Hevea brasiliensis* cultivated under relatively controlled conditions and may not fully represent the structural heterogeneity and management variability observed in Amazonian forest-based systems, particularly those involving *Hevea guianensis*.

In addition, empirical modelling of cernambi (coagulated natural rubber) production has not yet been reported, despite its relevance in traditional extractive systems. These findings reinforce the relevance of developing context-specific models that account for the structural complexity and management conditions of Amazonian rubber systems, particularly those involving *Hevea guianensis* and the production of both latex and cernambi.

Previous efforts to model rubber yield, such as the simulation and validation of yield prediction models based on stem volume, climatic variables and disturbance indices, have demonstrated the feasibility and accuracy of these approaches (Huang *et al.,* 2020). Such methodological advances provide a strong basis for developing models tailored to different environmental conditions and management strategies.

In this study, we therefore develop and assess mathematical models to estimate latex and cernambi production based on dendrometric variables and morphometric indices. In this context, our approach aims to support the management of Amazonian rubber plantations by providing quantitative tools to estimate latex and cernambi production based on structural attributes of the trees, contributing to improved decision-making in traditional extractive systems.

Based on this context, the present study aimed to: i) evaluate the productive performance of rubber plantations located in the Tapajós National Forest by diameter class; and ii) develop and assess statistical models to estimate latex and cernambi production, considering dendrometric variables and morphometric indices.

MATERIAL AND METHODS

Study area

The study was conducted in the Terra Rica (27.41 ha) and Ponte (2.90 ha) rubber plantations, located within the Tapajós National Forest, in Belterra, Pará, northern Brazil. The plantations are approximately 1.5 km apart, at UTM coordinates 725 124.12 m E and 9 686 356.97 m S (Figure 1).

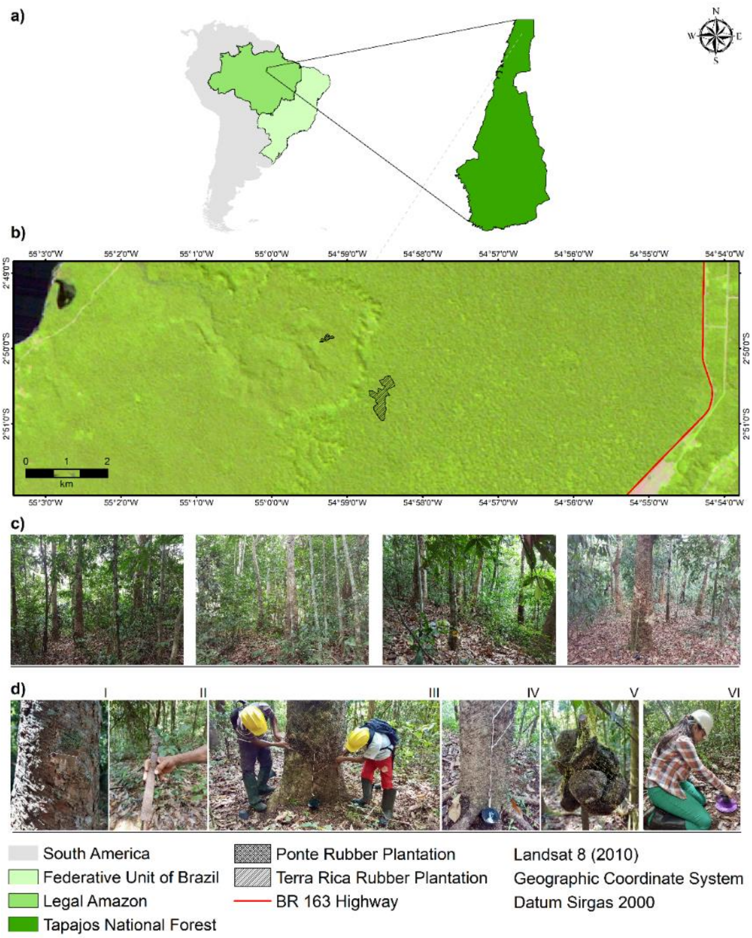

Figure 1. Study area and field activities conducted in the Tapajós National Forest, Pará, Brazil. a) Geographic location of the Tapajós National Forest within the Brazilian Amazon. b) Location of the Terra Rica and Ponte rubber plantations used in the study. c) Representative vegetation conditions observed within the sampled plantations. d) Field procedures and production assessment: I – sampled *Hevea guianensis* tree; II – tapping tool used for latex extraction; III – latex tapping operation; IV – latex collection; V – cernambi (coagulated natural rubber) formation; VI – measurement of latex and cernambi production.

Source: The authors.

The region has an Ami climate, tropical humid with annual thermal variation below 5°C, according to Köppen (Alvares *et al.*, 2013). Average annual temperature is 25.5°C, rainfall 1,820 mm and relative humidity around 90%. The vegetation is Dense Ombrophilous Forest, with a predominance of large canopy trees, woody lianas, palms and epiphytes (Andrade *et al.*, 2015).

Both rubber plantations consist of *Hevea guianensis* trees planted approximately 80 years ago, combined with natural regeneration that occurred after the abandonment of previous cultivation. The planted trees have an average spacing of eight meters and are arranged in rows following the terrain slope, whereas naturally regenerated trees are randomly distributed, resulting in a final stand density of 96.6 trees per hectare.

Production assessment

A census inventory was conducted in January 2018, including all rubber trees with *DBH* (measured at 1.30 m) ≥ 5 cm, totalling 2 872 individuals. In addition to *DBH*, total height (*Ht*) and commercial height (*Hc*) were measured. Trees were classified into *DBH* classes with 10 cm intervals. Commercial height refers to the distance from the tree base to the first bifurcation of the stem.

Latex and cernambi production were quantified from a sample of 101 trees distributed across all observed *DBH* classes during the harvesting season, from January to September. Tapping was performed weekly on Mondays, Wednesdays and Fridays. The sampling encompassed young and adult trees to capture the full range of production patterns during the local tapping season, which spans both the Amazonian winter (rainy season) and summer (dry season). A simple random sampling method was used, and the sample size was calculated based on the variability of latex production, treating the population as finite. The following expression was applied (Soares and Paula-Neto, 1997):

$$n = \frac{t^2 \times CV^2}{(E\%)^2 + \frac{t^2 \times (CV)^2}{N}} \quad (1)$$

where: n=number of trees to be sampled; *t*=value of t associated with a given probability level and degrees of freedom; CV=coefficient of variation of latex production; *E%*=required precision (10%); *N*=total number of trees in the population.

This approach ensured statistical representativeness of the sample and the reliability of the production estimates. During each collection, both latex (liquid) and cernambi (coagulated latex, i.e., solid rubber) were weighed using a digital scale. The latex mass was recorded in its liquid form (g tapping^{-1} tree^{-1}), and in the following collection, the mass of cernambi (g tapping^{-1} tree^{-1}) was measured, corresponding to the solidified form of natural rubber (Figure 1).

For modelling purposes, latex and cernambi production data were expressed as the total sum of all collections during the harvesting period, in kg tree^{-1} year^{-1}.

To test whether there were significant differences in production across *DBH* classes, a multiple comparison test was applied using Fisher's Least Significant Difference (*LSD*) method (Fisher, 1935). This analysis was performed using R software, version 4.0.1 (R Core Team, 2023).

To investigate potential relationships with latex and cernambi production, 14 variables were analyzed, including dendrometric variables, morphometric indices and combined variables (Table 1).

Table 1. Dependent and independent variables used in the development of models to estimate latex (kg) and cernambi (kg) production per tree per year, in *Hevea guianensis* plantations located in the Tapajós National Forest, Belterra, Pará

Dependent variables		*La; Ce*
Independent variables	*Dendrometrics*	*DBH; BT; Ht; Hc; Hcp;* D_{crown}*;* $Area_{crown}$
	Morphometric indices	*SR; CI; SI; CF; CP*
	Combined variables	D^2h*;* $D_c^2\ hcp$

Where: La=latex production (kg tree^{-1} *year*$^{-1}$*); Ce=cernambi production (kg tree*$^{-1}$ *year*$^{-1}$*); DBH=diameter at breast height (cm); BT=bark thickness (mm); Ht=total height (m); Hc=commercial height (m); Hcp=crown height (m);* D_{crown}*=crown diameter (m);* $Area_{crown}$*=crown area (m*^{2}*); SR=slenderness ratio (%); CI=coverage index (%); SI=salience index (%); CF=crown form (m); CP=crown percentage (%);* $D^2h=DBH^2\times Ht$ *(cm*^{2}*×m);* $D_c^2\ hcp=(D_{crown}^2)\times Hcp$ *(m*^{2}*×m).*

The crown diameter (D_{crown}) and crown area ($Area_{crown}$) were calculated using equations (2) and (3):

$$D_{crown} = 2 * \frac{\sum_{i=1}^{n} Rc_i}{n} \quad (2)$$

$$Area_{crown} = \pi * \overline{Rc} \quad (3)$$

Where Rc_i and $\overline{Rc}$ are the individual and average crown radius in metres, respectively.

The morphometric indices *SR*, *CI*, *SI*, *CF* and *CP* were calculated using equations (4) to (8):

$$SR = \frac{Ht}{DBH} * 100 \quad (4)$$

$$CI = \frac{D_{crown}}{Ht} * 100 \quad (5)$$

$$SI = \frac{D_{crown}}{DBH} * 100 \quad (6)$$

$$CF = \frac{D_{crown}}{Hcp} \quad (7)$$

$$CP = \frac{Hcp}{Ht} \quad (8)$$

Where: *DBH*=diameter at breast height (cm); *Ht*=total height (m); *Hcp*=crown height (m); D_{crown}=crown diameter (m); *SR*=slenderness ratio (%); *CI*=coverage index (%); *SI*=salience index (%); *CF*=crown form (m); *CP*=crown percentage (%).

The combined variables were calculated by multiplying dendrometric variables, according to equations (9) and (10):

$$D^2h = (DBH \wedge 2) * Ht \quad (9)$$

$$D_c{}^2hcp = (D_{crown} \wedge 2) * Hcp \quad (10)$$

Where: *DBH*=diameter at breast height (cm); *Ht*=total height (m); *Hcp*=crown height (m).

Modelling latex and cernambi production

Three approaches were adopted to select the independent variables used in the models to estimate latex (*La*) and cernambi (*Ce*) production: (i) Spearman correlation analysis, (ii) a bidirectional stepwise procedure using the Variance Inflation Factor (VIF) as a diagnostic criterion, and (iii) a bidirectional stepwise procedure based on the Akaike Information Criterion (AIC).

Approach 1: Spearman correlation was calculated, following Zar (1999), to assess the degree of association between latex (*La*) and cernambi (*Ce*) production and the other covariates listed in Table 1, which were candidates for the regression models. As a selection criterion, all variables with a Spearman correlation coefficient (S) greater than 0.5 were selected. Each independent variable meeting this criterion was paired with each dependent variable, tested both in its original scale and its logarithmic form, as described in Table 2.

Table 2. Regression model structure for the dependent variable (y_i) and each independent variable with Spearman correlation greater than 0.5 (X_i).

	Criterion
$y_i = X_i$	• Independent variable: in the **original** scale; • Dependent variable: in the **original** scale.
$\ln y_i = X_i$	• Independent variable: in the logarithmic scale; • Dependent variable: in the **original** scale.
$y_i = \ln X_i$	• Independent variable: in the **original** scale; • Dependent variable: in the logarithmic scale.
$\ln y_i = \ln X_i$	• Independent variable: in the logarithmic scale; • Dependent variable: in the logarithmic scale.

Where: ln = natural logarithm (Napierian logarithm)

Therefore, for each variable with S≥0.5, four simple linear regression models were tested, derived from Table 2 and incorporated into the general expression 11.

$$Y = \beta_0 + \beta_1 * X + \varepsilon \quad (11)$$

Approach 2: Regression models were developed using the bidirectional Stepwise procedure (combining Forward and Backward selection), following Draper and Smith (1998). The process began with the progressive inclusion of covariates (Forward), and after each new inclusion, variables were re-evaluated for possible removal (Backward). Variables were retained in the final models only when statistically significant at the 5% significance level.

This procedure was employed as a variable-selection approach aimed at identifying parsimonious and operationally applicable combinations of structural predictors.

The natural logarithm (ln) of all independent variables listed in Table 1 was added to the dataset together with their original values. To reduce multicollinearity effects that could compromise coefficient estimation (Zhao *et al*., 2013), variables showing exact linear dependency or strong redundancy were excluded prior to model fitting. Subsequently, the Variance Inflation Factor (VIF) was used as a multicollinearity diagnostic criterion during the stepwise procedure, adopting VIF ≤ 10 as the threshold for variable retention, as recommended by Orso *et al*., (2020).

This approach was applied to both latex (*La*) and cernambi (*Ce*) production, tested on original and logarithmic scales, resulting in two models for each dependent variable.

Approach 3: In this approach, models were also developed using the bidirectional Stepwise procedure described by Draper and Smith (1998), but variable selection was based on the Akaike Information Criterion (AIC) rather than the Variance Inflation Factor (VIF). Similar to Approach 2, all variables were log-transformed and evaluated for multicollinearity prior to model fitting.

Variables were iteratively included or excluded until no further improvement in the AIC statistic was observed, retaining only variables significant at the 5% level.

As in Approach 2, the procedure was applied to latex (*La*) and cernambi (*Ce*) production, tested on both original and logarithmic scales, resulting in two models for each dependent variable.

Model evaluation

All linear models were fitted using the ordinary least squares (OLS) method, implemented in R software, version 4.0.1 (R Core Team, 2023). The statistics used to evaluate model performance were the adjusted coefficient of determination (R^2adj), the relative standard error of estimate (Syx%) and the Akaike Information Criterion (AIC). All statistics were recalculated for the response variable in its original scale (Table 3), in addition to graphical analysis of residual dispersion in percentage (Res%).

Table 3. Statistical criteria used to evaluate the models fitted to estimate latex and cernambi production in *Hevea guianensis* plantations in the Tapajós National Forest, Belterra, Pará

Criteria	Formulas
Adjusted coefficient of determination	$R^2adj = 1 - \left(\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2}\right) * \left(\frac{n-1}{n-p}\right)$
Relative standard error of estimate	$Syx\% = \frac{\sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n-p}}}{\bar{y}} * 100$
Akaike Information Criterion	$AIC = n + n * \ln(2\pi) + n * \ln(\hat{\sigma}^2) + 2 * (p + 1)$
Residuals	$Res\% = \frac{y_i - \hat{y}_i}{y_i} * 100$

Where: y_i*=observed value:* $\hat{y}_i$*=estimated value:* $\bar{y}$*=mean of observed values; ln=natural logarithm; n=number of observations; p=number of model parameters;* $\hat{\sigma}^2 = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}$.

The modelling procedures adopted in this study were designed to identify parsimonious relationships between structural variables and latex/cernambi production under Amazonian forest conditions, with potential applicability to similar forest-based rubber systems.

For models that included logarithmic transformation of the independent variable, the Meyer correction factor was applied to the estimated values. To verify the assumptions of variance homoscedasticity and residual normality, the Breusch-Pagan test (Breusch and Pagan, 1979) and the Shapiro-Wilk test (Shapiro and Wilk, 1965) were performed, respectively. In addition to these tests, normality and homoscedasticity were also evaluated using the normality plot (Q-Q plot) and residual percentage plots.

For models that presented satisfactory statistical performance, concordance limit plots were constructed based on the Bland-Altman analysis proposed by (Huang *et al.*, 2019). This method is based on two paired data sets, where the difference between each pair of observed values is plotted against the mean of the respective pair (Equation 12). Furthermore, upper and lower limits for these differences were established based on the mean of the differences and the respective standard deviation, according to Equations 13 and 14.

$$Mean\ measurements = \frac{d_{1_i} + d_{2_i}}{2} \quad (12)$$

$$L_s = \bar{d} + 1{,}96 * S_d \quad (13)$$

$$L_i = \bar{d} - 1{,}96 * S_d \quad (14)$$

where: $\bar{d}$ is the mean of the differences between the paired observations; S_d is the standard deviation of the differences; d_{1_i} is the observed value for observation i; d_{2_i} is the estimated value for observation i.

According to Huang *et al.* (2019), for an estimation method to be considered consistent within the evaluated dataset, 95% of the mean observations must fall within the upper (L_s) and lower (L_i) limits.

To further assess the predictive performance of the selected model, a 10-fold cross-validation procedure was applied. The dataset was randomly partitioned into ten approximately equal subsets. At each iteration, nine subsets were used for model calibration and the remaining subset was used for validation. This process was repeated until all observations had been used once as validation data. Cross-validation performance was evaluated using the cross-validated coefficient of determination (R^2_{cv}), root mean square error ($RMSE_{cv}$), mean absolute error (MAE_{cv}), bias ($Bias_{cv}$) and relative standard error of estimate (Syx_{cv}%).

RESULTS AND DISCUSSION

Structural variability and production overview

Based on the data presented in Table 4, the rubber tree population analysed in the Tapajós National Forest showed an average *DBH* of 36.6 cm, with a coefficient of variation (CV) of 32.3%, indicating high diameter heterogeneity. The mean total height was 15.7 m, while mean crown height was 6.9 m, the latter showing the highest variability (CV=48.2%). This structural heterogeneity reflects the coexistence of planted and naturally regenerated trees, with a wide size range, as indicated by *DBH* values varying from 10.5 cm to 96.8 cm.

Table 4. Descriptive statistics of the rubber tree population in plantations located in the Tapajós National Forest, Belterra, Pará

Parameter	***DBH*** **(cm)**	***Ht*** **(m)**	***Hc*** **(m)**
Mean	36.6	15.7	6.9
Std. Dev.	11.8	3.8	3.3
CV (%)	32.3	23.9	48.2
Minimum	10.5	3.0	1.0
Maximum	96.8	29.0	20.0
No. of trees		2 872	

Where: Std. Dev.=standard deviation; CV (%)=coefficient of variation; No. of trees=number of individuals; DBH=diameter at breast height (cm); Ht=total height (m); Hc=commercial height (m).

The sampling results complement the population data, providing detailed information on the structural and productive aspects of rubber trees in the Tapajós National Forest (Table 5). The average production of latex and cernambi was 5.0 kg tree^{-1} year^{-1} for both, with high coefficients of variation (31.6% and 28.1%, respectively), reflecting significant productive heterogeneity among the measured trees.

Table 5. Descriptive statistics of the sample for latex production (kg tree^{-1} year^{-1}) and cernambi production (kg tree^{-1} year^{-1}) in rubber plantations located in the Tapajós National Forest, Belterra, Pará

Variables		Mean	Std. Dev.	CV (%)	Minimum	Maximum
Dependent	*La*	5.0	1.6	31.6	2.9	10.4
	Ce	5.0	1.4	28.1	2.9	9.4
Independent	*DBH* (cm)	42.5	14.4	33.9	14.9	78.9
	BT (mm)	0.5	0.2	31.4	0.1	1.0
	Ht (m)	17.3	3.7	21.2	10.0	25.0
	Hc (m)	11.0	2.7	24.5	5.5	19.0
	Hcp (m)	6.3	3.4	53.9	1.0	14.5
	D_{crown} (m)	11.5	3.6	31.7	4.0	20.7
	$Area_{crown}$ (m²)	113.4	68.6	60.5	12.6	337.6
	CP (%)	34.7	15.5	44.6	5.3	72.5
	CF (m)	2.9	2.9	101.2	0.6	16.8
	SR (%)	43.8	12.6	28.8	25.5	89.1
	CI (%)	0.7	0.2	36.0	0.3	1.4
	SI (%)	29.8	14.0	46.9	8.1	84.8
	D^2h (cm² × m)	38 010.7	29 969.2	78.8	2226.1	137 093.5
	$D_c^2\ hcp$ (m² × m)	940.1	796.0	84.7	22.1	4141.3

Where: La=latex production (kg tree^{-1} year^{-1}); Ce=cernambi production (kg tree^{-1} year^{-1}); DBH=diameter at breast height (cm); BT=bark thickness (mm); Ht=total height (m); Hc=commercial height (m); Hcp=crown height (m); D_{crown}=crown diameter (m); $Area_{crown}$=crown area (m²); SR=slenderness ratio (%); CI=coverage index (%); SI=salience index (%); CF=crown form (m); CP=crown percentage (%); $D^2h=DBH^2 \times Ht$ (cm²×m); $D_c^2\ hcp=(D_{crown}^2) \times Hcp$ (m²×m); Std. Dev.=standard deviation; CV (%)=coefficient of variation.

The independent variables evaluated showed very high coefficients of variation, highlighting the marked structural heterogeneity among the sampled trees. Crown area (60.5%) reflected significant differences in space occupancy; the salience index (46.9%) and the coverage index (36.0%) evidenced variations in dominance levels and spatial occupation. The parameters D2h (78.8%) and D_c^2hcp (84.7%) further reinforced this variability and proved to be relevant variables for modelling latex and cernambi production, as their association with productivity highlights the role of tree structure in productive performance.

Distribution of diameter classes and production trends

Figure 2 shows the diameter distribution of the rubber tree population analysed in the Tapajós National Forest, revealing an asymmetric pattern. The highest concentration of trees occurred in the intermediate diameter classes, reflecting the predominance of individuals at an advanced development stage. In contrast, both the lower and upper diameter classes showed lower frequencies, indicating a reduced proportion of young and very old trees in the studied population. The sampled trees adequately represent the population distribution, ensuring data reliability for structural and productive analyses.

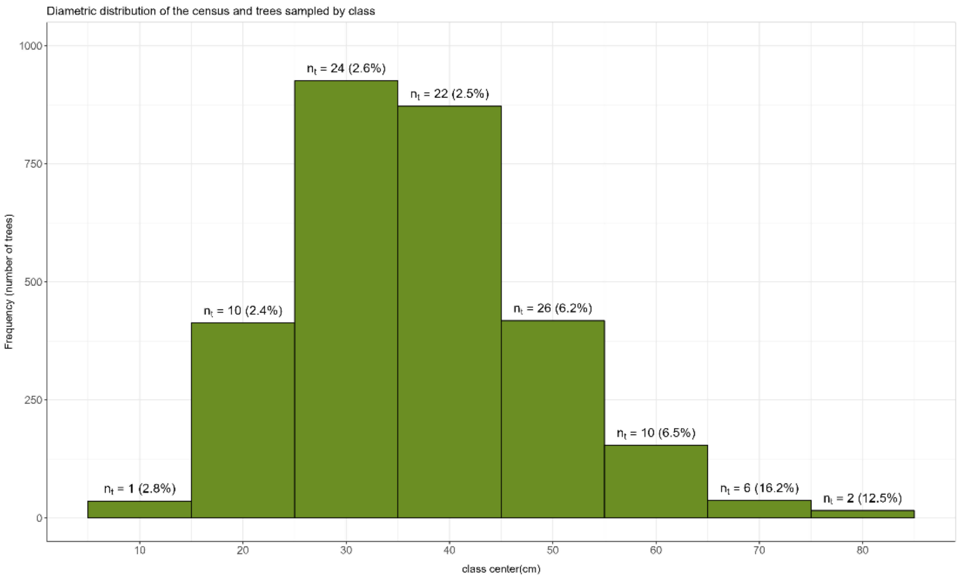

Figure 2. Diameter distribution of the inventoried *Hevea guianensis* population and the corresponding number of sampled trees used for latex and cernambi production measurements in each diameter class in the Tapajós National Forest, Belterra, Pará, Brazil. Values above the bars indicate the number of sampled trees (nt) and the sampling intensity (%) within each diameter class.

Source: The authors.

The multiple mean comparison test indicated significant differences in latex and cernambi production across *DBH* classes (Table 6).

Table 6. Comparison of latex and cernambi production by diameter class using the LSD (Least Significant Difference) method in rubber plantations located in the Tapajós National Forest, Belterra, Pará

***DBH* Class Centre (cm)**	**Latex Production**	**Cernambi Production**	**No. of Trees**
10	3.650 **c**	3.623 **b**	1
20	4.066 **c**	4.064 **b**	10
30	4.130 **c**	4.228 **b**	24
40	4.947 **b**	5.013 **a**	22
50	5.163 **b**	5.228 **a**	26
60	6.385 **a**	5.990 **a**	10
70	6.454 **a**	6.566 **a**	6
≥ 80	7.693 **a**	6.726 **a**	2

Where: Means followed by different letters indicate significant differences among diameter classes according to the LSD method at a 95% probability level.

Correlation between structural attributes and production

The Spearman correlation test revealed that the variables most strongly correlated with latex production (*La*) and cernambi production (*Ce*) were D^2h and *DBH*, respectively (Table 7). Both variables showed positive, moderate and highly significant correlations (p<0.01).

Table 7. Spearman correlation between dependent and independent variables and respective significance levels in rubber plantations located in the Tapajós National Forest, Belterra, Pará.

Independent Variables	Dependent Variables	
	La	*Ce*
DBH	0.526**	0.539**
BT	0.245*	0.235*
Ht	0.444**	0.442**
Hc	0.380**	0.338**
Hcp	0.225*	0.262*
D_{crown}	0.201*	0.186^{ns}
$Area_{crown}$	0.202*	0.186^{ns}
CP	0.110^{ns}	0.162^{ns}
CF	-0.129^{ns}	-0.161^{ns}
SR	-0.274**	-0.294**
CI	-0.086^{ns}	-0.115^{ns}
SI	-0.256**	-0.279**
D^2h	0.544**	0.551**
$D_c^2\ hcp$	0.324**	0.345**

*Where: La=latex production (kg tree^{-1} year^{-1}); Ce=cernambi production (kg tree^{-1} year^{-1}); DBH=diameter at breast height (cm); BT=bark thickness (mm); Ht=total height (m); Hc=commercial height (m); Hcp=crown height (m); D_{crown}=crown diameter (m); $Area_{crown}$=crown area (m²); SR=slenderness ratio (%); CI=coverage index (%); SI = salience index (%); CF=crown form (m); CP=crown percentage (%); $D^2h = DBH^2 \times Ht$ (cm² × m); $D_c^2\ hcp=(D_{crown}^2)\times Hcp$ (m²×m); ^{ns} =non-significant; *=significant at 95% probability; **=significant at 99% probability.*

Other important structural variables also showed significant positive correlations with latex and cernambi production. The main ones were total height (*Ht*), commercial height (*Hc*) and crown height (*Hcp*). Crown area ($Area_{crown}$) showed a significant correlation with latex but not with cernambi.

Among the negative correlations, the slenderness ratio (*SR*) was significant only for cernambi. The coverage index (*CI*), although also negative, was not significant.

Bark thickness (*BT*) was positively and significantly correlated with both products, but with low correlation coefficients. Crown diameter (D_{crown}) showed a low and non-significant correlation with cernambi.

These results further reinforce the relevance of D^2h and DBH as the main predictors of production, while also highlighting that structural variables, such as height and crown attributes, can differently influence latex and cernambi. This underscores the importance of developing specific models for each product.

Performance of regression models across modelling approaches

Table 8 presents the models selected for latex and cernambi production. Models were fitted on both original and logarithmic scales, with similar performance across approaches. Coefficients and fit statistics for latex models are in Table 9.

Table 8. Models selected for latex and cernambi production modelling, based on variable selection approaches 1, 2 and 3, in rubber plantations located in the Tapajós National Forest, Belterra, Pará

Variable	Approach	Model No.	Model
Latex	1 – Highest correlation	1	$La = b_0 + b_1 \times DBH$
		2	$La = b_0 + b_1 \times D^2h$
		3	$\ln La = b_0 + b_1 \times DBH$
		4	$\ln La = b_0 + b_1 \times D^2h$
		5	$La = b_0 + b_1 \times \ln DBH$
		6	$La = b_0 + b_1 \times \ln D^2h$
		7	$\ln La = b_0 + b_1 \times \ln DBH$
		8	$\ln La = b_0 + b_1 \times \ln D^2h$
	2 – Stepwise VIF ≤ 10	9	$La = b_0 + b_1 \times D^2h + b_2 \times \ln Hc$
		10	$\ln La = b_0 + b_1 \times D^2h + b_2 \times \ln Hc$
	3 – Stepwise AIC	11	$La = b_0 + b_1 \times D^2h + b_2 \times \mathrm{BT} + b_3 \times \ln BT + b_4 \times \ln Hc$
		12	$\ln La = b_0 + b_1 \times D^2h + b_2 \times \mathrm{BT} + b_3 \times \ln BT + b_4 \times \ln Hc$
Cernambi	1 – Highest correlation	1	$Ce = b_0 + b_1 \times DBH$
		2	$Ce = b_0 + b_1 \times D^2h$
		3	$\ln Ce = b_0 + b_1 \times DBH$
		4	$\ln Ce = b_0 + b_1 \times D^2h$
		5	$Ce = b_0 + b_1 \times \ln DBH$
		6	$Ce = b_0 + b_1 \times \ln D^2h$
		7	$\ln Ce = b_0 + b_1 \times \ln DBH$
		8	$\ln Ce = b_0 + b_1 \times \ln D^2h$
	2 – Stepwise VIF ≤ 10	9	$Ce = b_0 + b_1 \times D^2h + b_2 \times \ln Hc$
		10	$\ln Ce = b_0 + b_1 \times D^2h + b_2 \times \ln Hc$
	3 – Stepwise AIC	11	$Ce = b_0 + b_1 \times D^2h + b_2 \times BT + b_3 \times \ln BT + b_4 \times \ln Hc$
		12	$\ln Ce = b_0 + b_1 \times D^2h + b_2 \times BT + b_3 \times \ln BT + b_4 \times \ln Hc$

Where: La = latex production (kg tree^{-1} year^{-1}); Ce = cernambi production (kg tree^{-1} year^{-1}); DBH = diameter at breast height (cm); BT = bark thickness (mm); Hc = commercial height (m); D^2h = $DBH^2 \times Ht$ ($cm^2 \times m$); ln = natural logarithm.

Table 9. Estimated coefficients and fit statistics of the models fitted to estimate latex production (kg tree^{-1} year^{-1}) in rubber plantations located in the Tapajós National Forest, Belterra, Pará

Model	b_0	b_1	b_2	b_3	b_4	R^2adj	Syx%	AIC
1	2.448378**	0.059923**	-	-	-	0.293	26.530	347.473
2	3.85**	0.0000301**	-	-	-	0.321	26.010	343.489
3	1.0906558**	0.011135**	-	-	-	0.295	26.500	347.254
4	1.354**	0.00000509**	-	-	-	0.309	26.240	345.262
5	-3.489**	2.3**	-	-	-	0.268	27.000	351.030
6	-4.721*	0.952**	-	-	-	0.285	26.690	348.702
7	-0.02415**	0.43051**	-	-	-	0.278	26.810	349.597
8	-0.25586^{ns}	0.17831**	-	-	-	0.298	26.450	346.860
9	1.127^{ns}	0.00002753**	1.189*	-	-	0.346	25.520	344.565
10	0.7871**	0.000004973**	0.2478**	-	-	0.335	25.750	342.388
11	-4.744706*	0.049112**	5.246706*	-2.04326*	1.436359**	0.364	25.180	357.797
12	-0.282357^{ns}	0.009045**	0.972691*	-0.368309*	0.287482**	0.360	25.250	340.378

*Where: b_0, b_1, b_2, b_3, b_4=estimated model coefficients; R^2adj=adjusted coefficient of determination; Syx%=standard error of estimate in percentage; AIC=Akaike Information Criterion; ^{ns}=non-significant; *=significant at 95% probability; **=significant at 99% probability.*

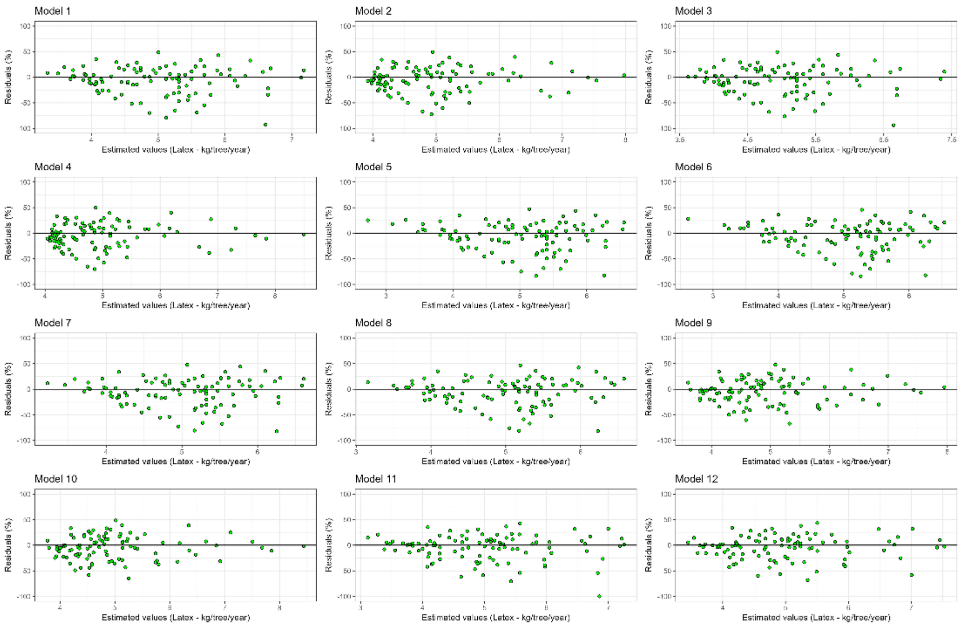

Figure 3. Residual distribution plots (%) for the twelve models evaluated to estimate latex production in rubber plantations in the Tapajós National Forest, Belterra, Pará, Brazil. Each panel corresponds to one fitted model, showing residuals (%) as a function of estimated latex production values (kg tree^{-1} year^{-1}). The horizontal line represents the zero-residual reference.

Source: The authors.

Overall, the models showed similar statistical performance, indicating moderate fit quality, especially considering the high heterogeneity of the data. Most variables were statistically significant, supporting their inclusion. However, residual analysis (Figure 3) indicated heteroscedasticity for models 1, 3, 5, 6 and 8, reducing their reliability. Model 12 had good statistical performance but used bark thickness redundantly, limiting its operational use. Additionally, the intercept coefficient (b_0) was not significant.

Fit statistics for cernambi models (Table 10) were also similar to those observed for latex production, with evaluation metrics showing very close results among the models.

Table 10. Estimated coefficients and fit statistics of the models fitted to estimate cernambi production (kg tree^{-1} year^{-1}) in rubber plantations located in the Tapajós National Forest, Belterra, Pará

Model	b_0	b_1	b_2	R^2adj	Syx%	AIC
1	2.72869**	0.05338**	-	0.293	23.670	324.475
2	4.001**	0.00002619**	-	0.305	23.460	322.725
3	1.1465750**	0.010036**	-	0.289	23.720	324.964
4	1.389**	0.00000483**	-	0.291	23.690	324.695
5	-2.7249*	2.0935**	-	0.280	23.880	326.323
6	-3.7952**	0.8615**	-	0.293	23.650	324.362
7	0.10722^{ns}	0.3974**	-	0.286	23.780	325.470
8	0.09368^{ns}	0.16332**	-	0.302	23.500	323.096
9	1.735^{ns}	0.00002405**	0.9899*	0.326	23.100	324.551
10	0.9233**	0.000004395**	0.2035*	0.313	23.330	322.521
11	0.098441^{ns}	0.049328**	1.181462*	0.327	23.080	324.393
12	0.621266**	0.009227**	0.23596**	0.322	23.180	321.219

*Where: b_0, b_1, b_2=estimated model coefficients; R^2adj=adjusted coefficient of determination; Syx%=standard error of estimate in percentage; AIC=Akaike Information Criterion; ^{ns}=non-significant; *=significant at 95% probability; **=significant at 99% probability.*

Residual analysis (Figure 4) revealed heteroscedasticity in models 1, 3, 5, 6, 7 and 8, which, despite the good fit statistics, may compromise the accuracy of the estimates.

The homoscedasticity and normality tests (Table 11) indicated that Model 4 met the assumptions for latex, with p-values > 0.05 in both the Breusch-Pagan and Shapiro-Wilk tests. Model 10 showed a p-value slightly below 0.05 for homoscedasticity test; however, the residual plots did not indicate any evident patterns of heteroscedasticity. A similar pattern was observed for cernambi, with Model 4 fully meeting assumptions and Model 10 close to the significance threshold without evident issues.

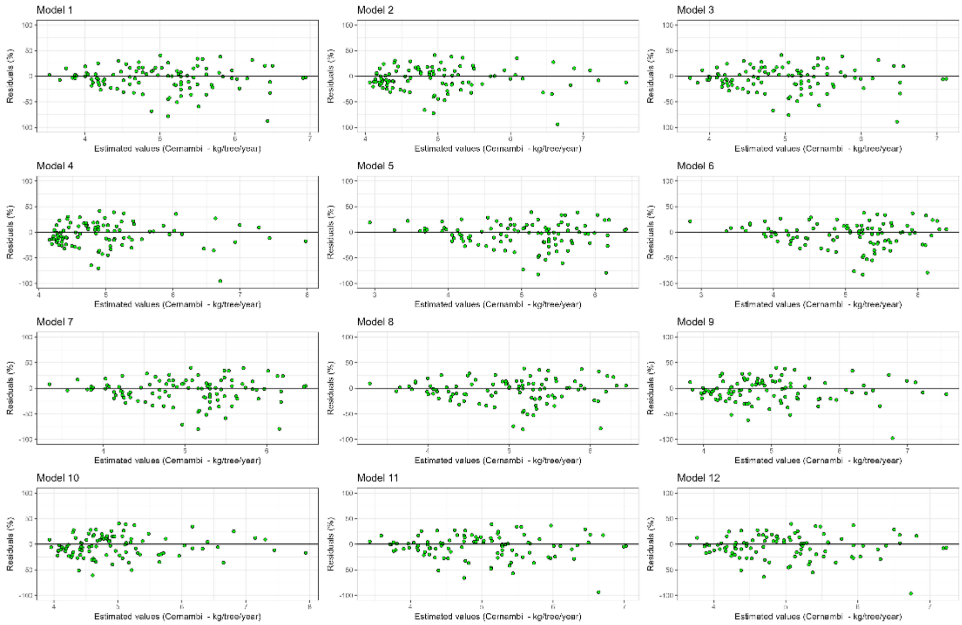

Figure 4. Residual distribution plots (%) for the twelve models evaluated to estimate cernambi production in rubber plantations in the Tapajós National Forest, Belterra, Pará, Brazil. Each panel corresponds to one fitted model, showing residuals (%) as a function of estimated cernambi production values (kg tree^{-1} year^{-1}). The horizontal line represents the zero-residual reference.

Source: The authors.

Table 11. *p*-values for the homoscedasticity (Breusch-Pagan test) and normality (Shapiro-Wilk test) of residuals for models estimating latex (kg tree^{-1} year^{-1}) and cernambi (kg tree^{-1} year^{-1}) production in rubber plantations located in the Tapajós National Forest, Belterra, Pará.

Model	***p*-value**			
	Breusch-Pagan Test		**Shapiro-Wilk Test**	
	La	***Ce***	***La***	***Ce***
1	0.0009	0.0002	0.0046	0.0072
2	0.0023	0.0007	0.0024	0.0027
3	0.0408	0.0118	0.9640	0.8260
4	0.1213	0.0516	0.9965	0.5930
5	0.0010	0.0002	0.0073	0.0130
6	0.0007	0.0002	0.0124	0.0163
7	0.0298	0.0075	0.7956	0.6279
8	0.0294	0.0080	0.8709	0.6158
9	0.0012	0.0004	0.0009	0.0015
10	0.0940	0.0447	0.8450	0.5262
11	0.0000	0.0001	0.0197	0.0046
12	0.0059	0.0085	0.8506	0.8342

Where: La=latex; Ce=cernambi.

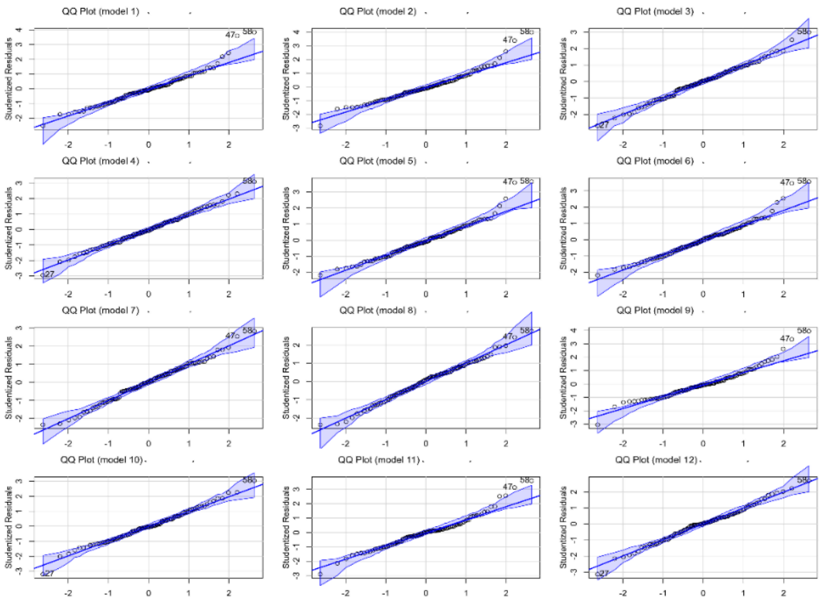

Figure 5. Quantile-quantile (Q-Q) plots of studentized residuals for the twelve models evaluated to estimate latex production in rubber plantations in the Tapajós National Forest, Belterra, Pará, Brazil. Each panel corresponds to one fitted model. Source: The authors.

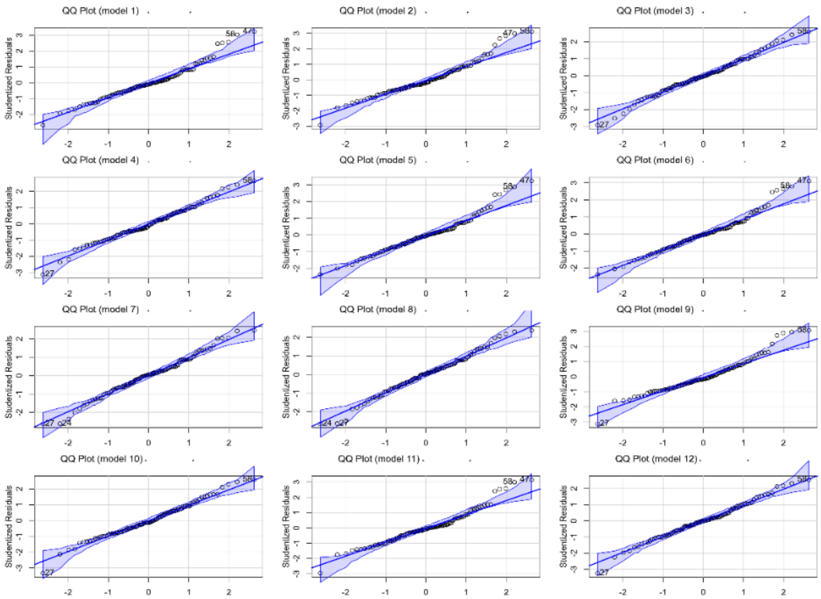

Figure 6. Quantile-quantile (Q-Q) plots of studentized residuals for the twelve models evaluated to estimate cernambi production in rubber plantations in the Tapajós National Forest, Belterra, Pará, Brazil. Each panel corresponds to one fitted model. Source: The authors.

Normality plots (Figures 5 and 6) confirmed that the residuals of Models 4 and 10 follow a distribution close to normal, as evidenced by the proximity of the points to the reference line in the Q-Q plots. This graphical analysis complements the results of the statistical tests, supporting the consistency of the evaluated models within the sampled dataset.

Among the evaluated models, Models 4 and 10 stood out as the most suitable for latex estimation, combining satisfactory statistical performance with operational simplicity. These models use variables that are easily obtained in the field, such as *DBH*, total height (*Ht*) and commercial height (*Hc*), which favours their practical application.

For cernambi, Models 4 and 10 also showed the most suitable performance among the evaluated models. Model 4 had all significant coefficients and fully met the statistical assumptions. Model 10 presented significant coefficients and showed no evident residual patterns, despite the *p*-value of the homoscedasticity test being slightly below the significance threshold. Both models rely on practical variables - D^2h for Model 4 and D^2h plus ln *Hc* for Model 10 - which ensures operational simplicity, an essential feature for field applications, particularly in sustainable management projects and production monitoring.

Selection of models and final equations

The Bland-Altman plots (Figure 7) indicated agreement between observed and estimated values for both latex and cernambi. Over 95% of the points were within the agreement limits, supporting the consistency of the fitted models within the sampled dataset.

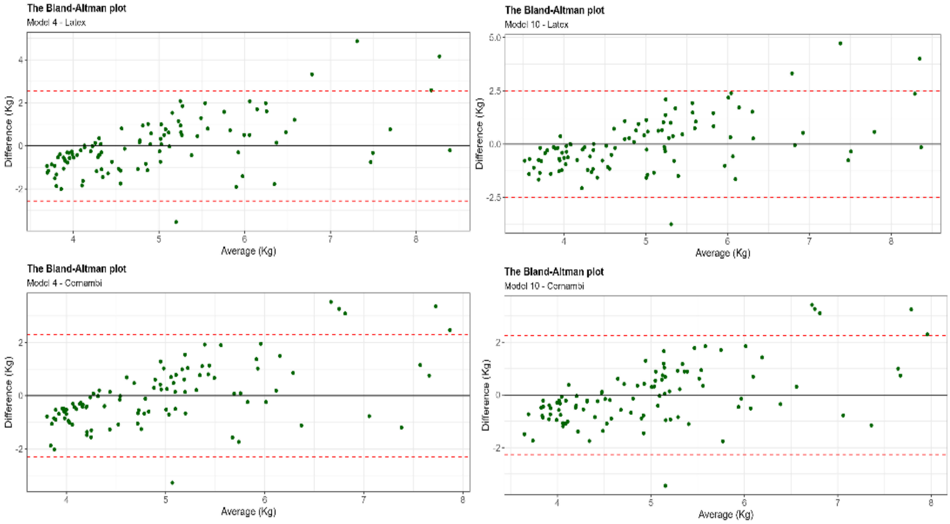

Figure 7. Bland-Altman agreement plots for Models 4 and 10 applied to latex and cernambi production estimation in rubber plantations in the Tapajós National Forest, Belterra, Pará, Brazil. The panels show the agreement between observed and estimated values for latex (upper panels) and cernambi (lower panels). The solid horizontal line represents the mean difference between observed and estimated values (bias), and the dashed lines indicate the upper and lower limits of agreement. Source: The authors.

Based on the results obtained and the analyses performed, Model 4 was selected as the most suitable alternative for estimating latex and cernambi production in rubber plantations in the Tapajós National Forest, Belterra, Pará. This choice was supported by its consistent statistical performance and operational simplicity, using only *DBH* and total height (*Ht*) as explanatory variables. In comparison, although Model 10 showed similar statistical performance, it requires an additional variable (ln *Hc*), which may slightly increase the complexity, even though it is easily obtainable in the field.

The fitted equation to estimate latex production (*La*) is:

$$\ln La = 1.354 + 0.00000509 \times D^2h$$

The equation to estimate cernambi production (*Ce*) is:

$$\ln Ce = 1.389 + 0.00000483 \times D^2h$$

These equations indicate that the estimated production of latex and cernambi is positively associated with the product of the square of the diameter (DBH^2) and total height (*Ht*), reflecting a pattern consistent with the productive structure of the studied plantations. This simplicity supports its practical application in forest inventories, especially in areas with similar ecological and structural characteristics.

To further assess the predictive performance of Model 4, a 10-fold cross-validation procedure was applied (Table 12).

Table 12. Cross-validation statistics for Model 4 selected to estimate latex and cernambi production in rubber plantations located in the Tapajós National Forest, Belterra, Pará.

Product	R^2_{cv}	$RMSE_{cv}$	MAE_{cv}	$Bias_{cv}$	Syx_{cv} (%)
La	0.294	1.317	0.994	0.008	26.14
Ce	0.259	1.204	0.932	0.006	24.15

Where: La=latex; Ce=cernambi; R^2_{cv}=cross-validated coefficient of determination; $RMSE_{cv}$=root mean square error (kg tree^{-1} year^{-1}); MAE_{cv}=mean absolute error (kg tree^{-1} year^{-1}); $Bias_{cv}$=mean prediction bias (kg tree^{-1} year^{-1}); Syx_{cv} (%)=cross-validated relative standard error of estimate.

The similarity between the calibration statistics (R^2adj and Syx%) and the cross-validation statistics (R^2_{cv} and Syx_{cv}%) indicates that model performance remained stable when applied to unseen observations. The low bias values observed for both latex and cernambi further support the consistency of the selected models and suggest that model performance was not substantially inflated by calibration on the full dataset.

DISCUSSION

The heterogeneity in the rubber tree population reflects the complexity of areas combining planted and naturally regenerated trees. Although classified as plantations, these areas lack the uniformity of conventional plantations, showing variability typical of poorly managed stands (Scolforo, 2005; Gomes *et al.*, 2019).

This variability is particularly relevant for developing statistical models capable of accounting for differences across diameter classes, aiming to more accurately estimate latex and cernambi productivity.

The structural diversity, driven by varying tree origins and sizes, affects microclimate, light interception and productivity (Bizuti *et al.,* 2016). This variability suggests that management practices should account for differences in diameter classes and competition levels among trees, which is expected in mixed systems combining planting and natural regeneration (Scolforo, 2005). Practices incorporating structural variables may optimize production while preserving natural regeneration and ensuring long-term sustainability. The sampling results further reinforce the need for management and modelling approaches capable of accounting for this structural complexity.

In this context, agroforestry systems are viable alternatives to monoculture, aligning with growing global demand for natural rubber (Vicente *et al.*, 2011). Studies involving *Hevea brasiliensis* have shown that the species performs well in low-light, low-fertility and rainfall-variable environments, favouring diversified systems that balance sustainability and profitability (Vicente *et al.,* 2011). Although these observations were reported for *H. brasiliensis,* they provide a useful ecological and management reference due to the functional similarities among *Hevea* species in tropical production systems.

Diameter distribution showed an asymmetric pattern, concentrated in intermediate classes, indicating a predominance of trees at more advanced developmental stages and with higher productivity. This resembles the normal distribution in planted forests (Campos and Leite, 2017), reflecting the plantations' origin from decades-old stands. The scarcity of smaller trees suggests limited regeneration, likely due to seed bank depletion, competition, or poor recruitment conditions. The low number of large trees may result from past intensive management, premature harvesting, or lack of silvicultural interventions. As noted by Schroth *et al.* (2004), the scarcity of mature rubber trees in natural forests limits the productivity of traditional extractivism, reinforcing the role of rubber plantations as a viable alternative for natural rubber production.

This asymmetric pattern demands management strategies that promote regeneration and the recruitment of new individuals, ensuring the continuity of production (Carvalho *et al.*, 2020). In this context, thinning is a promising practice, especially in abandoned plantations where competition limits development. By opening the canopy, it stimulates light availability, succession (St-Onge *et al.*, 2013; Spiazzi Favarin *et al.*, 2024), seed germination and recruitment (Gomes *et al.*, 2010; Araki and Awaya, 2020), supporting long-term sustainability (Dietmaier *et al.,* 2019). Thinning thus enhances both productivity and economic viability.

Latex and cernambi production revealed significant differences across diameter classes, with larger and older trees proving more productive due to greater structural maturity. Younger and intermediate trees allocate more energy to vegetative growth and therefore exhibit lower productivity. Similar trends were observed by Gama *et al.* (2017) in Jamaraquá, where production increased with *DBH*. This underscores the need to consider structural characteristics for sustainable management.

In Terra Rica and Ponte plantations, trees with *DBH*≥60 cm were more productive for latex, while *DBH* ≥ 40 cm stood out for cernambi, corroborating the findings of (Gama *et al.*, 2017). However, their reported yields were higher, likely due to active management, unlike the abandoned stands in this study (Araújo, 2010). Productivity differences also depend on density, domestication level and spatial distribution (Gama *et al.*, 2017; Chao *et al.*, 2023; King-Smith *et al.*, 2025).

Although the production assessment was based on a subset of 101 sampled trees from a total inventoried population of 2,872 individuals, the sampling procedure was statistically defined considering the finite population structure and the variability of latex production (Soares and Paula-Neto, 1997). Furthermore, the sampled trees adequately represented the structural variability and the diameter range observed in the plantations. The reduced frequency of individuals in extreme *DBH* classes reflects the natural asymmetric structure of the studied stands, where very large trees are inherently less abundant. Similar limitations have been reported for tropical forest modelling studies, in which adequate modelling performance was obtained with moderate sample sizes when comprehensive model evaluation procedures were adopted (Leão *et al.*, 2021). Nevertheless, caution is recommended when interpreting predictions or mean comparisons involving poorly represented extreme diameter classes.

The native rubber plantations in the Tapajós National Forest are crucial for traditional populations and local livelihoods, but variability in tree size poses management challenges. A deeper understanding of structural factors supports strategies that balance productivity and ecological resilience.

Although latex production modelling is well established for *Hevea brasiliensis* in several plantation contexts, fewer studies have addressed Amazonian forest-based rubber systems, particularly those involving *Hevea guianensis*. The available literature has largely focused on biomass estimation (Li *et al.*, 2023) or on latex yield prediction based on climatic variables, mainly in Southeast Asian contexts (Rao *et al.*, 1998; Raj *et al.*, 2005). In Brazil, modelling approaches remain limited and are often restricted to isolated case studies with narrow structural or spatial scope (Azevedo, 2022). Similar predictive efforts using structural and environmental predictors have shown promising results for dry rubber yield in other contexts (Huang *et al.*, 2020), reinforcing the relevance of developing site-specific models under Amazonian conditions. In this sense, the inclusion of cernambi production represents an additional contribution, as empirical modelling of this product remains limited in the literature.

The Spearman test in this study identified D^2h and *DBH* as the best predictors for latex and cernambi, respectively, results consistent with findings in other Amazonian and tropical contexts (Jaramillo-Giraldo *et al.*, 2017; Schroth *et al.*, 2004). Azevedo (2022) also employed Spearman correlation for variable selection but faced low model performance due to high variability in productivity, which limits predictive accuracy. *DBH* and total height were equally relevant in allometric biomass models for *Hevea brasiliensis* in India (Brahma *et al.*, 2017), reinforcing the relevance of structural variables as predictors within the genus *Hevea*.

In progenies of *Hevea* evaluated under Brazilian conditions, structural and morphological traits such as girth, bark thickness and leaf dimensions also showed significant correlations with rubber yield, reinforcing the role of such variables as reliable indicators for productivity (De Castro Sant'Anna *et al.*, 2020). While *DBH* or height alone may be sufficient in some contexts, our results suggest that combining these variables into a composite index like D^2h better represents structural complexity within heterogeneous stands.

Although D^2h is commonly associated with biomass-related structural attributes, its relationship with latex and cernambi production likely reflects indirect effects of tree structural development on productive potential, including crown expansion, bark availability, conductive tissue development and carbon allocation capacity. Therefore, D^2h should be interpreted as a biologically meaningful structural descriptor associated with production performance rather than as a direct representation of physiological latex production mechanisms.

Several factors influence latex production, including tapping methods, panel size, soil characteristics, climatic conditions, water availability, genetic potential, planting density, wind exposure, pests and diseases (Mesquita *et al.*, 2006; Moraes *et al.*, 2013; Li *et al.*, 2014; Gama *et al.*, 2017; Azevedo, 2022; Zhai *et al.*, 2023). Studies such as (Suwanchana *et al.*, 2020; Sugiarto *et al.*, 2024) reinforce the complexity of these interactions, showing that latex yield is strongly influenced not only by environmental factors like rainfall and soil moisture but also by clone selection, tapping frequency and fertilization strategies. These findings help explain the moderate explanatory capacity of the fitted models, highlighting the multidimensional nature of productivity dynamics in rubber plantations and the importance of integrating structural, environmental, genetic and management-related variables into modelling approaches.

Although D^2h and *DBH* likely integrate part of the environmental, genetic and management-related influences on productivity, a portion of the unexplained variability may still be associated with factors not explicitly incorporated into the fitted models, such as soil properties, rainfall variability, tapping intensity and genetic variation among individuals.

Findings indicate that *DBH* and height are key variables, with significant positive correlations for both products. Canopy-related variables, especially crown area, showed significant correlation with latex but not cernambi, suggesting light plays a larger role in latex production.

The low and mostly non-significant correlations observed for morphometric indices indicate that these variables have limited predictive capacity for latex and cernambi production in the studied plantations.

Among the evaluated models, Models 4 and 10 showed the most suitable statistical performance. Although Model 10 presented slightly higher explanatory power and lower prediction error, the differences relative to Model 4 were modest. Therefore, Model 4 was preferred because it achieved comparable predictive performance while relying only on *DBH* and total height, variables routinely collected in forest inventories. In contrast, Model 10 requires an additional predictor (ln *Hc*), increasing model complexity and data collection effort. Under these circumstances, the marginal improvement in statistical performance did not outweigh the operational advantages of the more parsimonious Model 4.

The 10-fold cross-validation results further reinforced the suitability of Model 4 for practical applications. The similarity between calibration statistics and cross-validation statistics indicates that predictive performance remained stable when the model was applied to unseen observations. In addition, the low bias values obtained for both latex and cernambi suggest limited systematic prediction error and support the robustness of the selected model within the sampled dataset. These findings provide additional evidence that the selected model can generate reliable estimates under the range of structural conditions represented in the sampled plantations.

The moderate explanatory power observed for the selected models should be interpreted in the context of the high structural, environmental and management-related heterogeneity characteristic of Amazonian rubber plantations. In this sense, the cross-validation results indicate that the predictive relationships identified by the model remain stable despite this inherent variability.

The simplicity of Model 4 and its consistent statistical performance make it a valuable tool for future studies and practical applications, especially in sustainable management projects that require fast and accessible measurements. Additionally, the use of easily measurable variables increases its applicability in tropical regions with similar forest characteristics. Thus, the results of this study may be applicable to rubber plantations under similar ecological, structural and management conditions, supporting their use as a site-specific planning tool for Amazonian rubber systems.

Production modelling is vital for developing adaptive strategies, particularly considering the species' climate sensitivity (Pinizzotto *et al.*, 2021). Das *et al.* (2022) demonstrated that, in India, rubber plantations are being cultivated under hot and humid tropical climates, similar to the Tapajós region, and that the impact of anthropogenic disturbances and native management practices are fundamental variables for developing appropriate management strategies when assessing forest conservation and the ecosystem services provided by plantations.

The results have direct implications for management, highlighting the importance of integrating structural and productive information into planning, which enables the development of adaptive strategies that consider diameter variability and tree development stages. However, some limitations must be acknowledged, such as the absence of edaphoclimatic factors in the analysis, which significantly influence productivity. Future studies should address these gaps by incorporating genetic and environmental variables, as well as considering long-term dynamics, to provide a more comprehensive understanding of the productivity of Amazonian rubber plantations. This study contributes to the development of quantitative tools for supporting the management of latex and cernambi production in *Hevea guianensis* plantations in the Tapajós National Forest.

CONCLUSIONS

Latex and cernambi production in *Hevea guianensis* plantations was positively associated with tree size, particularly with diameter- and height-related structural attributes. Among the evaluated predictors, D^2h proved to be the most suitable variable for modelling production, while morphometric indices showed limited predictive capacity.

The selected models exhibited satisfactory statistical performance, operational simplicity and stable predictive behaviour under cross-validation, supporting their application for estimating latex and cernambi production within the range of structural conditions represented in the studied plantations.

These findings contribute to the quantitative support of *Hevea guianensis* management under Amazonian conditions, particularly in community-based production systems, providing practical tools to support production planning and the sustainable use of forest resources.

ACKNOWLEDGEMENTS

The authors thank the institutions that supported the development of this research: the National Council for Scientific and Technological Development – Brazil (CNPq), the Coordination for the Improvement of Higher Education Personnel – Brazil (CAPES), the Tapajós Flona Mixed Cooperative (COOMFLONA), the Chico Mendes Institute for Biodiversity Conservation (ICMBio), the Federal Rural University of the Amazon (UFRA), the Federal University of Paraná (UFPR) and the Forest Ecosystem Management Laboratory at the Federal University of Western Pará (UFOPA).

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