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**Articles**

# Diametric modeling of five commercial species in a forest concession area in the Altamira National Forest in the Amazon biome

## Modelagem diamétrica de cinco espécies comerciais em área de concessão florestal na Floresta Nacional de Altamira no bioma Amazônia

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## ABSTRACT

The study of the diameter distribution of commercial species in the Amazon is fundamental for the planning and execution of the best forest management practices. Studies on this topic are essential for conservation and ecology of commercial species. This work aims to analyze the diameter structure of five forest species in three annual production units under forest concession, in the Altamira National Forest, in the state of Pará. Via forest census data, trees with a diameter at breast height ≥ 39 cm were measured. Then, the probability density functions were adjusted: Beta, Gamma, Normal, Weibull 2P, Weibull 3P. Species on the Red List of threatened species with high commercial value were found in the area. The diametric modeling demonstrated a unimodal pattern with a negative exponential trend. There was a decrease in the frequency of individuals from the diameter classes close to the Minimum Cutting Diameter (50 cm). The species *Cedrela odorata* and *Cordia bicolor* showed low frequencies of individuals per diameter class, with values being below three individuals per 100 hectares. The function Weibull 3P was able to represent the diameter distribution of *Cedrela odorata*, *Cordia bicolor*, *Handroanthus impetiginosus,* and *Handroanthus* sp species. In turn, Beta was able to represent the diameter structure for the *Handroanthus serratifolius* species.

**Keywords:** Forest census; Endangered species; Probability density functions; Sustainable forest management

## RESUMO

O estudo da distribuição diamétrica de espécies comerciais da Amazônia é fundamental para o planejamento e a execução de boas práticas de manejo florestal. Esses estudos são essenciais para a conservação e ecologia dessas espécies. O objetivo deste trabalho foi analisar a estrutura diamétrica de cinco espécies florestais em três unidades de produção anual sob concessão florestal, na Floresta Nacional de Altamira, no Pará. Por meio de dados de censo florestal, foram mensuradas as árvores que possuíam diâmetro à altura do peito ≥ 39 cm. Em seguida foram ajustadas as funções de densidade probabilística: *Beta*, *Gamma*, Normal, *Weibull 2P*, *Weibull 3P*. A área indicou a presença de espécies na Lista Vermelha de vulnerabilidade e ameaça para espécies com alto valor comercial. As modelagens diamétricas demonstraram um padrão unimodal com uma tendência exponencial negativa. Ocorreu uma diminuição na frequência de indivíduos a partir das classes diamétricas próximas do Diâmetro Mínimo de Corte (50 cm). As espécies *Cedrela odorata* e *Cordia Bicolor*, apresentaram baixas frequências de indivíduos por classe de diâmetro, com os valores estando abaixo de três indivíduos a cada 100 hectares. A função *Weibull 3P* foi capaz de representar a distribuição diamétrica das espécies *Cedrela odorata*, *Cordia bicolor*, *Handroanthus impetiginosus* e *Handroanthus sp*. Por sua vez, a função *Beta* foi capaz de representar a estrutura diamétrica para a espécie *Handroanthus serratifolius*.


**Palavras-chave**: Censo florestal; Espécies ameaçadas; Funções densidade de probabilidade; Manejo florestal sustentável

# 1 INTRODUCTION

The Amazon is the largest Brazilian biome, covering 5,015,146 km², corresponding to about 58.93% of the Brazilian territory (IBGE, 2022). The biome houses a great diversity of plant formations with distinct characteristics. However, the evident heterogeneity, combined with the lack of information about its behavior, has created challenges in the proper use of forest resources in the ecosystem (Silva Santos; Stepka; Hess, 2023). It is essential to know the characteristics of each species to enable the use of best silvicultural and conservation practices in the management of forest resources (Cruz; Nakajima; Silva; Hosokawa; Jardim; Corte, 2021).

One of the main dendrometric information of a forest is the diameter distribution of its individuals, which represents the number of individuals in each diameter class. Whether for production or sustainable use of forest resources, the diameter distribution allows the characterization of wood reserve available before and after logging, creating greater probabilities of temporal projections about tree population (Silva Santos; Stepka; Hess, 2023).

The study of diameter distribution enables identifying different forest typologies (Cruz; Nakajima; Silva; Hosokawa; Jardim; Corte, 2021). Diameter distribution is an essential and easy-to-use characteristic to represent the structure of a forest (Bila; Sanquetta, Dalla Corte; Freitas, 2022), via mathematical formulations, which can be important for the good planning and control of future forest activities, including future production planning (Limeira; Gregório; Silva; Ramos; Santana; Andrade; Santos, 2020). One of the ways to describe the diameter structure of a forest or species is using probability density functions (PDF), as they estimate the number of trees that occur within certain centers of diameter classes (Cruz; Nakajima; Silva; Hosokawa; Jardim; Corte, 2021; Campos; Leite, 2017).

Some species with high-value become heavily exploited in the Amazon, which can reduce their populations to critical levels (Vieira; Gomes; Saints; Olive tree; Range; Marie; Lafetá; Moura; Figueiredo, 2021). Given this context, some Amazonian species become increasingly susceptible to the Red List of threatened species, such as the *Cedrela odorata* (Brazil, 2021; CNCFlora, 2023), the *Handroanthus serratifolius* (Lohmann, 2023a), and the *Handroanthus impetiginosus* (CNCFlora, 2023; Lohmann, 2023b). Studies on these species' characteristics—especially regarding diameter, which is greatly influenced by wood harvesting—are extremely important to support the sustainability of forest activities, especially to correctly define their cutting cycle (Cruz; Nakajima; Silva; Hosokawa; Jardim; Corte, 2021).

Thus, this study aims to analyze the diameter distribution of five high-value species via PDF, in three Forest Management Units (FMU) in FLONA, Altamira/PA, in the Amazon Biome.

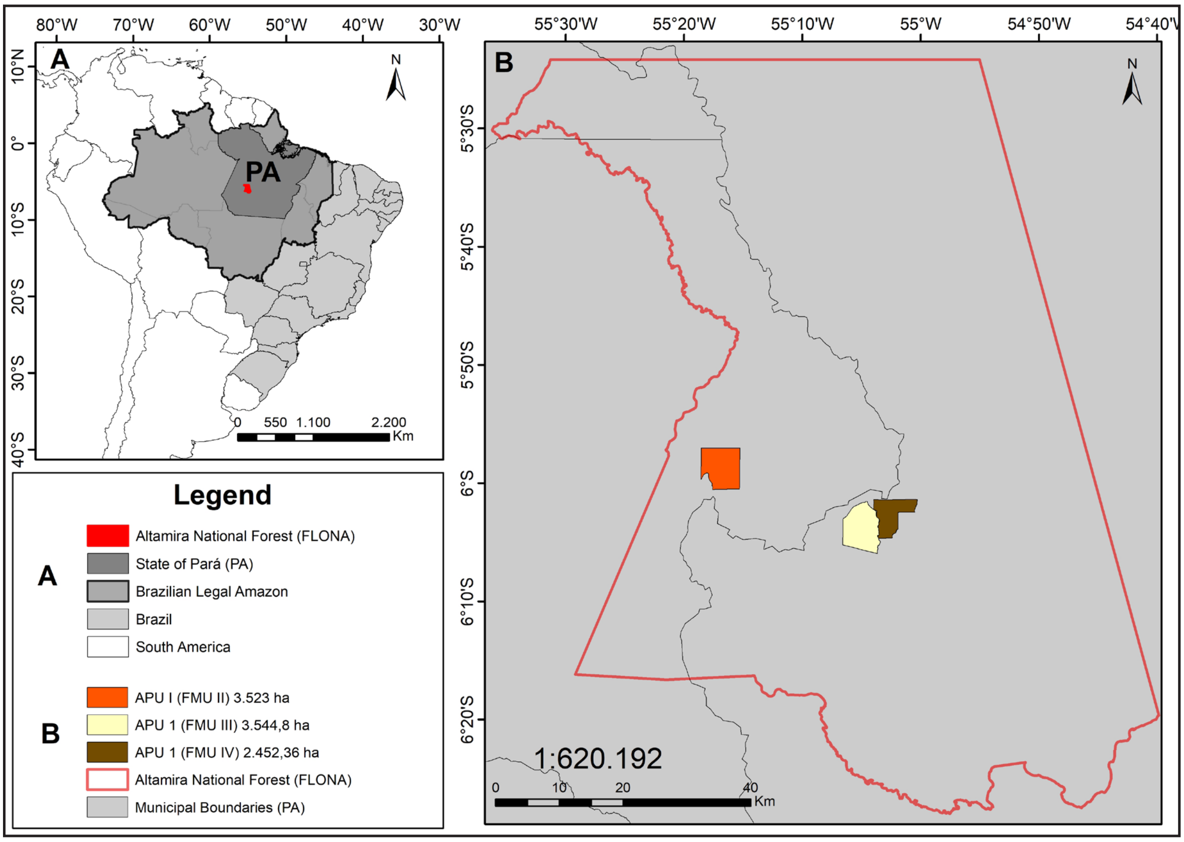
## 2 MATERIALS AND METHODS

### 2.1 Study area

Altamira National Forest (FLONA) is located between the Xingu and Tapajós rivers, in Amazon biome within the state of Pará. Maximum annual temperatures in this area range from 31°C and 33°C (ICMBio, 2012), and average annual rainfall is around 1,800–2,800 mm, with a short dry season (UCB, 2023). Based on Köppen' classification, the region climate is monsoon (Am) (UCB, 2023).

FLONA is composed of two phytophysiognomies, being the Open Ombrophilous Forest with 77.74% and the Dense Ombrophilous Forest with 22.26% (UCB, 2023). Figure 1 shows further details on the geometry and location of the study areas.

Figure 1 – Location of the state of Pará (PA) in the Brazilian Legal Amazon (A), Brazil, with emphasis on FLONA Altamira (B) and the study areas in FMU II, FMU III e FMU IV




Source: Authors (2024)

In where: Annual Production Unit (APU); Forest Management Unit (FMU); Forest Management Unit II; Forest Management Unit III; Forest Management Unit IV, National Forest (FLONA).

### 2.2 Database

The data from the forest census were in File Geodatabase Feature Class and were provided by the Brazilian Forest Service via an educational partnership with the State University of Santa Catarina - UDESC. The database was extracted with the ArcGIS® software. The forest census of commercial species was carried out in 2016, from which the following information was extracted: georeferenced location of commercial trees; stem diameter measured at 1.30 m from the ground; diameter at breast height (DBH) ≥ 39 cm; scientific name; popular name, and basal area of the five species with the highest commercial value. Using Table to Excel to MS Excel format, which served as a basis for the modeling processing of the diametric structure, the data from the 1st Annual Production Units (APUs I) of FMU II, FMU III and FMU IV, of the Altamira FLONA (Figure 1).

### 2.3 Diametric structure modeling

The diametric structure modeling was performed via PDF for the five species with the highest commercial value: *Cedrela odorata* (cedar); *Cordia bicolor* (salmwood); *Handroanthus impetiginosus* (pink ipe); *Handroanthus serratifolius* (yellow ipe); and *Handroanthus* sp. (yellow ipe).

Commercial value of the volume per m³ was based on the report presented by the Forest Products Commercialization and Transport System (SISFLORA/PA), for 2016, which assessed the following values: R$ 412/m³ for Cedar; R$ 369/m³ for salmwood; R$ 653/m³ for pink ipe; R$ 503/m³ for yellow ipe; and R$ 512/m³ for *Handroanthus* sp. (SISFLORA, 2016).

To compare the results of the adjusted models, the data were extrapolated to an area scale, considering the recommended value for the UT size, which is 100 ha (Equation 1). Other studies have used different scales in the Amazon (Oliveira, 2020; Silva Santos; Stepka, 2021). The determination of the diameter classes was made via the Sturges' rule (1926) (Equation 2). A value of eight was defined for the interval range

(Equation 3) for the five species with the highest commercial value.

$$Fu(x) = N/100\ (ha) \tag{1}$$

$$k = 1 + 3.322 * log_{10}(N) \tag{2}$$

$$Interval\ Amplitude = \frac{highest\ value - lowest\ value}{number\ of\ classes\ (k)} \tag{3}$$

in which: *Fu* (x) = frequency; N = number of individuals; *k* = number of classes; Log = logarithm to base 10.

The variables frequency (N/100 ha) and DBH were entered in the Table Curve software 2D (Systat Software, Inc) version 3, which served as a basis for finding the parameters of the models to be used (Table 1). Then, the Kolmogorov–Smirnov adherence test was conducted to verify which model would best represent each measured species. Kendall and Stuart (1976) reported that this estimation verifies the maximum absolute difference (D) from the accumulated observed frequency (Fo $_{(x)}$) and the cumulative expected frequency (Fe $_{(x)}$) (Equation 4).

$$D_{calc} = \frac{> |\ Fo - Fe|}{n} \tag{4}$$

Dalla Lana, Lins, Brandão, Netto, Marangon and Retslaff (2013) observed that the function with the lowest $D_{Calc}$ would indicate the best adhesion between the diametric distributions. Thus, $Dn = \frac{1.63}{\sqrt{n}}$ verifies significance at 99% probability. Therefore, if $D_{Calc}$ is ≥ $D_n$, $H_0$ is rejected (different distributions), and if $D_{Calc}$ is ≤ $D_n$, $H_0$ is accepted (similar distributions).

Table 1 – Probability density functions for species modeling with the highest commercial value present in APUs 1 of FMU II, FMU III and FMU IV in FLONA Altamira (PA), Brazil

| Model | Functional relation | Distribution mean | Distribution variation |
|---|---|---|---|
| Normal (Gauss) | $f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} * (Fu * A)$ | - | - |
| Weibull 3p | $f(x) = \frac{c}{b}\left(\frac{x-a}{b}\right)^{c-1} e^{-\left(\frac{x-a}{b}\right)^c} * (Fu * A)$ | $\mu_x = a + b * \Gamma\left(1+\frac{1}{c}\right)$ | $\sigma^2 = b^2 * \left\|\Gamma\left(1+\frac{2}{c}\right) - \Gamma^2\left(1+\frac{2}{c}\right)\right\|$ |
| Weibull 2p | $f(x) = \frac{c}{b}\left(\frac{x}{b}\right)^{c-1} e^{-\left(\frac{x}{b}\right)^c} * (Fu * A)$ | $\mu_x = b * \Gamma\left(1+\frac{1}{c}\right)$ | $\sigma^2 = b^2 * \left[\Gamma\left(1+\frac{2}{c}\right) - \Gamma^2\left(1+\frac{2}{c}\right)\right]$ |
| Gamma | $f(x) = \frac{x^{\alpha-1} e^{-\frac{x}{\beta}}}{\beta^\alpha \Gamma(\alpha)} * (Fu * A)$ | $\mu_x = \alpha * \beta$ | $\sigma^2 = \beta^2 * \alpha$ |
| Beta | $f(x) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)+\Gamma(\beta)} x^{\varsigma-1} (1-x)^{\beta-1} * (Fu * A)$ | $\mu_x = \frac{\alpha}{\alpha+\beta}$ | $\sigma^2 = \frac{\alpha * \beta}{(\alpha+\beta)^2 * (\alpha+\beta+1)}$ |

Source: Authors (2024)

In where: $\mu$ = distribution mean; σ = distribution standard deviation; a, b, and c = parameters of location (a), scale (b), and shape (c) of the distribution to be estimated; $\alpha$ and $\beta$ = distribution parameters; $\Gamma$ = gamma function, ς = beta class; x: class; Fu: Frequency used (N/100ha); A: Class amplitude; FLONA = National Forest; UPA = Annual production unit; FMU = Forest management unit.

## 3 RESULTS AND DISCUSSIONS

### 3.1 Descriptive statistics of commercial species

The studied forest community presented 7,277 individuals for the five evaluated species. Of this total, *Handroanthus* sp. had 2,269 individuals found only in FMU II; *Handroanthus impetiginosus* presented 1,973 distributed in the three areas; *Handroanthus serratifolius* with 1,884 trees present in FMU III and IV; *Cedrela odorata* with 1,041 individuals present in the three studied areas and, finally, the *Cordia bicolor* with 110 individuals present at FMU II.

The smallest mean diameter was found in the *Cordia bicolor* species with about 56.66 cm (σ = 10.99 cm); followed by the *Handroanthus* sp. with 61.71 cm (σ = 12.77 cm); *Cedrela odorata* with 65.11 cm (σ = 15.63 cm); *Handroanthus serratifolius* with 66.00 cm (σ = 15.00 cm);,and, finally, the highest mean among the five species was recorded in *Handroanthus impetiginosus* with 69.59 cm (σ = 16.77 cm) (Table 2).

Table 2 – Descriptive statistics of the commercial species present in APUs 1 of FMU II, FMU III and FMU IV in the Altamira National Forest (PA), Brazil

| **Descriptive statistic** | **Stem diameter at 1.30 cm above the ground** | | | | |
|---|---|---|---|---|---|
| | ***C. odorata*** | ***C. bicolor*** | ***H. impetiginosus*** | ***H. serratifolius*** | ***H.* sp.** |
| Abundance | 1,041 | 110 | 1,973 | 1,884 | 2,269 |
| Mean | 65.11 | 56.66 | 69.59 | 66.00 | 61.71 |
| Standard error | 0.48 | 1.05 | 0.38 | 0.35 | 0.27 |
| Median | 62.71 | 54.43 | 66.85 | 63.66 | 60.48 |
| Mode | 63.66 | 45.52 | 63.66 | 60.48 | 63.66 |
| Standard deviation | 15.63 | 10.99 | 16.77 | 15.00 | 12.77 |
| Variation | 244.40 | 120.80 | 281.21 | 224.99 | 163.11 |
| Variation coefficient (%) | 24.01 | 19.40 | 24.10 | 22.73 | 20.70 |
| Kurtosis | 1.00 | 0.90 | 1.15 | 2.18 | 1.62 |
| Skewness | 0.95 | 1.04 | 0.89 | 1.13 | 0.88 |
| Interval | 88.81 | 50.29 | 115.34 | 113.21 | 112.36 |
| Minimum | 39.79 | 40.43 | 40.00 | 39.79 | 40.43 |
| Maximum | 128.60 | 90.72 | 155.34 | 153.00 | 152.79 |

Source: Authors (2024)

The smallest diameters were found in the *Cedrela odorata* and *Handroanthus serratifolius* species, both with 39.79 cm. The largest diameter was found in the *Handroanthus impetiginosus* species, with about 155.34 cm, which also had the largest diameter range. All species had diameters with coefficients of variation lower than 25%. This variation was smaller when compared to the study by Silva Santos, Stepka and Hess (2023), in a forest management area located in the Tapajós-Arapiuns Extractive Reserve (RESEX), state of Pará, in which a 31% diameter variation was recorded for 10 species with commercial value.

Regarding shape measurements, all species showed asymmetry and positive kurtosis, indicating a Leptocurtic curve, i.e., the diameter distribution has a lower degree of flattening than the curve of a normal distribution. Similar behavior was found in the study by Limeira, Gregório, Silva, Ramos, Santana, Andrade, and Santos (2020), who observed the same trend in the diametric distribution of species located in riparian forests. Regarding commercial species native to the Amazon, Silva Santos, Stepka and Hess (2023) recorded a similar behavior, with a trend of Leptocurtic distribution for ten commercialized species *(Handroanthus impetiginosus* (Mart. ex DC.) Mattos, *Hymenaea courbaril* L., *Hymenaea parvifolia* Huber, *Goupia glabra* Aubl., *Apuleia leiocarpa* (Vogel) J.F.Macbr., *Couratari guianensis* Aubl., *Caryocar villosum* (Aubl.) Pers., *Manilkara paraensis* (Huber) Standl., *Holopyxidium jarana* Huber ex Ducke, *Dipteryx odorata* (Aubl.) Forsyth f.), in a forest management area in the Tapajós-Arapiuns Extractive Reserve (RESEX), Pará.

## 3.2 Diametric modeling

Regarding accumulated frequencies per 100 hectares, for the five commercial species evaluated, in ascending order, they were: *Cordia bicolor* with three individuals; *Cedrela odorata* with 10.93 individuals; *Handroanthus impetiginosus* with 20.72 individuals; *Handroanthus serratifolius* with 31.41 individuals, and *Handroanthus* sp. with 64.41 individuals (Table 3).

Table 3 – Descriptive statistics of the commercial species present per 100 hectares at APUs 1 of FMU II, FMU III, and FMU IV in the Altamira National Forest (PA), Brazil

| DAP | *C. odorata* | | *C. bicolor* | | *H. impetiginosus* | | *H. serratifolius* | | *H.* sp. | |
|---|---|---|---|---|---|---|---|---|---|---|
| Classes | F abs. | F acc. | F acc. | F acc. | F abs. | F acc. | F abs. | F acc. | F abs. | F acc. |
| 36 | 0.02 | 0.02 | - | - | - | - | 0.05 | 0.05 | - | - |
| 44 | 1.23 | 1.25 | 0.71 | 0.71 | 1.50 | 1.50 | 2.43 | 2.48 | 8.88 | 8.88 |
| 52 | 2.11 | 3.36 | 0.99 | 1.70 | 2.83 | 4.33 | 5.22 | 7.70 | 14.76 | 23.64 |
| 60 | 2.76 | 6.12 | 0.85 | 2.55 | 4.72 | 9.04 | 8.74 | 16.44 | 17.91 | 41.56 |
| 68 | 1.74 | 7.87 | 0.26 | 2.81 | 3.80 | 12.85 | 6.47 | 22.91 | 10.62 | 52.17 |
| 76 | 1.29 | 9.16 | 0.20 | 3.01 | 3.06 | 15.90 | 3.42 | 26.32 | 7.04 | 59.21 |
| 84 | 0.77 | 9.93 | 0.06 | 3.07 | 1.99 | 17.89 | 1.98 | 28.31 | 2.95 | 62.16 |
| 92 | 0.62 | 10.54 | 0.06 | 3.12 | 1.49 | 19.38 | 1.85 | 30.16 | 1.53 | 63.70 |
| 100 | 0.16 | 10.70 | - | 3.12 | 0.56 | 19.93 | 0.65 | 30.81 | 0.43 | 64.12 |
| 108 | 0.11 | 10.81 | - | 3.12 | 0.35 | 20.28 | 0.30 | 31.11 | 0.17 | 64.29 |
| 116 | 0.06 | 10.87 | - | 3.12 | 0.23 | 20.51 | 0.10 | 31.21 | 0.09 | 64.38 |
| 124 | 0.05 | 10.92 | - | 3.12 | 0.14 | 20.65 | 0.13 | 31.34 | - | 64.38 |
| 132 | 0.01 | 10.93 | - | 3.12 | 0.03 | 20.68 | 0.02 | 31.36 | - | 64.38 |
| 140 | 0.00 | 10.93 | - | 3.12 | 0.02 | 20.70 | 0.03 | 31.39 | - | 64.38 |
| 148 | - | 10.93 | - | 3.12 | 0.01 | 20.71 | - | 31.39 | - | 64.38 |
| 156 | - | 10.93 | - | 3.12 | 0.01 | 20.72 | 0.02 | 31.41 | 0.03 | 64.41 |

Source: Authors (2024)

In where: F abs = Absolute frequency, F acc. = Accumulated frequency.

No significant difference ($H_0$) was found between the estimates generated from the models and the diameter distribution of the evaluated species, indicating the ability of the probability density functions to represent the diameter structure of the five species. Thus, for only one model to be representative for each species, the lowest value measured by the test was used as a criterion for choosing Kolmogorov–Smirnov at 99% probability, as it is the most accurate for the data set (Table 4).

Table 4 – Statistics and parameters of the probability density functions for the five species with the highest commercial value in FLONA Altamira (PA), of APUs 1 of FMU II, FMU III and FMU IV, using the Kolmogorov–Smirnov test at 99% adherence

| | **Normal** | **Weibull 3P** | **Weibull 2P** | **Gamma** | **Beta** | **$D_{tab.}$** |
|---|---|---|---|---|---|---|
| | | | *Cedrela odorata* | | | |
| $D_{calc.}$ | 0.1076 | 0.0205 | 0.1188 | 0.0765 | 0.0935 | 0.4927 |
| | μ= 60.82 | μ= 63.64 | μ= 59.67 | μ= 62.57 | μ= 63.41 | |
| | σ= 13.92 | σ= 14.33 | σ= 14.36 | σ= 14.18 | σ= 45.94 | |
| | - | a= 35.99 | | | | |
| Parameter | - | b= 31.20 | b= 65.19 | α= 19.45 | α= 3.24 | |
| | - | c= 2.01 | c= 4.73 | β= 3.21 | β= 7.48 | |
| | | | *Cordia bicolor* | | | |
| $D_{calc.}$ | 0.0878 | 0.0303 | 0.1258 | 0.0590 | 0.0495 | 0.9225 |
| | μ= 53.05 | μ= 54.80 | μ= 51.63 | μ= 54.18 | μ= 56.01 | |
| | σ= 9.88 | σ= 9.53 | σ= 10.06 | σ= 9.95 | σ= 49.15 | |
| | - | a= 34.59 | | | | |
| Parameter | - | b= 22.82 | b= 55.67 | α= 29.64 | α= 1.89 | |
| | - | c= 2.24 | c= 5.95 | β= 1.82 | β= 4.74 | |
| | | | *Handroanthus impetiginosus* | | | |
| $D_{calc.}$ | 0.0552 | 0.0226 | 0.0773 | 0.0237 | 0.0633 | 0.3581 |
| | μ= 65.13 | μ= 68.82 | μ= 63.87 | μ= 67.35 | μ= 69.71 | |
| | σ= 15.90 | σ= 15.62 | σ= 16.22 | σ= 15.93 | σ= 56.41 | |
| | - | a= 39.29 | | | | |
| Parameter | - | b= 33.31 | b= 70.02 | α= 17.86 | α= 2.21 | |
| | - | c= 1.97 | c= 4.46 | β= 3.76 | β= 6.73 | |
| | | | *Handroanthus serratifolius* | | | |
| $D_{calc.}$ | 0.0861 | 0.0614 | 0.1026 | 0.0624 | 0.0402 | 0.2908 |
| | μ= 62.12 | μ= 63.89 | μ= 60.53 | μ= 63.63 | μ= 64.13 | |
| | σ= 12.30 | σ= 12.41 | σ= 12.50 | σ= 12.67 | σ= 44.47 | |
| | - | a= 35.99 | | | | |
| Parameter | - | b= 31.47 | b= 65.50 | α= 25.18 | α= 4.72 | |
| | - | c= 2.39 | c= 5.59 | β= 2.52 | β= 14.08 | |

To be continued ...

Table 4 – Conclusion

| | Normal | Weibull 3P | Weibull 2P | Gamma | Beta | $D_{tab.}$ |
|---|---|---|---|---|---|---|
| | | | *Handroanthus* sp. | | | |
| $D_{calc.}$ | 0.0668 | 0.0125 | 0.0996 | 0.0366 | 0.0644 | 0.2031 |
| | μ= 58.21 | μ= 60.67 | μ= 56.76 | μ= 59.77 | μ= 62.41 | |
| | σ= 12.36 | σ= 11.97 | σ= 12.72 | σ= 12.41 | σ= 53.38 | |
| | - | a= 36.37 | | | | |
| Parameter | - | b= 27.43 | b= 61.73 | α= 23.19 | α= 2.09 | |
| | - | c= 2.13 | c= 5.12 | β= 2.57 | β= 9.11 | |

Source: Authors (2024)

In where: $D_{Calc.}$ = maximum absolute difference between the adjusted probability density function and the values observed in the area for each method, $D_{tab.}$ = is the Kolmogorov–Smirnov value (α: 0.01); μ = average (cm); σ = standard deviation (cm).

The Weibull 3P function obtained the best adhesion for the representation of the diameter distributions of the species *Cedrela odorata* ($D_{tab.}$ = 0.4927 > $D_{calc.}$ 0.0205), *Cordia bicolor* ($D_{tab.}$ = 0.9225 > $D_{calc.}$ = 0.0303), *H. impetiginosus* ($D_{tab.}$ = 0.3581 > $D_{calc.}$ = 0.0226), and *H.* sp. ($D_{tab.}$ = 0.2031 > $D_{calc.}$ = 0.0125). For the *H. serratifolius* species, the model with the best adhesion to represent the diameter structure was the Beta function ($D_{tab.}$ = 0.0402 > $D_{calc.}$ = 0.2908).

The parameters *c* of the Weibull function indicated the asymmetry form of the distribution. In this sense, the aforementioned models obtained values equivalent to a unimodal distribution with positive asymmetry ($c_{min}$ = 1.97 and $c_{max}$ = 2.24), i.e., the frequency of individuals decreases with the largest centers of the diameter class (Figure 2). According to the literature, some authors obtained positive results regarding the use of Weibull 3P function to represent the diametric structure of native species (Ribeiro et al. 2014) and Amazonian species (Cruz, Nakajima, Silva, Hosokawa, Jardim, Corte, 2021; Silva Santos; Stepka; Hess, 2023; Silva Santos e Stepka, 2021; Vieira; Gomes; Santos; Oliveira; Gama; Mendonça; Lafetá; Moura; Figueiredo, 2021; Vieira; Oliveira; Gama; Figueiredo; Lafetá, 2021; Sales et al. 2023).

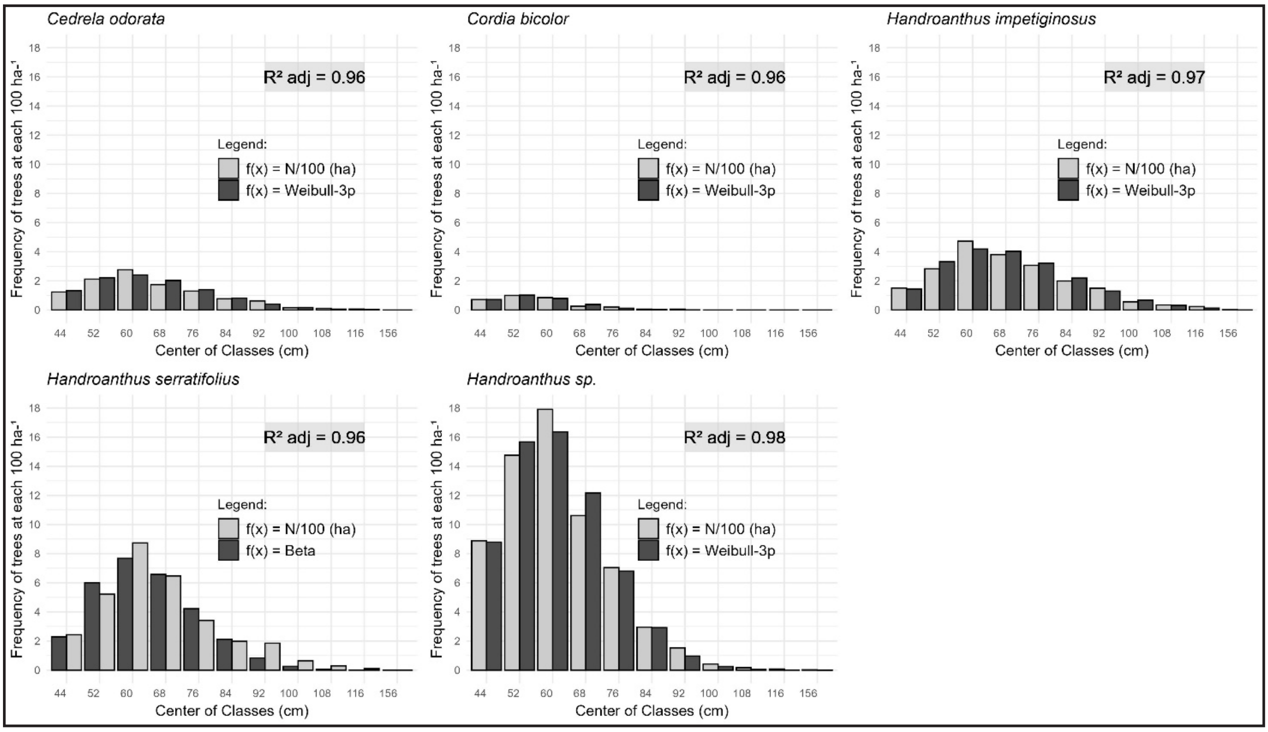
From the best adherence models by the test Kolmogorov–Smirnov, the adjusted coefficient of determination ($R^2_{adj}$) was calculated, and diametric modeling graphs were generated for the species analyzed in the three study areas of FLONA Altamira (Figure 2). We can observe that all functions presented $R^2_{adj}$ above 0.96 for the five species evaluated, corroborating the capacity of the selected models.

The diametric modeling demonstrated a unimodal pattern with a negative exponential trend. The models showed a decrease in the frequency of individuals from 52 to 60 cm diameter classes. These classes are close to the minimum diameter cutting of 50 cm, suitable for forest management plans. Such outcome, few individuals in the largest diameter classes, is a common characteristic of ecologically balanced native forests.

Regarding frequency of individuals by diameter classes (Figure 2), it was found that the species *Handroanthus* sp., *Handroanthus serratifolius*, and *Handroanthus impetiginosus* had the highest frequencies, and their values fit the minimum requirement of three individuals per 100 hectares, established by Normative Instruction No. 5/2006, which provides for the technical procedures for the preparation, presentation, execution and technical evaluation of sustainable forest management plans (PMFS) in the Brazilian Legal Amazon (Brasil, 2006).

Regarding the *Cedrela odorata* and *Cordia Bicolor* species, it can be observed that both presented the lowest frequencies of individuals per diameter class, with their values being close to the minimum requirement of three individuals per 100 hectares (Table 3), established in IBAMA Implementing Rule No. 1/2007 (Brasil, 2007). In the specific case of *Cedrela odorata*, low frequency of individuals based on commercial diameters may indicate an alteration of the forest, which may be a warning sign because this is a vulnerable species (Brasil, 2021). According to Article 2 of MMA Ordinance No. 443, of December 17th, 2014, species classified in this situation must be fully protected, and their collection, cutting, transport, storage, handling, processing, and commercialization are prohibited (MMA, 2014).

Figure 2 – Probability density functions adjusted via Kolmogorov–Smirnov test for the species with the highest commercial value in FLONA Altamira in APUs 1 of FMU II, FMU III and FMU IV, in the state of Pará (PA), Brazil




Source: Authors (2024)

In the case of *H. serratifolius* and *H. impetiginosus,* despite having high individuals' frequencies, they also fall into some level of vulnerability and/or threat, according to the Red List of the National Center for Flora Conservation (CNCFlora, 2023). Research indicates that the use of cutting cycles (CCs), currently between 25 and 35 years (Brasil, 2007), and the intensity of logging practiced in the Amazon are associated with reductions in timber resources (Brienen; Zuidema, 2006). However, lower logging activities and longer harvesting cycles may cause less damage to the forest, which would help ensure sustainable timber harvests in the near future (DeArmond; Emmert; Pinto; Lima; Higuchi, 2023).

Due to the complexity of the forest structure found in the Amazon, it is difficult to develop accurate models for estimating the growth rate of tropical trees (Andrade;

do Amaral Machado; Figueiredo Filho; Botosso; Miranda; Schöngart, 2019; Conde, 2022). Therefore, if there is no more careful selection regarding the management to which these species are subjected, they may be at risk of population decline.

Considering the above, we stress the need to conduct more comprehensive studies before and after forest management, aiming at deepening the investigation on the selective methods currently implemented within the Amazon. Logging must comply with the guidelines established by the competent environmental agencies, to ensure the proper conservation of natural resources, promoting the regeneration of forests and the maintenance of the local ecosystem balance.

## 4 CONCLUSIONS

The Weibull 3P function obtained the best adhesion for the representation of diameter distributions of the species *Cedrela odorata* ($D_{tab.}$ = 0.4927 > $D_{calc}$. In turn, the Beta function was able to represent the diameter structure for the *Handroanthus serratifolius* species.

The *Cedrela odorata* and *Cordia bicolor* species presented values close to the minimum requirement of three individuals per 100 hectares, highlighting the importance of monitoring these species, since they are exposed to the risk of local vulnerability. It was observed how much the probability density functions can help as another tool for the analysis of sustainable forest management in the Amazon.

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