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VEGETATION SUCCESSIONAL STRATA CLASSIFICATION IN THE AMAZON ESTUARY THROUGH QUANTILE REGRESSION

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Resumo

Classificação de estratos sucessionais da vegetação usando regressão quantílica no estuário amazônico. A classificação dos estratos sucessionais da vegetação é essencial para orientar ações de manejo florestal e conservação, especialmente em ambientes amazônicos de várzea. Desta forma, o objetivo do trabalho foi classificar os estágios sucessionais em uma região de floresta amazônica. Os dados foram coletados por meio de um inventário florestal permanente em uma área de várzea no estuário amazônico, nas proximidades da cidade de Gurupá-PA, distrito de Itatupã. Os dados foram ajustados a dois modelos hipsométricas, sendo: Curtis e Stoffels. Para selecionar a melhor equação foram utilizados a raiz quadrada do erro quadrático médio (RQEM), coeficiente de correlação de Pearson ($r_{\hat{y}y}$), critério de informação Akaike (AIC), bias e distância média absoluta (DMA). Foram plotadas também distribuição residual dos erros e gráfico de linhas de tendência e a classificação dos estratos sucessionais. Os resultados foram satisfatórios, a regressão quantílica foi eficiente e a equação de Stoffels apresentou os melhores resultados e a mesma equação por meio do ajuste de seus coeficientes, conseguiu classificar diferentes estágios sucessionais no estuário amazônico.
Palavras-chave: método robusto, equação de Stoffels, modelagem.

Abstract

Vegetation successional strata classification in the amazon estuary through quantile regression. Vegetation successional strata classification is essential for guiding forest management and conservation, particularly in Amazonian floodplain environments. This study sought to classify successional stages in a floodplain forest of the Amazon estuary by adjusting height–diameter models using quantile regression. Data were collected from a permanent forest inventory in Gurupá, Pará. Two models (Curtis and Stoffels) were tested, and their performance was evaluated using root mean square error (RMSE), Pearson's correlation coefficient, Akaike information criterion (AIC), bias, and mean absolute deviation (MAD). Residual distribution and trend line plots were also analyzed. Quantile regression proved to be an efficient method for fitting the models, with the Stoffels equation showing the best performance. By adjusting its coefficients, this equation enabled the classification of species across different successional strata, demonstrating the potential of quantile regression as a robust tool for analyzing forest structure in heterogeneous environments.
Keywords: robust method, Stoffels equation, modeling.

INTRODUCTION

The Amazon rainforest is home to one of the world's greatest biodiversity reserves, with a remarkable variety of vegetation types that support numerous endemic species. Through intricate ecological interactions, the Amazon biome forms a distinctive system composed of biotic and abiotic elements found only in this region (LOVEJOY & NOBRE, 2018). Beyond timber use, the Amazon forest provides a wide range of non-timber products, such as fruits, oils, fibers, resins, and medicinal plants, which are fundamental for local communities and regional economies. Forest inventories are therefore essential not only to quantify timber resources but also to assess the availability and ecological role of these non-timber products, contributing to a better understanding of forest use, management potential, and ecological dynamics (SANTOS *et al.*, 2017).

Managing multiple species facilitates the identification of successional stages and the grouping of species into ecological categories. Such studies contribute to the restoration of degraded areas and enhance plant populations' regenerative capacity and non-timber production potential, thereby increasing their economic value (WERDEN *et al.*, 2022).

Comprehending forest behavior and dynamics represents the first and most crucial stage in effective forest management planning. Such plans are usually grounded in existing forest data, encompassing stock volume, tree density, height, diameter, structural defects, and growth characteristics. Phytosociological assessments are indispensable for collecting this foundational information (PIMENTEL *et al.*, 2024).

In this regard, population ecology serves as a fundamental yet often neglected component of conservation science. By examining recruitment, mortality, and growth dynamics through time, it offers critical understanding of ecosystem resilience and natural regeneration processes. Integrating these dynamics is key to developing predictive models capable of reconciling long-term resource exploitation with conservation priorities (MA *et al.*, 2016).

In ecological succession studies, height-diameter models provide valuable insights into vegetation's vertical structure and species distribution across strata. To understand the relationship between total height (H) and diameter at breast height (D), height is measured up to the first branch using a hypsometer, depending on crown visibility and bole height (hf) (CAMPOS & LEITE, 2017). Height-diameter equations are essential for estimating heights in dense areas where direct measurement is not always feasible. Several models may be applied based on stand type or species, such as Stoffels, Curtis, parabolic, and linear models, which are widely recommended for such analyses (DA SILVA *et al.*, 2024).

Quantile regression can be a key tool for classifying forest successional strata, offering a more robust and detailed analysis than traditional methods. Unlike ordinary least squares (OLS), which estimates the conditional mean of the dependent variable, quantile regression estimates different quantiles of the conditional distribution, providing a broader understanding of data variability. This is particularly important in forest studies, where structural heterogeneity is typical and simple averages may not adequately reflect the diversity of tree heights and diameters across successional stages.

Thus, we hypothesize that quantile regression models are capable of accurately distinguishing forest successional strata based on structural variables. This approach can reveal variations not captured by mean regression, making it especially useful for heterogeneous forest environments. The aim was to investigate the successional stage of a floodplain forest in the Amazon estuary using quantile regression to classify tree species.

MATERIAL AND METHODS

Database

The data were collected from a forest inventory conducted in an Amazon estuary area known locally as "Rio Chato," located within the municipality of Gurupá, Pará, in the district of Itatupã. The "Rio Chato" area comprises 54 hectares, with coordinates 0°32'54.68"S and 51°15'11.10"W. According to the Köppen classification, the regional climate is equatorial (type Am), being hot and humid—typical of the Amazon region.

For the forest inventory, six permanent plots of 5,000 m² each (50×100 m) were established using a systematic and evenly spaced design, totaling 30,000 m² of sampled area. Only trees with a diameter at breast height (DBH) ≥ 4.78 cm, corresponding to a circumference of 15 cm, were considered.

Data Analysis

The parameters of the height-diameter models were estimated using quantile regression via the Simplex algorithm, and trend lines were adjusted based on the quantile level proposed by Rodrigues *et al.* (2016):

The quantile regression model is:

$$Q_\tau(y_i) = \beta_0(\tau) + \beta_1(\tau)x_{i1} + \cdots \beta_p(\tau)x_{ip}, \ldots i = 1 \ldots \ldots . n$$

The $\beta_j(\tau)$s parameters are estimated by solving the minimization problem:

$$min_{\beta 0 \ldots\ldots \beta p(\tau)} \sum_{i=1}^{n} \rho\tau \left(y_i - \beta_0(\tau) - \sum_{j=1}^{p} x_i \beta_j(\tau) \right)$$

Where: $\rho_\tau(r) = \tau \max(r,0) + (1-\tau) \max(-r,0)$.

The function $\rho_\tau(r)$ is called the check loss function, as its shape resembles a check mark.

For each quantile level τ, solving the minimization problem yields a distinct set of regression coefficients. Note that τ = 0.5 corresponds to the median regression, and $2\rho_{0.5}(r)$ equals the absolute value function.

The height-diameter models used in this study were selected based on Gama e Andrade (2018) and include two logarithmic models, as shown below:

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Table 1. Height-diameter models were tested with data from the forest inventory of the Amazonian estuary area known as Rio Chato/PA.
Tabela 1. Modelos hipsométricos testados com os dados provenientes do inventário florestal de uma área de estuário amazônico denominado por Rio Chato/PA.

Nº	Author	Model
1º	Curtis	$lnH = \beta_0 + \frac{\beta_1}{D} + \varepsilon$
2º	Stoffels	$lnH = \beta_0 + \beta_1 lnD + \varepsilon$

Where:
ln = natural logarithm;
H = total tree height;
D = diameter at 1.30 m from ground level;
β_0,β_1,β_2= parameters estimated via regression.
These models were fitted using the quantreg package in the R software.

The response variable (total height) was log-transformed prior to model fitting in order to reduce the scale of variation and mitigate the effect of extreme values commonly observed in forest inventory data. This type of transformation is particularly useful when modeling variables with skewed distributions, such as tree heights, which often show asymmetric patterns due to ecological variability across successional stages. Although quantile regression does not require the assumptions of normality or homoscedasticity, transforming the response variable can improve interpretability and numerical stability of the model, especially when comparing across quantiles in heterogeneous forest structures (KOENKER, 2005).

To identify the model that provided the best fit, criteria were defined according to the accuracy in estimating the dependent variable — in this case, height (H). The evaluation was carried out using several statistical measures: root mean square error (RMSE), Pearson correlation coefficient, Akaike Information Criterion (AIC), bias, and mean absolute deviation (MAD). Additionally, graphical analyses of residuals and trend line plots for each regression percentile were examined.

Classification of Successional Strata

After selecting the best-fitting equation, species were classified into ecological successional strata based on height using height-diameter equations adjusted at quantile levels (q) of 10%, 30%, 50%, 70%, 90%, and 99%. Curves were generated for each quantile and plotted to represent the overall height-diameter relationship for the study area.

Species found in the lowest quantiles were classified as suppressed, those in intermediate quantiles as co-dominant, and those in the highest quantiles as dominant.

RESULTS

After selecting the best-fitting equation, species were classified into ecological successional strata based on height using height-diameter equations adjusted at quantile levels (q) of 10%, 30%, 50%, 70%, 90%, and 99%. Curves were generated for each quantile and plotted the overall height-diameter relationship for the study area. Species found in the lowest quantiles were classified as suppressed, those in intermediate quantiles as co-dominant, and those in the highest quantiles as dominant.

Table 2. Statistical criteria were evaluated for the height-diameter equations from the forest inventory of an Amazon estuary area called Rio Chato/PA.
Tabela 2. Critérios estatísticos avaliados nas equações hipsométricas, proveniente do inventário florestal de uma área de estuário amazônico denominado por Rio Chato/PA.

Equations	RSME	$r_{y\hat{y}}$	AIC	Bias	MAD
Curtis	4.5003	0.7943	216.286	-0.5001	2.5908
Stoffels	4.4570	0.7953	217.332	-0.0864	2.7720

Legend: RMSE = root mean square error; $ry\hat{y}$ = Pearson correlation coefficient; AIC = Akaike Information Criterion; Bias in percentage; MAD = mean absolute deviation.

Regarding the AIC results, both logarithmic models (Curtis and Stoffels) demonstrated low information loss, indicating a better quality of fit. These models also showed low bias, suggesting a slight underestimation of the dataset values, with results close to zero. In terms of mean absolute deviation (MAD), Curtis and Stoffels presented similar values, around 2.

Figure 1 displays the residuals plotted against the estimated values. Each graph corresponds to a different model: Stoffels and Curtis, respectively. Both equations exhibited a good residual distribution along the axis. For the Curtis model, residuals were concentrated between 5 m and 25 m. The Stoffels equation showed the best residual distribution in this dataset, providing accurate height predictions without significant underestimation or overestimation.

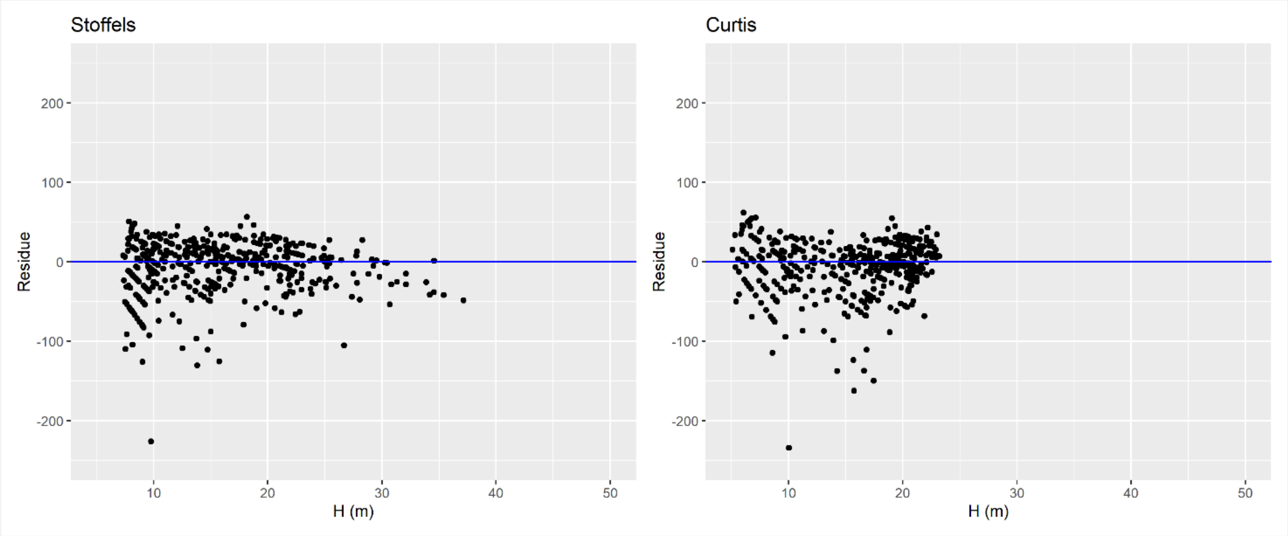

Figure 1. Graphical representation of the distribution of residuals for the Stoffels and Curtis equations, respectively, from the forest inventory of an Amazon estuary area called Rio Chato/PA.

Figura 1. Representação gráfica da distribuição dos resíduos relativos das equações de Stoffels e Curtis respectivamente, proveniente do inventário florestal de uma área de estuário amazônico denominado por Rio Chato/PA.

Figure 2 displays the trend lines fitted by the proposed height-diameter models. The graph reveals that tree heights in the dataset reach up to 40 meters, with most trees having diameters of up to 0.5 meters. This indicates that the majority of the data are concentrated in this diameter interval, reflecting the predominant size structure of the sampled trees.

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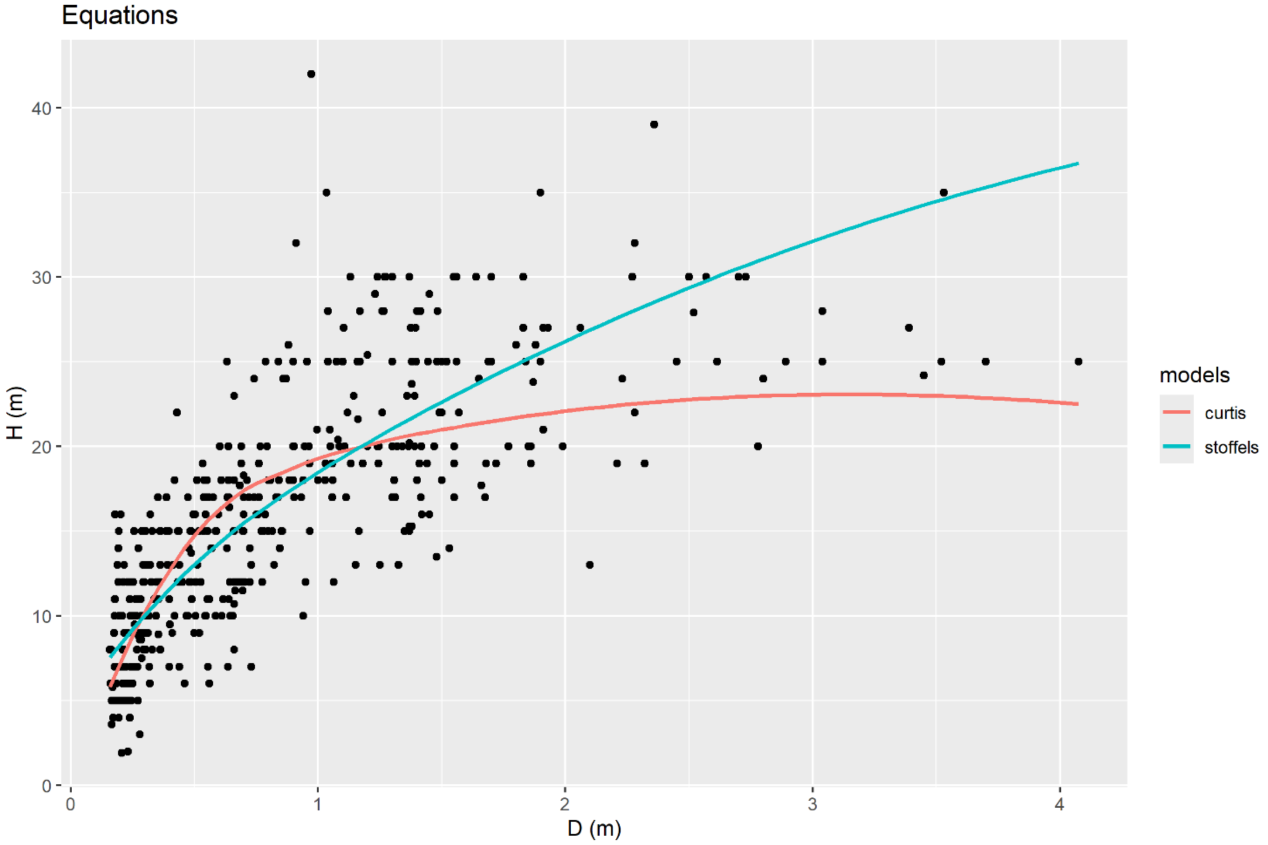

Figure 2. The trend line graph is fitted by the tow height-diameter equations from the forest inventory of an Amazon estuary area called Rio Chato/PA.

Figura 2. Gráfico de linha de tendência ajustado pelas duas equações hipsométricas, proveniente do inventário florestal de uma área de estuário amazônico denominado por Rio Chato/PA.

The Stoffels equation best fits the data, achieving a better adjustment than the Curtis model. Although Curtis performed well, it failed to predict the height of trees taller than 25 m.

Figure 3 presents the classification the successional strata, where each band across the plot represents a percentile fitted by the best height-diameter equation (Stoffels), according to the statistical criteria: 10%, 30%, 50%, 70%, 90%, and 99%, from bottom to top, respectively.

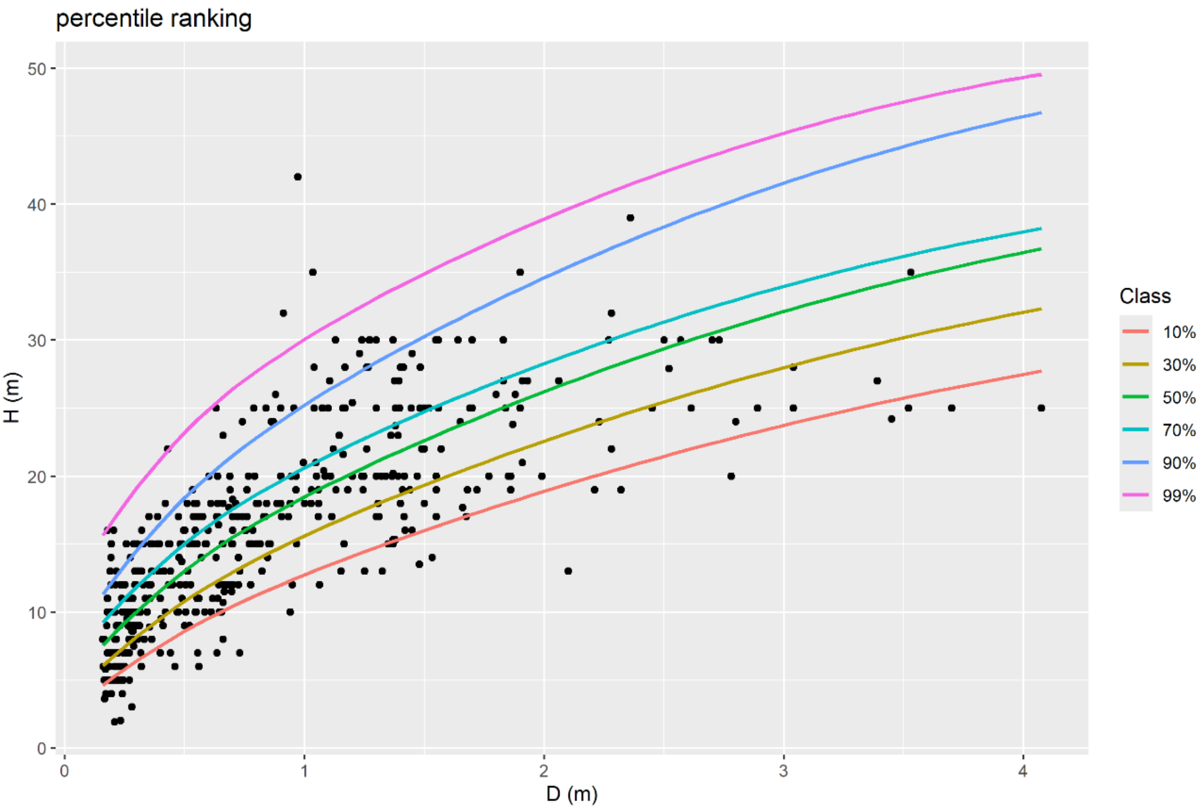

Figure 3. Percentile graph (10%, 30%, 50%, 70%, 90%, and 99% from bottom to top, respectively) from the forest inventory of an Amazon estuary area called Rio Chato/PA.

Figura 3: Gráfico de percentis 10%, 30%, 50%, 70%, 90% e 99% de baixo para cima respectivamente, proveniente do inventário florestal de uma área de estuário amazônico denominado por Rio Chato/PA.

The analysis of the height-diameter distribution showed a gradual variation across percentiles. Approximately 9.68% of the trees were grouped in the first percentile (10%), followed by 20.50% in the second (30%) and 20.05% in the third (50%). The fourth percentile (70%) contained 19.82% of individuals, and the fifth (90%) included 20.27%. The remaining 9.01% were in the sixth and last percentile (99%), while 0.68% of the trees exceeded the 99th percentile and were identified as outliers.

The data indicate a relatively uniform distribution of trees across the different strata, suggesting a well-structured and balanced forest. While approximately 50.23% of the individuals were below the median (50th percentile), the forest continued to display structural diversity, with trees occupying every stratum in distinct proportions.

Table 3 describes the distribution of different species across specific percentiles after adjusting a height-diameter model using quantile regression. The percentiles are labeled P10, P30, P50, P70, P90, P99, and outlier. Each column represents a percentile of the tree height distribution adjusted by the model. The number in each cell indicates the count of individuals of a given species in that specific percentile.

Table 3. Distribution of species per percentile from the forest inventory of an Amazon estuary area called Rio Chato/PA.

Tabela 3- Distribuição de espécies por percentil proveniente do inventário florestal de uma área de estuário amazônico denominado por Rio Chato/PA.

Species	***P 10***	***P 30***	***P 50***	***P 70***	***P 90***	***P 99***	***outlier***	***Total***
Calophytlum resilience			3	2	1	1		7
Allantoma integrifolia			1		3			4
Allantoma sp.			2		2	1		5

Species	P 10	P 30	P 50	P 70	P 90	P 99	outlier	Total
Amburana cearensis				1				1
Anaxagorea manausensis	3		1		3			7
Annona cherimola	1							1
Calycophyllum spruceanum	1	2	4	4	3		1	15
Candolleodendron sp.	1			1				2
Caraipa grandiflora	4	7	10	4	10	3		38
Carapa guianensis	2	8	15	17	13	10		65
Cecropia pachystachya			2					2
Handroanthus umbellatus.			1					1
Hevea brasiliensis	3	3	2	3	2	1		14
Hura crepitans				1				1
Hura crepitans	1	1						2
Indeterminado			1					1
Indeterminado 2	1							1
Indeterminado 3	2		2	2	1			7
indeterminate 4	2							2
Indeterminado 5		1						1
Indeterminado 6	4	3	1					8
Inga alba			1	1				2
Lecythis lurida	1							1
Licania macrophylla	1	1	5	2	3			12
Matisia paraensis	1	3						4
Mora paraensis	1	5	6	9	6	2		29
Pachira aquatica		1						1
Pachira aquatica	1							1
Parviflora sp		1	2			3		6
Pentaclethra macroloba	4	5	2	2	3	1		17
Pseudolmedia macrophylla				1	1			2
Pterocarpus amazonicum		1			1			2
Pterocarpus draco		2			2			4
Rinorea lindeniana	3	6						9
Sapium prunifolium		3	1	1	2			7
Spondias mombin		2						2
Sterculia excelsa						1		1
Sterculia speciosa		3	2	5	3			13
Swartzia acuminata	1	12	5	8	3	2	1	32
Symphonia globulifera	1	3	4	1	6	5		20
Terminalia argentea		1		1	1	1		4
Terminalia guianensis	2	4	1	2	3			12
Vatairea guianensis		1		1				2
Virola surinamensis	2	12	15	19	18	9	1	76
Total	**43**	**91**	**89**	**88**	**90**	**40**	**3**	**444**

Forty-four species were recorded and distributed across the percentiles. The number of individuals varied significantly between percentiles, indicating variability in height distribution within and among species.

The most abundant species were *Virola surinamensis*, 76 individuals, and *Carapa guianensis*, 65 individuals, found across all percentiles. *Caraipa grandiflora* was most abundant in the P50 percentile (10 individuals), while *Swartzia acuminata* was most represented in P30 (12 individuals).

This table provides a detailed overview of the height-diameter relationship of tree species in a floodplain forest area, modeled through percentiles using quantile regression. This approach allows for a robust analysis of height-diameter relationships, highlighting intra- and interspecific variation in tree heights.

DISCUSSION

According to the residual distributions presented in this study, the Stoffels equation showed the lowest estimation error and the highest correlation. The adjusted models behaved similarly to those analyzed by Jesus *et al.* (2015) in clonal stands of Eucalyptus urophylla × Eucalyptus grandis in the Federal District and by Souza *et al.* (2017), who fitted traditional height-diameter models for a hybrid Eucalyptus urophylla × Eucalyptus grandis stand at eight years of age in Pacajá, Pará, achieving high precision statistics. Although these studies were conducted in planted forests, they reinforce the statistical robustness of nonlinear models. Comparable evidence has also been reported in natural tropical forests, where nonlinear height-diameter models, analogous to the Stoffels formulation, provided accurate and site-specific predictions of tree height (SCARANELLO *et al.*, 2012; LIMA *et al.*, 2021). These findings support the selection of the Stoffels model based on the statistical criteria evaluated, as it yielded superior results in fitting and precision for estimating tree height. According to Machado *et al.* (2019), nonlinear models better explained the height variable, with the Stoffels model showing the best fit.

At this stage, analyzing residual distributions is essential. Draper and Smith (1981) and Silveira (2009) state that even if all statistics indicate a good model fit, residual analysis is crucial for choosing the best equation, as it helps identify errors across class amplitudes or in one or more tested variables. The AIC and bias criteria also pointed to lower information loss in the Curtis model, which showed higher values and, thus, greater loss of information. Sanquetta *et al.* (2015) suggest that AIC can be a reliable fit criterion in forest inventories.

Supporting this study, Zonete *et al.* (2010), when estimating biometric parameters in eucalyptus clones, observed a strong correlation between the 90th percentile (height) and conventional variables such as mean tree height and dominant tree height. According to Cade and Noon (2003), quantile regression allows a more detailed analysis of relationships between variables, especially in forest ecosystems where data can be highly heterogeneous.

This approach provides a more comprehensive view of forest structure, identifying different strata and contributing to more efficient and sustainable forest management. Furthermore, quantile regression techniques have been successfully applied in various forestry contexts, such as site classification (Araujo *et al.*, 2016) and for mitigating the influence of outliers (Abreu *et al.*, 2021).

Thus, as Sanquetta (1995) emphasized, identifying the different strata within a forest is crucial for forest management, as this type of analysis helps to understand natural regeneration strategies, growth, and survival for each species. Quantile regression, by modeling different quantiles of variable distributions, offers a more detailed understanding of internal forest dynamics, enabling the identification of areas and species that stand out under different environmental and management conditions.

This methodological advancement offers practical applications in forest management, particularly in floodplain forests where tree growth patterns are irregular and influenced by hydrological and edaphic variability (JUNK *et al.*, 2011). Classifying species into successional stages using quantile curves enhances decision-making for selective logging, enrichment planting, and conservation zoning. It also strengthens biodiversity monitoring protocols by highlighting vertical structure complexity beyond average trends (POORTER *et al.*, 2021).

Furthermore, this approach demonstrates that height-diameter modeling can be extended beyond prediction to classification, providing an analytical bridge between biometric modeling and ecological interpretation (KOENKER, 2005). Such integration of robust statistical methods with ecological frameworks represents a significant step toward modernizing forest inventory practices in tropical environments. It provides a basis for using height–diameter quantiles as indicators of forest dynamics, regeneration conditions, and even gradients of anthropogenic disturbance.

Finally, the successful application of the Stoffels equation using quantile regression reinforces the viability of this method for use in other tropical forest regions, promoting more adaptive, data-sensitive approaches to stratification. This advancement is particularly relevant in the context of REDD+ projects, restoration initiatives, and forest certification programs, which increasingly demand precise, transparent, and replicable ecological assessments (STRASSBURG *et al.*, 2020).

CONCLUSIONS

- Quantile regression facilitated a refined analysis of the interrelationships among variables, a crucial aspect in complex forest ecosystems like the Amazon. This approach offered a comprehensive understanding of forest structure, supporting the identification of distinct strata and promoting more efficient and sustainable forest management.
- The use of quantile regression proved highly effective for modeling height–diameter relationships and identifying successional stages in Amazonian forests. This strong analytical framework supports the design of conservation policies and sustainable management approaches. Its use can also be expanded to other forest ecosystems to improve growth modeling and productivity predictions, reinforcing biodiversity preservation and overall forest sustainability.

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