A new approach to maximize the wood production in the sustainable management of Amazon forest

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Abstract
• *Key message* We presented a method to determine the optimal wood production in Amazon forest. The database that feeds the procedure is faster to obtain when compared to other methods. The simulations resulted in higher wood volume production when compared to the current management system. Moreover, it avoids overexploiting several species which could occur due to felling trees before maturity.
• *Context* Currently in Brazil, generalized forest law rules the management of the entire set of timber species and typologies. However, it is important to consider dynamics specificity of each species to ensure management sustainability, especially for the Amazon forest with its wide floristic diversity.
• *Aims* To develop a procedure to determine which logging diameter would achieve optimal wood production by species, using *Apuleia leiocarpa* (Vogel) J.F. Macbr., *Erisma uncinatum* Warm., *Hymenolobium excelsum* Ducke, and *Trattinnickia burserifolia* Mart. as studying case.
• *Methods* Two main methodologies of analysis by species were combined: probability density function (PDF) and growth modeling. The growth models were used to derive the volume increment curves at the individual tree level. To detect the points of maximum annual increment in volume at the population tree level, we used PDF with adjusted growth equations.
• *Results* The population maximum annual volumetric increments occurred in smaller diameters compared to that of the individual level. When combining shorter cutting cycles with the population biological rotation point considered the minimum felling diameter (MFD), we observed higher annual increments in volume than that achieved using the Brazilian law criteria (MFD = 50 cm) or other MFD tested.
• *Conclusion* The procedure proposed may be used by forest managers and forest law-makers, aiming to maximize sustainable wood production in the Amazon forest.

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1 Introduction

Natural forests are steadily accumulating biomass, reflected in the production of carbon and wood. The forest functions must be maintained after logging, and the remaining stocks must allow a continuous production of wood for the next interventions, ensuring forest management sustainability (Ong and Kleine 1996; Van Gardingen et al. 2006; Braz et al. 2015; Avila et al. 2017). The management must be carefully planned and be consistent with the initial natural forest structure (e.g., density, diameter distribution, growth, mortality, and regeneration) of the species of interest (Seydack et al. 1995; Bick et al. 1998).

According to Seydack (2012), a challenge for forestry scientists is to combine modeling and simulation tools to understand tropical forest dynamics, enabling production maximization. The complexity of tropical forest structure requires flexible and adaptable systems for its management, in which decisions about logging intensity, cutting cycle, and minimum felling diameters (MFD) should be based on the characteristics of each species in each compartment (Schöngart 2011; Braz et al. 2015; Groenendijk et al. 2017; Dionisio et al. 2018). MFD should be defined for all commercial species, representing a powerful tool in maximizing increment for tropical forests under management as in the Amazon region. However, in Brazil, the forest laws determine fixed MFD for all timber species (e.g., Brasil 2006). It is not calculated based on specific criteria relevant to the sites and species of interest (Schöngart 2008). Considering the number of species that are commercialized in all types of Amazon forests, the lack of knowledge about species-specific dendrometric information probably is the biggest limitation for forest management planning.

Knowledge of the density, diameter distribution, recruitment, ingrowth, tree growth, and survival of interest species allows identification of the ideal moment of intervention and its production potential (Bick et al. 1998). The forest balance equation depends on how tree increment occurs over time. Studies of species growth at individual level, structure, and reproductive biology are the basis for defining the management guidelines that guarantee sustainability for wood production in tropical forests (Vanclay 1989; Miranda et al. 2018a; Dionisio et al. 2018). However, information about individual species distribution pattern and growth in Amazon forest is scarce. Future stock projection is difficult for tropical forest due to its great diversity (Orellana and Figueiredo Filho 2017).

Most studies of the species forest growth and structure in the Amazon basin were carried out with permanent plots (Silva 1989 and 1997; Higuchi 1996; Fortini et al. 2015; Avila et al. 2017; D'Oliveira et al. 2017) and supported the management guidelines in the Brazilian forest law (Silva 1989, 1997; Higuchi 1996). However, describing forest growth behavior requires long-term information when permanent plots are used as data source (Bick et al. 1998). The successive measurements can make it difficult or even imply a failed simulation, due to the time spent to replicate a structure that represents the initial diameter classes up to the biological diameter limit of the species (Brienen and Zuidema 2006a; Miranda et al. 2018a). In some species, less than one individual per hectare occurs in Amazonian primary forest structure, especially when considering trees with commercial dimensions (Miranda et al. 2018a), and extensive sample areas are therefore required to properly represent a population of individual species (Groenendijk et al. 2017; Miranda et al. 2018a). In addition to area size, timescale is also a limiting factor in studying forest dynamics with permanent plots (Brienen and Zuidema 2006a; Miranda et al. 2018a). In Brazil, permanent plots monitored for more than 40 years are rare. These periods are short compared to the age of commercial trees, which are rarely less than 100 years old (Brienen and Zuidema 2006a; Schöngart 2008; Rosa et al. 2017). Then how would it be possible to overcome these temporal and logistical difficulties? Reasonably easy-to-measure dendrometric data could help to solve this issue: diameter distribution and growth series.

Diameter distribution is a useful feature to describe the forest properties since the diameter is easily obtained and correlated with other variables such as volume, which defines the economic value of the forest area (Bailey and Dell 1973). Diameter is widely used in the forest sector to assess the effect of environmental and anthropogenic disturbances (Kohyama 1986; Coomes et al. 2003; Wright et al. 2003; Bettinger et al. 2009; Hossain et al. 2015), to describe successional patterns (Kohyama 1986; Wright et al. 2003; Wang et al. 2009), and for the prediction of the future stock of a stand (De Liocourt 1898; Meyer 1952; Carvalho 1981; Condit et al. 1998; Bettinger et al. 2009; Hossain et al. 2015; Orellana and Figueiredo Filho 2017).

Growth series obtained by dendrochronology became more popular as an alternative to permanent plot data to supply the demand for information and growth models of species (Brienen 2005; Brienen and Zuidema 2006a; Schöngart 2011; Mattos et al. 2015; Canetti et al. 2017; Groenendijk et al. 2017; Miranda et al. 2018a). Growth ring analysis is a fast and reliable tool for assessing tree age, determining its increment over the life cycle, and identifying growth differences between species (Groenendijk et al. 2017; Rosa et al. 2017).

This study aimed to develop a procedure based on combining probability density functions for diameter structure and growth models obtained by growth rings analysis to determine the MFD for optimal wood production. The procedure was tested on four species in the Brazilian Amazon, using as studying case *Apuleia leiocarpa* (Vogel) J.F. Macbr., *Erisma uncinatum* Warm., *Hymenolobium excelsum* Ducke, and *Trattinnickia burserifolia* Mart. We tested the hypothesis that the combination of diameter structure and species growth pattern can be used to infer the ideal MFD to obtain the maximum volume growth of the population. The results may be used as a basis to forest management plans and to contribute to the revision of the forest management regulations elsewhere in tropical countries.

2 Material and methods

This study was conducted in the Sinop micro-region (11° 50′ S; 54° 50′ W), Mato Grosso (MT) state, in the Brazilian Amazon. The region comprises 9 municipalities, encompassing nearly 40 thousand km^2 (IBGE 2010) and the main forest type is evergreen seasonal forest (IBGE 2012). The micro-region presents flat relief and tropical climate with a dry season during autumn and winter (Alvares et al. 2013). All compartments from which data were collected were included in sustainable forest management plans authorized by the State Environmental Agency (SEMA-MT).

The species *Apuleia leiocarpa* (Vogel) J.F. Macbr., *Erisma uncinatum* Warm., *Hymenolobium excelsum* Ducke, and *Trattinnickia burserifolia* Mart. were studied. Together, these species represent 25% of the commercial volume logged in the micro-region of Sinop, the second-largest tropical wood production hub in Brazil (Ribeiro et al. 2016).

To understand the population structure of the tree species and its development over time, forest management simulations were performed combining the following methodologies: fitting probability density function of diameter distribution (PDF), growth and height modeling, and projection matrices by diameter class.

2.1 Fitting probability density function of the diameter structure of species

Probability density functions were fitted to diameter distributions to describe the pattern of the diameter structures of the species in the study area. The data were obtained from complete census of six forest compartments carried out in the municipalities of Santa Carmem, Sinop, and União do Sul, totaling 5432 ha. Forest inventories were conducted from 2011 to 2014, by measuring all trees with dbh ≥ 40 cm ($n = 3617$ for *A. leiocarpa*, 13,655 for *E. uncinatum*, 1814 for *H. excelsum*, and 16,162 for *T. burserifolia*).

Data from temporary sample plots of 0.25 ha (10 m × 250 m) were also used to complement the densities of the smaller diameter trees ($20 \leq$ dbh ≤ 40 cm), not covered in the complete census. These plots were measured in four compartments in the municipalities of Santa Carmem and Feliz Natal, MT. All trees with dbh ≥ 20 cm were measured. Altogether, data from 138 plots were used, adding up to 36 ha inventoried. On average, there were 35 trees ha^{-1} with $20 \leq$ dbh < 40 cm (5 of *A. leiocarpa*, 11 of *E. uncinatum*, 4 of *H. excelsum*, and 121 of *T. burserifolia*).

The dbh data for each species were grouped into diameter classes of 10-cm range to fit the PDFs. Normal, beta, gamma, log normal, Johnson's SB, and Weibull with three parameters (Scolforo 1998) PDFs were fitted. The diameter structure of each species included the largest diameter class in which live individuals were found in the complete census. To avoid total numbers of individuals less than one tree per ha per species (as occurred for *A. leiocarpa* and *H. excelsum*), the densities of individuals were considered on a 10-ha scale (i.e., number of trees 10 ha^{-1}).

The goodness-of-fit tests of PDFs by species were performed in two steps, using the Kolmogorov–Smirnov test ($\alpha = 0.05$). Initially, the goodness-of-fit of the theoretical PDFs to the empirical data was tested in each of the six forest compartments. In the second stage, the goodness-of-fit of the PDFs fitted to the data of the entire Sinop micro-region (i.e., for the total data set) was tested considering sample inventories and complete census. The best PDF for each species was selected based on the lowest maximum absolute value between theoretical PDF and observed data (D_{calc}, for Kolmogorov–Smirnov test) and lowest error index (Reynolds et al. 1988).

2.2 Modeling diameter growth by species

To describe the growth pattern of each species in the study area, growth models were adjusted using dendrochronology. Healthy adult trees were selected for sampling, looking for representative individuals of the largest diameter classes to cover all phases of tree growth, from the sapling to senescence. Stem sections (discs) with approximately 5-cm thick were collected from trees from different forests compartments in the Sinop micro-region. These samples were obtained from the base of the first commercial log, approximately 1 m above the ground level, or immediately above the buttresses. We collected 9 discs samples from *A. leiocarpa*, 10 from *E. uncinatum*, 13 from *H. excelsum*, and 11 from *T. burserifolia*. The samples were dried and polished and the growth rings were measured with an accuracy of 0.01 mm on a LINTAB measurement table (Frank Rinn, Heidelberg, Germany), using the TSAP-Win software (Rinn 1996). Crossdating was carried out among radii of each tree and among trees.

The mean increment and time of passage were analyzed by dbh class. We adjusted the growth models of Gompertz, Johnson-Schumacher, Lundqvist-Korf, Logistic, Monomolecular, and Schumacher for each species (Burkhart and Tomé 2012).

The values of the asymptotes (β_0) were fixed at the upper limit of the largest diameter class recorded in the complete census used. To increase modeling accuracy, we used the nonparametric Bootstrap method with 100 iterations (Miller 2004), previously used in studies of modeling growth in

diameter (Brienen 2005; Mattos et al. 2015; Canetti et al. 2017). The models were fitted by nonlinear regression using the PROC NLMIXED procedure in the SAS® software. The most suitable growth model by species was selected based on the relative residual standard error ($S_{yx\%}$), corrected Akaike (Akaike 1974), and Bayesian information criteria (Schwarz 1978).

2.3 Obtaining growth curves in individual volume for each species

It was necessary to develop a model of height/diameter ratio per species to be used for the inferences of commercial volumes at each age. The commercial height of trees was estimated visually and noted by experienced technicians during censuses and temporary inventories. From these data, we selected randomly 30 trees of each species representing all diameter classes. The commercial height/dbh ratio per species was fitted by nonlinear regression (PROC NLMIXED procedure in the SAS® software) according to Eq. 1 (Schöngart 2008). Of the 30 trees, four came from sampling inventories ($20 \leq dbh < 40$ cm) and 26 from complete census ($dbh \geq 40$ cm). This selection method was adopted due to the difference of inclusion levels among inventories and the varying sizes of the measured areas.

To calculate the wood volume, we used commercial height and dbh for each age (obtained from the diameter growth equation), and taper functions developed for the municipality of Santa Carmem (MT) to calculate the wood volume. For *E. uncinatum* and *T. burserifolia*, we used species-level taper functions (Eqs. 2 and 3, respectively) developed by Lanssanova (2012). For *A. leiocarpa* and *H. excelsum*, we used the general taper function for the municipality (Eq. 4) developed by Lanssanova et al. (2018).

The di/dbh ratio of the growth samples was applied to calculate the youngest diameters at the dbh, from which the volume at each age was calculated. As a result, the volume growth curve of the individual tree was obtained for each species. From the volume growth curves, the mean annual volume increment (MAI_v) and current annual volume increment (CAI_v) curves for individual trees were obtained according to Eqs. 5 and 6.

$$H = \frac{dbh\,\beta_0}{dbh + \beta_1} \tag{1}$$

$$\frac{d_i}{dbh}_{E.uncinatum} = 1.20 + 2.97\frac{h_i}{H} + 10.95\left(\frac{h_i}{H}\right)^2 + 21.15\left(\frac{h_i}{H}\right)^3 + 19.51\left(\frac{h_i}{H}\right)^4 + 6.80\left(\frac{h_i}{H}\right)^5 \tag{2}$$

$$\frac{d_i}{dbh}_{T.burserifolia} = 1.13 + 1.89\frac{h_i}{H} + 7.16\left(\frac{h_i}{H}\right)^2 + 14.02\left(\frac{h_i}{H}\right)^3 + 12.56\left(\frac{h_i}{H}\right)^4 + 4.15\left(\frac{h_i}{H}\right)^5 \tag{3}$$

$$\frac{d_i}{dbh}_{General} = 1.21 + 2.94\frac{h_i}{H} + 10.94\left(\frac{h_i}{H}\right)^2 + 20.46\left(\frac{h_i}{H}\right)^3 + 17.93\left(\frac{h_i}{H}\right)^4 + 5.90\left(\frac{h_i}{H}\right)^5 \tag{4}$$

$$MAI_v = \frac{v_t}{t} \tag{5}$$

$$CAI_v = v_{t+1} - v_t \tag{6}$$

where dbh is the diameter at 1.30 m above ground level (cm); d_i is the diameter at the sample collection height (disc sample, cm); h_i is the height of sample collection (m); H is the commercial height of the tree (m); β_0 and β_1 are the model parameters fitted by nonlinear regression; MAI_v is the mean annual volume increment (m³); CAI_v is the current annual volume increment (m³); v_t is the accumulated commercial volume (m³), at different ages; and t is the age (years), according to the diameter growth curve.

We analyzed the volume production curves to identify the age of biological rotation of individual tree, which was defined as the intersection point of the CAI_v and MAI_v curves. If the age of biological rotation was not reached with the ages of the available samples, we extrapolated the growth equation in diameter to estimate that age. For the extrapolated diameters, the commercial volume and CAI_v and MAI_v were calculated, following the same procedures.

2.4 Obtaining volume growth curves for the population of each species

To obtain growth in volume per unit area for the population of each species over time, individual volume growth curves were associated to the PDFs. It was assumed that a species diameter distribution follows the same pattern that occurred in the past (Gotelli 2008; Lundqvist 2017), considering that the diameter distribution used is a stable structure, based on data from six primary forest compartments, with a balance between recruitment, ingrowth, and mortality. From this premise, the maximization of the population volume increments was obtained. The population was defined hereby as the number of trees from the first to the last diameter class in which there were individuals alive until the moment "*t*."

The input of the PDFs is the dbh of the trees and the output is the estimated number of trees per unit area. The growth equations developed to generate the diameter values were used to estimate the number of trees alive at each time "*t*," considering the species' growth curve. The procedure illustrated in Fig. 1 allowed us to estimate the population's diameter evolution over time (time × number of trees ha^{-1}). As the actual diameter distributions were established with data from dbh ≥ 20 cm, the calculations were performed from that diameter, according to the following procedure:

I.   The number of trees at each time "*t*" (identified by the PDF) was multiplied by the volume of the individual tree (*v*) at each time, resulting in the population production curve (*V*) at each time referring to the species growth curve.

II. From the population volume production curve, MAI$_v$ and CAI$_v$ were derived (Eqs. 5 and 6).

2.5 Management simulations

The projection method by diameter class (Alder 1995) was used to compare the volumetric increments obtained from the different combinations of cutting cycle and minimum felling diameter (MFD), according to the following management scenarios:

I.   MFD = 50 cm and cutting cycle = 35 years, according to the current Brazilian forest management law (Brasil 2006)

II. MFD defined by the biological rotation age of the population (intersection of the MAI$_v$ and CAI$_v$ curves) and cutting cycle = 35 years

III. MFD defined by the maximum CAI$_v$ and biological rotation age of the population and cutting cycle calculated using Eq. 7 (Schöngart 2008)

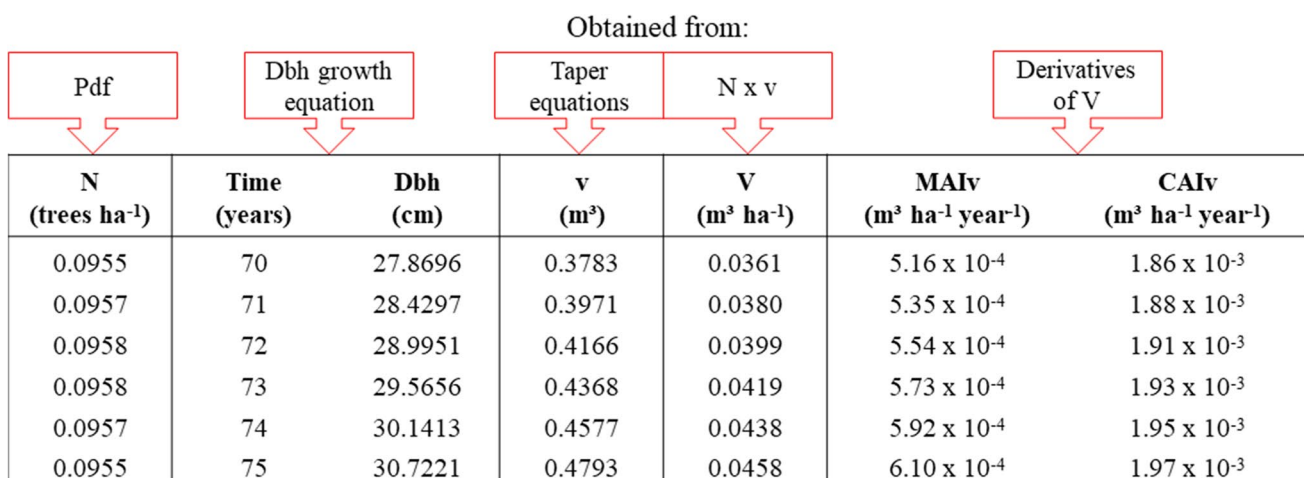$$Cutting\ cycle(years) = \frac{Age_{Max.CAIv}}{0.1dbh_{Max.CAIv}} \quad (7)$$

where cutting cycle (years) is the time interval between logging events in the forest (Schöngart 2008); dbh$_{Max.CAIv}$ is the minimum felling diameter, defined as the diameter at which the species reaches the maximum CAI$_v$; and Age$_{Max.CAIv}$ is the age at which the species reaches the MFD.

IV. MFD defined by dbh in which the maximum CAIv occurs at the individual tree level and cutting cycle calculated according to Schöngart (2008)

V.   MFD defined by the dbh of biological rotation age of the population in volume and increasing cutting cycles (10 to 70 years)

The mathematical procedure for simulations in the projection method by diameter class is presented in Eq. 8 (Alder 1995).

$$N_{k,t+1} = N_{k,t} + I_k - O_k - M_k - H_k \quad (8)$$

where $N_{k,t+1}$ is the number of trees in dbh class *k* in period *t + 1*; $N_{k,t}$ is the number of trees in class *k* in period *t*; I_k is the ingrowth in class *k* during the period; O_k is the number of trees passing from class *k* to subsequent classes, M_k is

	Obtained from:					
Pdf	Dbh growth equation	Taper equations	N x v		Derivatives of V	
N (trees ha^{-1})	**Time (years)**	**Dbh (cm)**	**v (m³)**	**V (m³ ha^{-1})**	**MAIv (m³ ha^{-1} year^{-1})**	**CAIv (m³ ha^{-1} year^{-1})**
0.0955	70	27.8696	0.3783	0.0361	5.16 x 10^{-4}	1.86 x 10^{-3}
0.0957	71	28.4297	0.3971	0.0380	5.35 x 10^{-4}	1.88 x 10^{-3}
0.0958	72	28.9951	0.4166	0.0399	5.54 x 10^{-4}	1.91 x 10^{-3}
0.0958	73	29.5656	0.4368	0.0419	5.73 x 10^{-4}	1.93 x 10^{-3}
0.0957	74	30.1413	0.4577	0.0438	5.92 x 10^{-4}	1.95 x 10^{-3}
0.0955	75	30.7221	0.4793	0.0458	6.10 x 10^{-4}	1.97 x 10^{-3}

Fig. 1 Scheme showing the methodological process for obtaining the curves of volume increment of the population. The boxes with red outline inform the data source of the column to which the arrows are directed. PDFs = probability density functions; N = number of trees per hectare; dbh = diameter at 1.30 m above ground level; v = volume of individual tree; V = species population volume (m³ ha^{-1}); MAI$_v$ = mean annual volume increment; and CAI$_v$ = current annual volume increment

the mortality in class k; and H_k is the trees logged during the period.

The matrices were built from the 30-cm dbh class, for every 5 years (t), until reaching the desired cutting cycle. We considered the wood volume of trees with a dbh higher than the MFD as the volume to be harvested (H_k). The following data were used:

I.   Initial diameter structure ($N_{k,t}$): obtained from PDFs fitted by species, considering dbh ≥ 30 cm.
II. Mean increment by diameter class (obtained from the growth equations). The number of trees passing to the subsequent classes (O_k) was calculated from the time of passage between diameter classes (Eq. 9), as described by Alder (1995).

$$O_k = \frac{t.i}{w} \quad (9)$$

where O_k is the number of trees migrating from class k to subsequent classes during the period considered; i is the mean increment (cm year^{-1}) of the diameter class k (obtained from the growth series); w is the interval between diameter classes (10 cm in the present study); and t is the period considered.

III. Ingrowth (I_k)—the number of trees in the 20-cm diameter class (smallest dbh class obtained) was considered as ingrowth.
IV. Mortality (M_i)—the mortality was estimated using Eq. 10 adapted from Lundqvist (2017).

$$M_i = 100\left(1 - \frac{N_{i+1}i_{i+1}}{N_i i_i}^{\frac{2}{t_i+t_{i+1}}}\right) \quad (10)$$

where M_i is the percentage of annual mortality in diameter class i; N_i is the number of trees in class i; N_{i+1} is the number of trees in the class subsequent to i; i_i and i_{i+1} are the mean annual increment in diameter (cm) of classes i and $i + 1$ (obtained from the growth equation); and t_i and t_{i+1} are the time of passage (years) from the diameter classes i and $i + 1$ to the subsequent classes (obtained from the growth equation).

After obtaining the final diameter structure of the projection matrix by diameter class, the number of trees was converted into volume (applying the taper functions previously described) to obtain the total wood production in the considered period. This production was divided by the cutting cycles, in order to proportionally compare the production of the tested MFD and cutting cycles.

Fig. 2 Probability density functions with better fitting for *Apuleia leiocarpa* (**A**), *Erisma uncinatum* (**B**), *Hymenolobium excelsum* (**C**), and *Trattinnickia burserifolia* (**D**). Dbh = diameter at 1.30 m above ground level (cm); Γ = gamma function; Dcalc. = maximum absolute value between fitted pdf and observed values in each compartment; IR = error index (Reynolds et al. 1988)

3 Results

3.1 Diameter structure

When testing the convergence of the general probability density functions (PDFs) adjusted to the measured density distributions for each species and for each forest compartment, the majority of the tested PDF fitted (Appendix Table 4). The only exceptions found were the normal function (all areas) and the Beta function (areas 3, 4, and 6) for *Trattinnickia burserifolia* Mart.

When considering the convergence of all PDFs tested to the total set of observed data by species, all functions fitted. The gamma function fitted better to the observed data for *Apuleia leiocarpa* (Vogel) J.F. Macbr., the normal function for *Erisma uncinatum* Warm. and *Hymenolobium excelsum* Ducke, and the Weibull with three parameters for *T. burserifolia* (Fig. 2). A unimodal pattern was observed for the diameter distributions of *A. leiocarpa*, *E. uncinatum*, and *H. excelsum*. On the other hand, *T. burserifolia* decreased in a regular number of trees, similar to the negative exponential distribution. The decreased tendency starts in *H. excelsum* at 45-cm, in *A. leiocarpa* at 55-cm, and in *E. uncinatum* at 75-cm diameter.

3.2 Height/dbh ratio

The fitted height/dbh model showed standard error deviation lower than 25% and balanced residual distribution for all species (Fig. 3). The species that reached the highest commercial heights were *E. uncinatum* and *H. excelsum*. The largest commercial height range occurred before reaching 60-cm dbh, ranging from 6.5 to 10.9 m. After 60-cm dbh, the commercial heights tended to stabilize, ranging from 10.9 to 13.4 m.

3.3 Diameter increment in dbh classes

The mean annual increment by dbh class and time of passage are shown in Figs. 4 and 5. *Apuleia leiocarpa* presented an initial increase in dbh increment and a decrease for the upper diameter classes (Fig. 4A), characterizing the U shape for the time of passage (Fig. 5A). *Erisma uncinatum*, *H. excelsum*, and *T. burserifolia* showed a higher increase in the upper classes (Fig. 4B, C, and D), assuming a decreasing time of passage (Fig. 5B, C, and D).
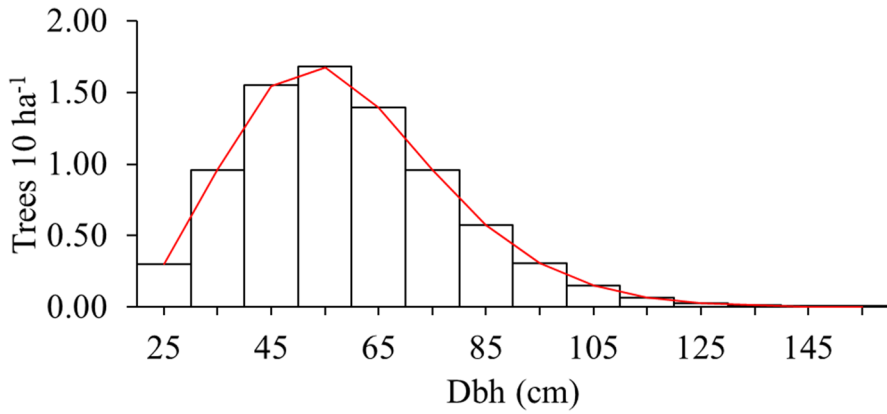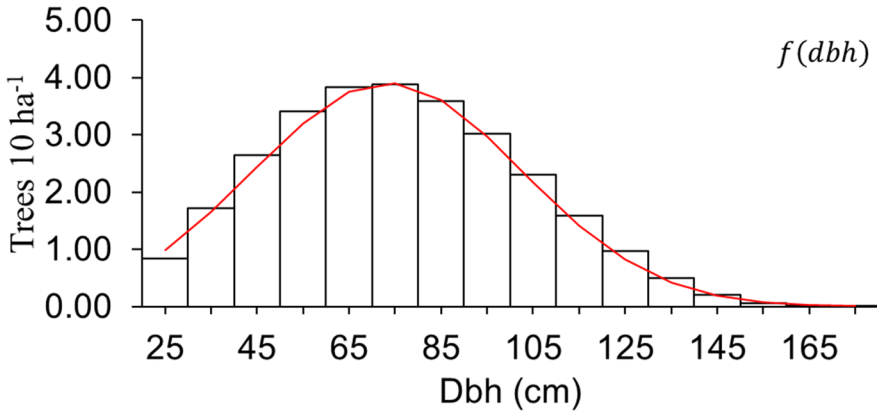
$$f(dbh) = \frac{dbh^{8.883-1}e^{\frac{-dbh}{6.657}}}{6.657^{8.883}\,\Gamma(8.883)}$$

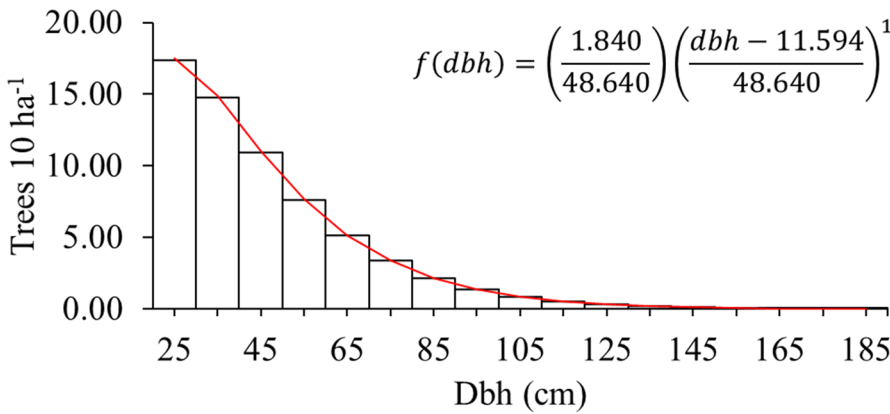$$D_{calc.} = 0.003$$
$$RI = 0.025$$

☐Observed frequency
—Gamma

A

$$f(dbh) = \frac{1}{73.368\sqrt{2\pi}}e^{\left(-\frac{1}{2}\right)\left[\frac{(dbh-29.179)}{73.368}\right]^2}$$

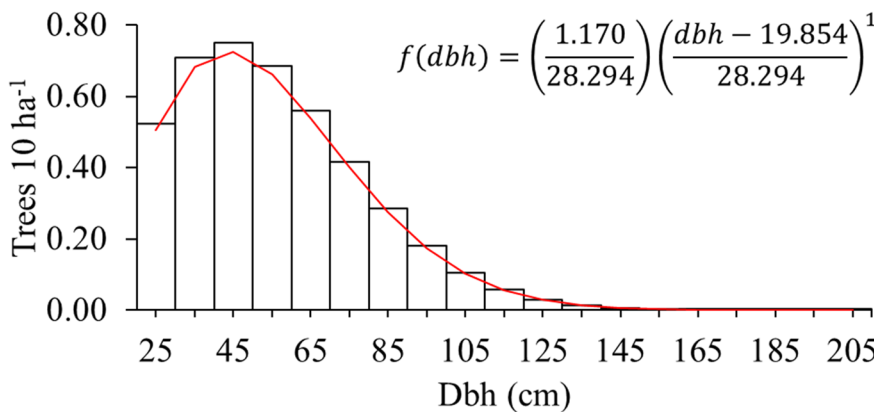$$D_{calc.} = 0.035$$
$$RI = 1.394$$

☐Observed frequency
—Normal

B

$$f(dbh) = \left(\frac{1.840}{48.640}\right)\left(\frac{dbh-11.594}{48.640}\right)^{1.840-1}e\left[-\left(\frac{dbh-11.594}{48.640}\right)^{1.840}\right]$$

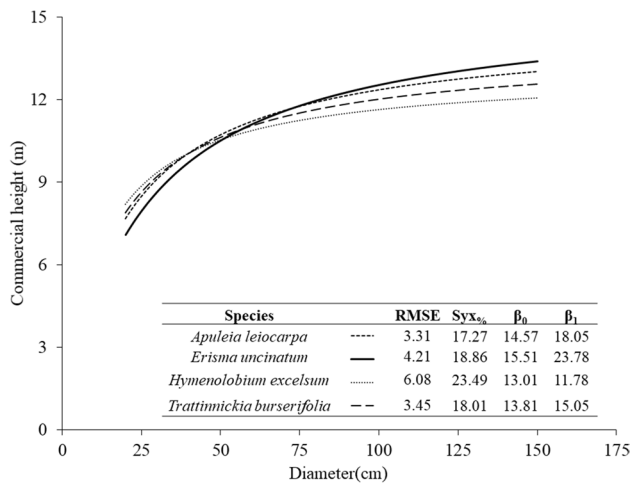$$D_{calc.} = 0.036$$
$$RI = 0.154$$

☐Observed frequency
—3p Weibull

C

$$f(dbh) = \left(\frac{1.170}{28.294}\right)\left(\frac{dbh-19.854}{28.294}\right)^{1.170-1}e\left[-\left(\frac{dbh-19.854}{28.294}\right)^{1.170}\right]$$

$$D_{calc.} = 0.008$$
$$RI = 0.500$$

☐Observed frequency
—3p Weibull

D

INRAӨ   Springer

Fig. 3 Height/dbh models of *Apuleia leiocarpa*, *Erisma uncinatum*, *Hymenolobium excelsum*, and *Trattinnickia burserifolia*. dbh = diameter at 1.30 m above ground level (cm); β_0 and β_1 = equation parameters fitted by nonlinear regression; $S_{yx\%}$ = relative residual standard error (%); RMSE = root mean square error. Number of observation per species = 30

3.4 Modeling accumulated diameter growth and generating increment curves

The Johnson-Schumacher model better fitted the time series of *A. leiocarpa* and *H. excelsum*, while the

Gompertz was better for *E. uncinatum* and *T. burserifolia* (Appendix Table 5). For diameter growth, *A. leiocarpa* and *H. excelsum* presented tendency to reach close to the asymptotic value registering lower increments after these diameter classes (Appendix Fig. 9A and C). However, *E. uncinatum* and *T. burserifolia* did not show the tendency toward an asymptote within the measured diameters (Appendix Fig. 9B and D), showing upward increments throughout the entire time series. *Apuleia leiocarpa*, *E. uncinatum*, and *T. burserifolia* reached the maximum current annual increment in volume (CAI_v) when considering the available data (Fig. 6A, B, and D). The maximum CAI_v for *H. excelsum* was estimated at approximately 245 years (Fig. 6C). These ages were estimated based on the largest dbhs found in each study area.

For the four species, the growth equation was used to estimate the biological rotation age, which for individual trees occurred at the 95-cm dbh for *A. leiocarpa*, 121-cm for *H. excelsum*, and 165-cm for *E. uncinatum* and *T. burserifolia*. The maximum CAI_v occurred close to the 60-cm dbh for *A. leiocarpa*, 80-cm for *H. excelsum*, and 120-cm for *E. uncinatum* and *T. burserifolia* (Table 1).

3.5 Increments by species population

The maximum CAI_v and biological rotation ages of the population volume (Table 2; Fig. 7) occurred in lower diameters

Fig. 4 Boxplot of the mean annual periodic increment by diameter class of *Apuleia leiocarpa* (**A**), *Erisma uncinatum* (**B**), *Hymenolobium excelsum* (**C**), and *Trattinnickia burserifolia* (**D**). Markers (x) represent the mean increment per diameter class, which were calculated only for the diameter classes with three or more trees. Dbh = diameter at 1.30 m above ground level
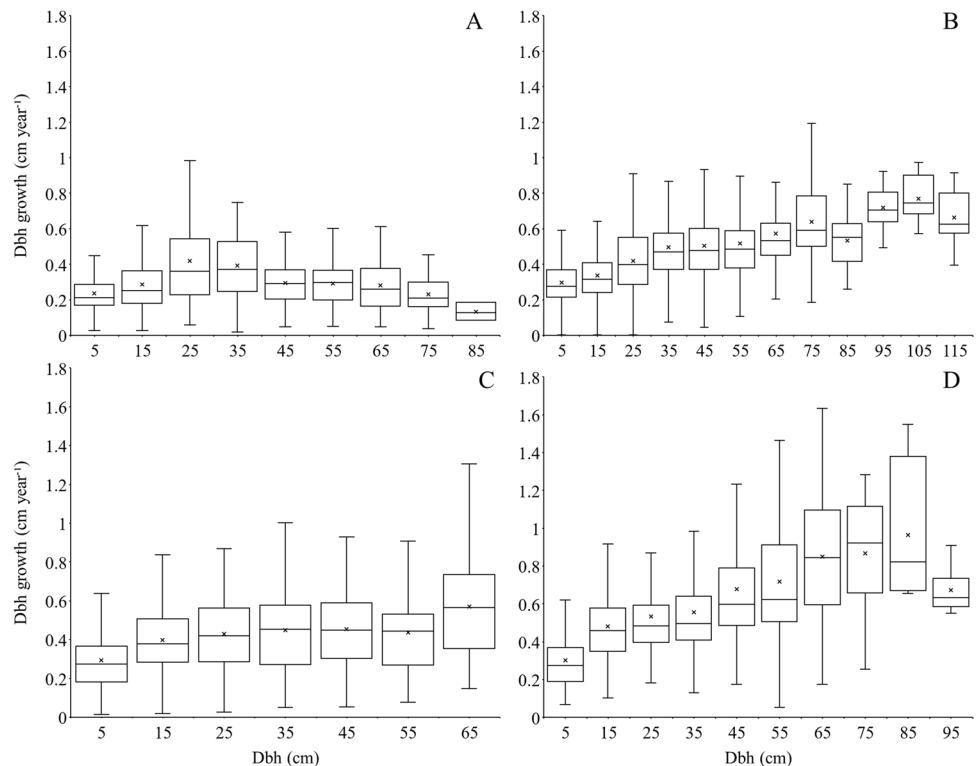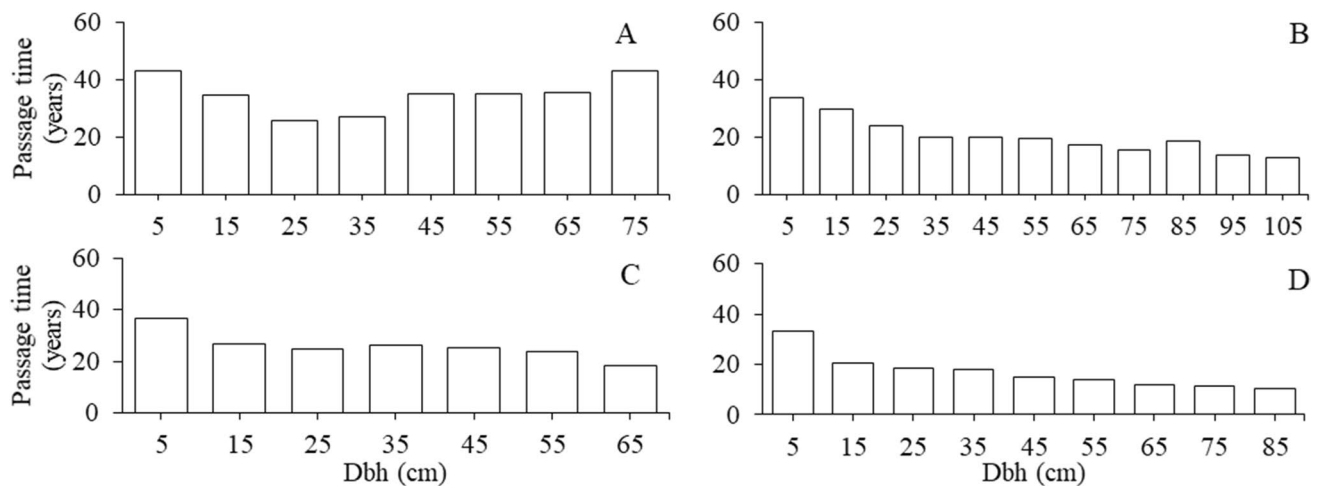
Fig. 5 Mean time of passage by diameter class for *Apuleia leiocarpa* (**A**), *Erisma uncinatum* (**B**), *Hymenolobium excelsum* (**C**), and *Trattinnickia burserifolia* (**D**) and their respective tendency lines. Only the time of passage for diameter classes with three or more trees was considered. Dbh = diameter at 1.30 m above ground level

than those recorded for individual trees (Fig. 6; Table 1). Those ages were reached for diameters within the stem samples. There was therefore no need for the extrapolation of the volume growth equations that was required for the individual diameter growth (Fig. 6).

3.6 Minimum felling diameter (MFD) and cutting cycle simulations

The MFD criteria determined by the biological rotation age of the population and with short cutting cycles (10 years) (Table 3) resulted in a higher annual volume yield for the four species. For *A. leiocarpa*, *H. excelsum*, and *T. burserifolia*, the maximum CAI_v age of the population and the cutting cycle, as suggested by Schöngart (2008), resulted in the least increment ($m^3\ ha^{-1}\ year^{-1}$) of all criteria. For *E. uncinatum*, the management criteria defined in the Brazilian forest law resulted in the least increment.

Considering the MFD defined by the population's biological rotation age, the annual volumetric production decreased for the four species as the cutting cycle increased (Fig. 8).

4 Discussion

4.1 Diameter distribution pattern of the species

Most of the probability density functions (PDFs) (Appendix Table 4) fitted to data in each forest compartment. Thus, a single PDF per species was fitted at the Sinop micro-region (Fig. 2). Fitting only one PDF per species across the micro-region suggests the existence of similarities in the species diameter structure in the typology. The micro-region's pattern agrees with the demographic equilibrium theory, which states that the diameter distribution balance may be scalar (Muller-Landau et al. 2006). The forest structure is regulated by general principles of growth, mortality (Wang et al. 2009), and ecological succession (Oliver 1992).

Even in distant or geographically isolated regions, species with resembling physiological and morphological characteristics can have a similar population structure (Oliver 1992). This occurs because the structures repeat over time in the forest (Gotelli 2008). Diameter structure models allow us to infer the diameter in which tree number reduces as a result of stagnant growth and increased mortality (De Madron and Forni 1997; Braz et al. 2014).

Ecologists use the diameter structure to indicate the health of the forest. A high number of smaller trees, as recorded for *Trattinnickia burserifolia* Mart. (Fig. 2D), would represent forest sustainability, since it would restore the upper classes (Kohyama 1986; Muller-Landau et al. 2006; Wang et al. 2009). These considerations originated from de Liocourt's (1898) and Meyer's (1952) theories that state the concept of a balanced forest following a negative exponential pattern.

However, several studies have found that some forest types and many individual species may not follow such a negative exponential model (Condit et al. 1998; Dawkins and Philip 1998; Nyland 2002; Pascal 2003; Braz 2010; Braz et al. 2014; Hossain et al. 2015), as occurred for three of the species in this study (Fig. 2A, B, and C).

A minor number of smaller trees, as recorded for *Apuleia leiocarpa* (Vogel) J.F. Macbr., *Erisma uncinatum* Warm., and *Hymenolobium excelsum* Ducke, could indicate that the populations are declining (Condit et al. 1998; Hossain et al. 2015). However, the forest diameter

Fig. 6 Volumetric increment curves (black) and dbh growth equation (red) for *Apuleia leiocarpa* (**A**), *Erisma uncinatum* (**B**), *Hymenolobium excelsum* (**C**), and *Trattinnickia burserifolia* (**D**). In the primary y-axis: MAI$_v$ = mean annual volumetric increment; CAI$_v$ = current annual volumetric increment. On the secondary y-axis: dbh = diameter at 1.30 m above ground level (cm) (growth equation fitted within the measured data range); Edbh = accumulated diameter at 1.30 m above ground level (growth equation outside the measured data range)
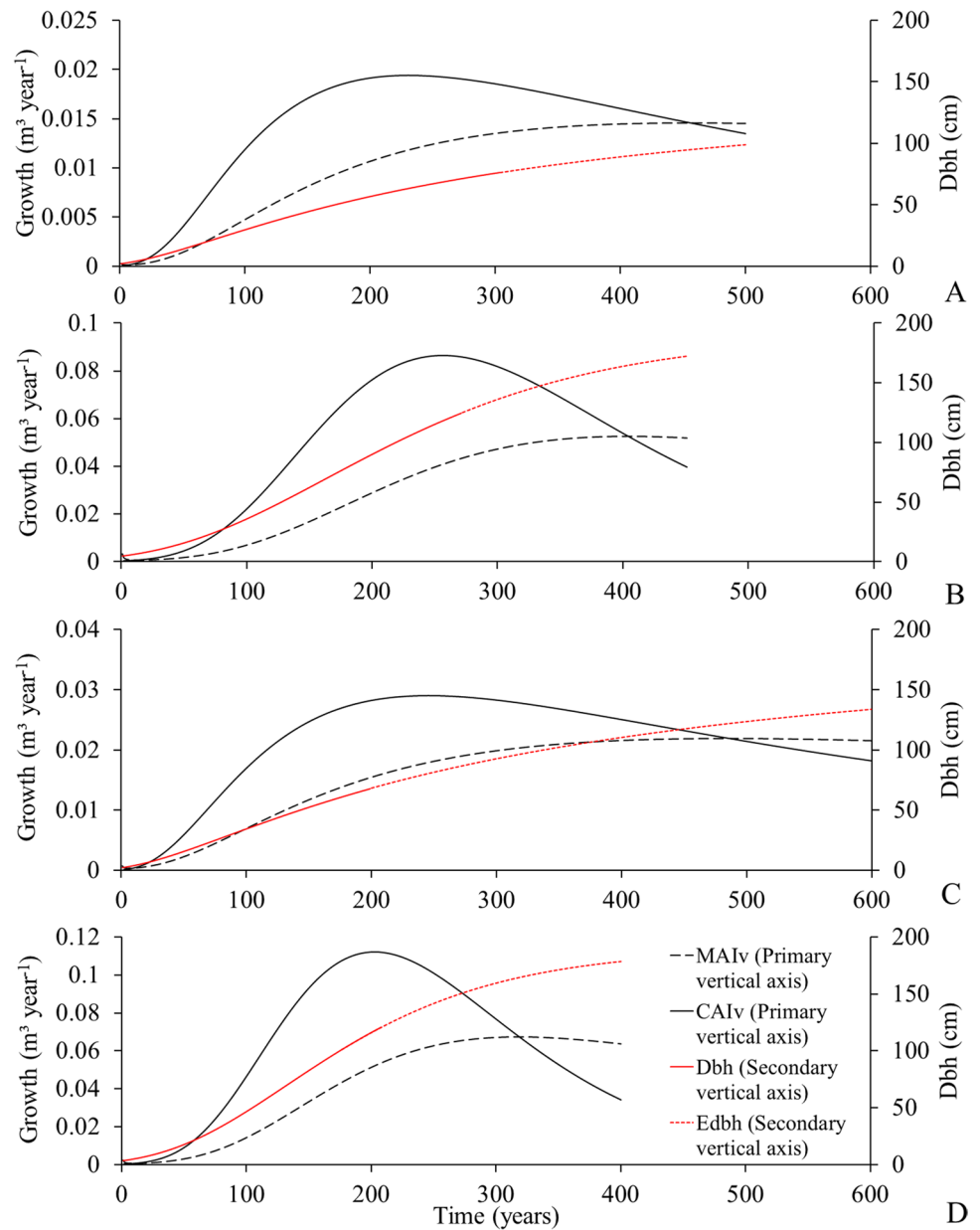
structure is not the only indicator defining population maintenance. Schaaf et al. (2006) pointed out that the highest density does not guarantee the species maintenance in the community, but their ability to compete within the ecological niche does. The authors stated that if the species has few trees with smaller diameters, but if the individuals tolerate competition for light in the lower canopy, they can remain in the forest. Therefore, it is necessary to consider other factors, particularly the species increment in the diameter classes (Condit et al. 1998).

Braz et al. (2014) identified over 60% of the basal area in the upper stratum in the Sinop micro-region, a situation described by Pascal (2003). This author

stated that the deficit of trees in some dbh classes or the accumulation in larger dbh classes can result from different causes. For example, a massive fruiting and germination due to favorable climatic conditions can engender an overstock of trees in a particular dbh class. These individuals can outgrow to larger dbh classes after a certain time, resulting in an imbalanced diameter structure curve. These same individuals may be stagnated in a certain dbh class when under the closed canopy of the forest.

An overstocked upper stratum may have its regeneration constrained due to inadequate access to light by trees in the lower canopy (Yegang and Jinxuan, 1988; Lamprecht 1990;

Table 1 Estimated ages and diameters on the biological rotation and the maximum current annual increment of individual tree volume for the species

Species	Biological rotation		Maximum CAI_v	
	Dbh (cm)	Age (years)	Dbh (cm)	Age (years)
Apuleia leiocarpa	95	455	63	231
Erisma uncinatum	165	409	119	257
Hymenolobium excelsum	121	480	80	245
Trattinnickia burserifolia	165	319	118	203

Dbh = diameter at 1.30 m above ground level; maximum CAI_v = maximum current annual increment for individual tree volume; biological rotation = intersection of the CAI_v and MAI_v (current and mean annual increment for individual tree volume) curves

Felfili 1997; Nyland 2002; Bettinger et al. 2009). In such cases, some species may need a longer timescale to regenerate (Felfili 1997). Over time, this factor de-characterizes both the negative exponential structure (Braz 2010; Bettinger et al. 2009) and the whole forest increment (Dawkins and Philip 1998).

4.2 Production modeling at individual tree level

Commercial height is an essential dendrometric variable for modeling production forests since it is used for volume prediction (Lappi 1997). Fitting parameters for the commercial height/dbh ratio (Fig. 3) allow us to calculate commercial volumes of individual trees and stand more accurately where there is no field measuring. Other authors used the commercial height/dbh ratio to model the wood volume in the Amazon forest (Brienen and Zuidema 2006a; Fortini and Zarin 2011; Miranda et al. 2018b).

Table 2 Estimated ages and diameters on the biological rotation and the maximum current annual increment by species population

Species	Biological rotation		Max. CAI_v	
	Dbh (cm)	Age (years)	Dbh (cm)	Age (years)
Apuleia leiocarpa	58	203	44	160
Erisma uncinatum	86	192	64	154
Hymenolobium excelsum	52	150	37	106
Trattinnickia burserifolia	58	116	34	80

Dbh = diameter at 1.30 m above ground level; max. CAI_v = maximum current annual increment for population volume; biological rotation = intersection of the curves of CAI_v and mean annual increment in volume for individual tree

According to Alder (1995), in natural forests, the initial increment of trees is slow, followed by a phase of higher increments until it reaches its maximum. After that maximum point, increment reduces until stagnation. *Apuleia leiocarpa*, *E. uncinatum*, and *T. burserifolia* followed this pattern (Figs. 4A, B and D and 5A, B, and D), while *H. excelsum* maintained constant growth during five diameter classes, not exceeding 0.5 cm year^{-1}, except in the 65-cm class (Fig. 4C). The constant growth of *H. excelsum* until larger sizes is a feature of late and emerging secondary species (Silva et al. 1985), whose crowns extend above the canopy average level. These functional groups have several microhabitats during their ontogenesis (Clark and Clark 1992). They are characterized as partial sciophytes, shade tolerants in the early development stages. However, they require a high degree of illumination to overcome the intermediate stages to maturity, increasing its increment during canopy opening (Maciel et al. 2017).

The decreasing tendency of time of passage (Fig. 5B, C, and D) for the late secondary species (*E. uncinatum*, *H. excelsum*, and *T. burserifolia*) is also a feature of partial sciophytes that are shade tolerant, but do not demand shade for growing (Maciel et al. 2017).

The U-shaped time of passage of the initial secondary species (*A. leiocarpa*) has already been pointed out by Brienen and Zuidema (2006b) for *Bertholletia excelsa* Bonpl., an initial secondary species (Gouveia et al. 2011). The same tendency was also registered for *Goupia glabra* Aubl. in the micro-region of Sinop, MT (Oliveira et al. 2015), which shows maximum increment in the 25-cm and 35-cm diameter classes, despite being a late secondary species (Araujo et al. 2009), as occurred for *A. leiocarpa* (Fig. 5A).

The biological rotation and maximum CAI_v ages (Fig. 6; Table 1) were consistent with the increment by diameter class (Fig. 4). *Apuleia leiocarpa*, an initial secondary species, reached biological rotation and maximum CAI_v ages in smaller diameters, while *H. excelsum* reached it in intermediate sizes. The other two species achieved biological rotation for an estimated dbh higher than 160 cm. The maximum CAI_v of an individual tree was used in scientific studies to define minimum felling diameters and cutting cycles for species in Amazonas state (Schöngart 2008; Rosa et al. 2017; Miranda et al. 2018a), and has already been included in state forest law (Amazonas 2010). If logging happens before the maximum CAI_v or after the maximum MAI_v, the volumetric production will be inefficient. In this case, the species would not have reached or would have passed their optimal increment (Schöngart 2008; Braz and Mattos, 2015). Therefore, knowing the maximum CAI_v and MAI_v per species is

Fig. 7 Volumetric and diameter increment curves for the population of *Apuleia leiocarpa* (**A**), *Erisma uncinatum* (**B**), *Hymenolobium excelsum* (**C**), and *Trattinnickia burserifolia* (**D**) (dbh ≥ 20 cm). In the primary y-axis: MAI_v = mean annual increment in volume; CAI_v = current annual increment in volume. In the secondary y-axis: dbh = diameter at 1.30 m above ground level (cm), obtained from the growth equation
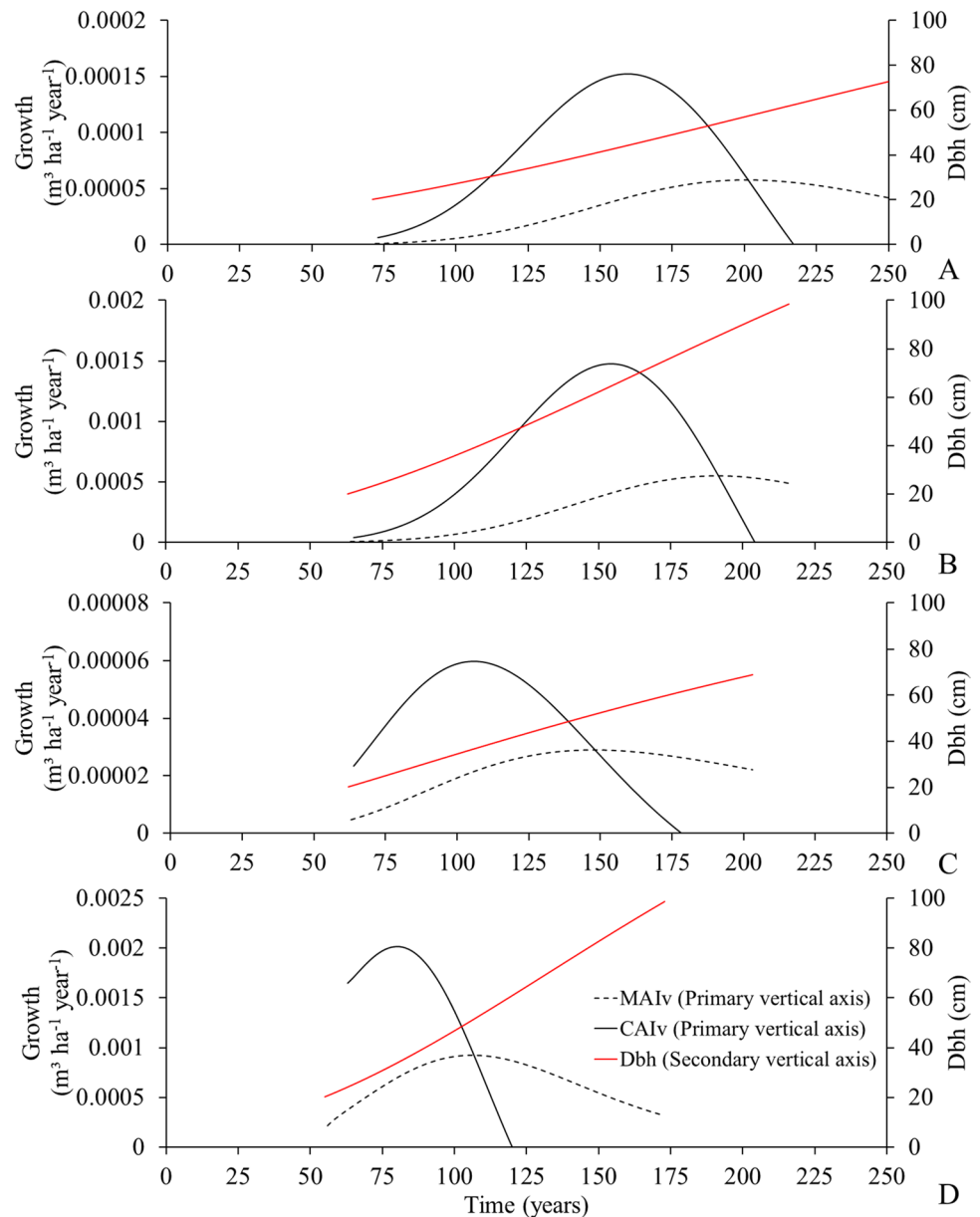
essential for sustainable management of natural forests. Considering these curves in forest management planning will prevent the species from suffering early intervention, damaging the remaining structure, and consequently threatening its sustainability.

The curves of individual wood volume increment indicate the ideal parameters for sustainable management of each species. However, other variables representing the species dynamics must be considered for decision-making. For example, it is essential to define available stock of trees by diameter class and survival

rates (Sebbenn et al. 2008; Free et al. 2014, 2017; Groenendijk et al. 2017).

4.3 Volumetric population growth

The maximum CAI_v estimated from the population increment curves occurred for diameters lower than 50 cm for *A. leiocarpa*, *H. excelsum*, and *T. burserifolia*, and at 64-cm diameter for *E. uncinatum* (Table 2; Fig. 7). The dbh when biological rotation age occurs, at which CAI_v and MAI_v curves intersected, was around 50 cm for *A.*

Table 3 Simulation results using different criteria for defining the minimum felling diameter and cutting cycle

Species	MFD	Law	Rot. pop	Rot. pop	CAI$_{v\ pop}$	CAI$_{v\ ind}$	Rot. pop	Rot. pop
Apuleia leiocarpa	Cutting cycle	Law	Law	SM	SM	SM	Short	Long
	MFD (cm)	50	57	57	44	63	57	57
	Cycle (years)	35	35	37	37	37	10	70
	Inc. (m³ ha⁻¹ year⁻¹)	0.0078	0.0107	0.0106	0.0055	0.0113	**0.0159**	0.0086
	Vol. (m³ 100 ha⁻¹)	27.46	37.52	39.09	20.49	41.82	15.86	60.53
Erisma uncinatum	MFD (cm)	50	86	86	64	119	86	86
	Cycle (years)	35	35	22	22	22	10	70
	Inc. (m³ ha⁻¹ year⁻¹)	0.0238	0.1140	0.1238	0.0643	0.0800	**0.1427**	0.0795
	Vol. (m³ 100 ha⁻¹)	83.27	398.90	272.28	141.51	176.01	142.74	556.66
Hymenolobium excelsum	MFD (cm)	50	52	52	37	80	52	52
	Cycle (years)	35	35	31	31	31	10	70
	Inc. (m³ ha⁻¹ year⁻¹)	0.0051	0.0054	0.0055	0.0029	0.0049	**0.0069**	0.0046
	Vol. (m³ 100 ha⁻¹)	17.69	18.84	17.03	8.86	15.31	6.90	31.86
Trattinnickia burserifolia	MFD (cm)	50	58	58	34	118	58	58
	Cycle (years)	35	35	17	17	17	10	70
	Inc. (m³ ha⁻¹ year⁻¹)	0.1511	0.2027	0.2776	0.1216	0.1966	**0.3622**	0.1384
	Vol. (m³ 100 ha⁻¹)	528.95	709.37	471.85	206.64	334.20	362.25	968.89

MFD minimum felling diameter; cycle = cutting cycle; *SM* Schöngart (2008) method; Rot.$_{pop.}$ = biological rotation age of the population; CAI$_{v\ pop.}$ = maximum current annual increment of the population; Legisl. = Normative Instruction parameters (Brasil 2006); Inc. = simulated mean annual volumetric increment; Vol. (m³ 100 ha⁻¹) = total volume produced in a 100-ha area, during the cutting cycle length. The highest simulated annual increments in volume are presented in bold

Fig. 8 Annual volume increment obtained from the simulation scenarios by the MFD defined by the population's biological rotation age and different cutting cycles for *Apuleia leiocarpa* (**A**), *Erisma uncinatum* (**B**), *Hymenolobium excelsum* (**C**), and *Trattinnickia burserifolia* (**D**)
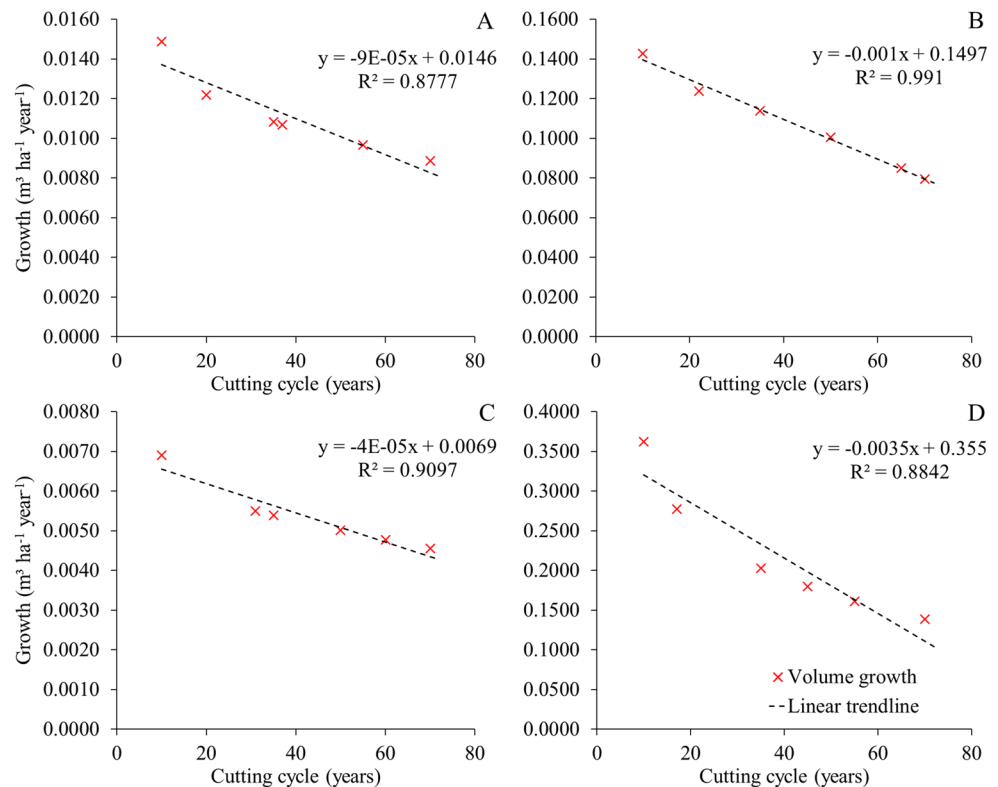
leiocarpa, *H. excelsum*, and *T. burserifolia*, while for *E. uncinatum*, this occurred at 86 cm. *Erisma uncinatum* has increased diameter increments (Fig. 4) and a high concentration of trees in the upper diameter classes, which explains its yield culmination in larger dbh sizes. This feature suggests the maintenance of larger dbh trees in the forest. In polycyclic management systems, the trees available for logging must reach at least the diameters with the highest growth potential in volume (Miranda et al. 2018b) represented by the minimum felling diameter (MFD). For this reason, it is essential to determine the diameter that provides the highest wood production for each species, based on the individual growth and the population demographic characteristics.

According to Miranda et al. (2018b), the species management in the mixed forest should be carried out within the diameters of the higher CAI_v and the biological rotation of the population to maximize the volume. However, we observed a large range between the maximum CAI_v and the biological rotation ages, of at least 36 years and 14-cm dbh (Table 2; Fig. 7). It remains unclear which MFD should be used to obtain the highest wood production for the next cutting cycle.

The CAI_v curves and biological rotation ages for all species population (Table 2; Fig. 7) were culminated in lower diamete increment curves at the individual level (Fig. 6; Table 1). The inclusion of the number of trees per diameter class anticipates the culmination since it indirectly represents the population mortality and survival rates (Assmann 1970; Rubin et al. 2006). As trees increase in size, the number of trees decreases due to mortality, causing a deceleration in the gross wood production, even though the remaining trees become larger (Seydack 2000; Lundqvist 2017). Therefore, even if individual trees are growing, the total production per unit area will decline much earlier (Assmann 1970).

According to Seydack (2000), the population demographic factors of commercial species are essential to determine the optimal parameters for forest management. In the natural forest structure, the available stock of trees by diameter class is a crucial feature for yield projection in terms of the number of trees, basal area, and volume (Ong and Kleine, 1996), since they indicate survival by diameter class. The recovery time of the wood volume in a post-intervention cycle is related to the species-specific growth and also to the number of trees in the smaller diameter classes to the intervention diameter (Brienen and Zuidema 2006a). Therefore, methods based on the production curves at the population level are recognized for being more accurate in predicting maximum volume yield in a natural forest, as it includes survival rates (Assmann 1970).

The procedure proposed in this work can be easily replicated to the remaining commercial species. At the community level, each species would have a specific MFD according to its maximization and logging would be carried out based on pre-logging censuses, which are mandatory for managing forests in Brazilian forest law (e.g., Brasil 2006). The forest manager has the location of each tree and dendrometric data in each forest compartment, which would allow precision forest management (Figueiredo et al. 2007) considering the specific MFD for each species population.

4.4 Volumetric production using different management criteria

The increments (m^3 ha^{-1} $year^{-1}$) of each species were, in general, compatible with other studies carried out in the Amazon, using permanent plots (Reis et al. 2010; Braz et al. 2018). Reis et al. (2010) obtained similar increments for *E. uncinatum* (Table 3), considering the cutting cycle and MFD of the Brazilian forest law (Brasil 2006).

The cutting cycles and alternative MFD from those defined in Brazilian forest law produced higher volumetric increment for the four studied species, similar to that obtained by Groenendijk et al. (2017) in tropical rainforest in Cameroon. *Erisma uncinatum* produced approximately seven times higher wood volume (ha^{-1} $year^{-1}$) applying short cutting cycle (10 years) and MFD 70% larger (86 cm) than the Brazilian mandatory MFD (50 cm). *Erisma uncinatum* presented the highest yield gain with the alternative MFD and cutting cycles, due to the higher number of trees and increments in dbh classes above 50 cm (Fig. 2 and Fig. 6). All results, especially those of *E. uncinatum*, showed the potential of maximizing the forest management yield considering population characteristics at the species level. The ideal MFD can increase volumetric increments, even without silvicultural treatments, and so should be considered to increase management productivity (Avila et al. 2017).

The MFD defined by the dbh of the biological rotation of the population produced higher annual increments for the four species, especially for shorter cutting cycles (Table 3). It is important to consider the optimal population increment rate instead of average increment data. This was previously considered by Ong and Kleine (1996) and Bick et al. (1998) when studying natural forests in Malaysia. These authors obtained the population increments from zero using permanent plots and simulations of forest production and found the maximum sustainable yield population, defining optimum logging rates and cutting cycles. Glauner et al. (2003) pointed out that the underlying principle of management is to improve the forest condition, converting its stock to an optimum level of increment of the commercial species.

In this study, the dbh of the maximum CAI_v (lowest among those tested as MFD) produced the lowest volume increments considering the tested cycles (Table 3). According to Bick et al. (1998), the harvested volume of two cycles must oscillate in the population growth curve between a lower and an upper limit of the maximum yield volume (i.e., the age of maximum CAI_v). These authors recommended an MFD above the dbh of maximum CAI_v. Our results are consistent with these recommendations, since the yield was higher when the logging was carried out at an age after the maximum population CAI_v, such as the biological rotation age.

When considering only the individual tree growth curve to define the logging parameters, we observed that the MFD was always higher, although the volumetric increments were lower, except for *A. leiocarpa* (Table 3). Contrary to the statement of Sebbenn et al. (2008) and Lacerda et al. (2013), the excessive MFD increase does not always imply higher forest productivity for all species. As mentioned, after reaching their productivity peak, the trees grow at moderate rates and the mortality is high. Slow growing trees should be logged before dying, through selective logging of mature trees of declining vigor (Seydack 2012; Lundqvist 2017).

The cutting cycles must be long enough so that remaining trees reach the MFD (Seydack et al. 1995). However, it cannot be too long, to ensure the trees' potential growth and forest economic sustainability (Mattioli et al. 2015). The simulations revealed that long cutting cycles resulted in smaller volumetric increments for all species (Fig. 8), reaching a loss higher than 60% compared to the 10-year cutting cycle, considering the same MFD (defined by population biological rotation). Therefore, increasing the cutting cycle indefinitely (Sebbenn et al. 2008) represents a technical error in a productive forest (Braz et al. 2015). Moreover, increasing the cut cycle requires long-term investment (Glauner et al. 2003), which is difficult in unstable political-economic environments (Groenendijk et al. 2017). On the other hand, short cutting cycles require logging planning, following the reduced impact logging standards.

In our proposal, stable structures were identified for six species, for which logging was simulated considering only those trees that reached the MFD. In this case, all previous diameter classes will be maintained and the remaining structure will naturally feed the larger diameter classes. Similarly, in the next cycle, only the trees that have already reached the MFD will be logged. It is important to emphasize that we considered in the simulations the balance between recruitment, ingrowth, and mortality. Moreover, trees with dbh above the MFD are at the beginning of senescence,

and regeneration considering the productive maturity is not compromised with the proposed procedure. According to Jennings et al. (2001), reproduction of trees in the Amazon begins at dbh much lower than 50 cm, not compromising the normal reproductive patterns of the different species.

Suitable cutting cycles depend on economic considerations (Bick et al. 1998) besides the MFD and the forest remaining structure. Economic analysis should support selecting the best cutting cycle for each specific case, considering the optimal parameters and exploitation feasibility for each species. Cost–benefit analyses can help assess forest management's economic and social aspects (Rosa et al. 2017). Moreover, higher MFD requires studies on tree health and risks of rot in older and bigger trees.

5 Conclusion

The diameter distribution of each species is similar throughout the evergreen seasonal forest in Brazilian Amazon. Modifications of the standard diameter structure by species can be combined with growth models for inferring tropical forest dynamics, as done in this study. The diameter distribution should support wood production planning and be the basis for monitoring forest logging.

The optimum population minimum felling diameter (MFD) of a species can significantly increase the volumetric increment and the total wood volume, maximizing the forest production under management. After determining the MFD, the best cutting cycle must be defined according to economic analysis, which will specify the best intervention time for the productive forest.

Currently in Brazil, the MFD used for all the species in the Amazon forest is fixed in 50-cm dbh. Our results showed that each species has a specific MFD that would guarantee higher wood production. By using a species-specific MFD, the sustainability of the production forest is maintained because it avoids early intervention that would damage the remaining structure. The methodology for species-level MFDs proved to be a useful tool and superior to the fixed parameters defined in the Brazilian law or the methodologies that consider only the individual tree growth. The procedure provides higher reliability for the maximized wood production. The ideal MFDs based on dendrochronology substantially reduce costs and time spent in collecting data for forest modeling. Our results should help to keep forests ecosystems alive by encouraging owners to practice sustainable forest management. This procedure should be evaluated by legal instances for improvement of Brazilian forest law.

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Appendix

Table 4 Goodness-of-fit test of the probability density function (PDF) fitted considering the total data set to the observed diameter distributions in each study area by the Kolmogorov–Smirnov test

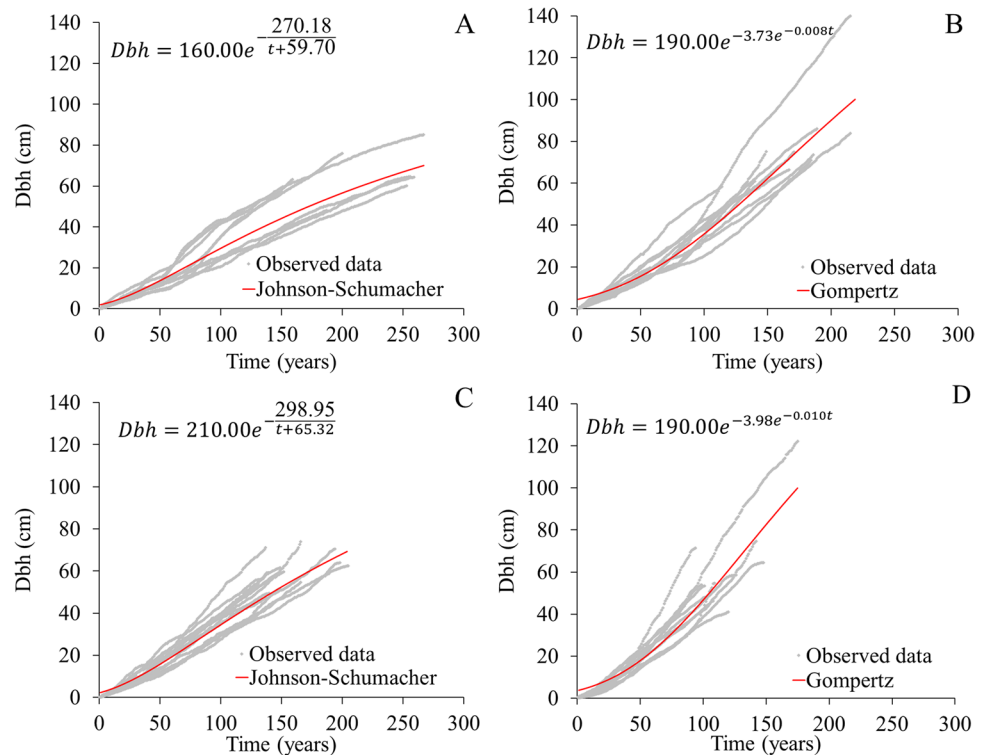| Species	D	PDF	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Apuleia leiocarpa	D_{calc}	Normal	0.048	0.100	0.078	0.139	0.089	0.063
		Beta	0.047	0.094	0.081	0.141	0.092	0.062
		Gamma	0.054	0.100	0.070	0.154	0.077	0.054
		Log normal	0.075	0.109	0.080	0.167	0.060	0.048
		Johnson's SB	0.045	0.095	0.075	0.147	0.085	0.060
		Weibull 3p	0.044	0.095	0.076	0.145	0.087	0.061
		D_{tab}	0.410	0.410	0.521	0.565	0.432	0.375
Erisma uncinatum	D_{calc}	Normal	0.049	0.256	0.084	0.055	0.082	0.044
		Beta	0.072	0.190	0.151	0.107	0.026	0.050
		Gamma	0.069	0.261	0.081	0.045	0.099	0.060
		Log normal	0.095	0.278	0.063	0.068	0.122	0.085
		Johnson's SB	0.047	0.257	0.083	0.056	0.082	0.043
		Weibull 3p	0.049	0.253	0.088	0.061	0.078	0.038
		D_{tab}	0.189	0.294	0.240	0.240	0.270	0.270
Hymenolobium excelsum	D_{calc}	Normal	0.124	0.124	0.124	0.124	0.151	0.124
		Beta	0.061	0.060	0.060	0.060	0.131	0.092
		Gamma	0.049	0.061	0.062	0.056	0.132	0.093
		Log normal	0.051	0.068	0.065	0.068	0.132	0.093
		Johnson's SB	0.049	0.058	0.063	0.050	0.129	0.090
		Weibull 3p	0.038	0.051	0.067	0.054	0.125	0.086
		D_{tab}	0.565	0.624	0.521	0.521	0.708	0.708
Trattinnickia burserifolia	D_{calc}	Normal	0.238*	0.238*	0.238*	0.238*	0.238*	0.238*
		Beta	0.187	0.170	0.170*	0.170*	0.170	0.170*
		Gamma	0.180	0.149	0.149	0.149	0.149	0.149
		Log normal	0.167	0.119	0.106	0.106	0.106	0.106
		Johnson's SB	0.127	0.071	0.071	0.071	0.071	0.092
		Weibull 3p	0.149	0.080	0.046	0.042	0.054	0.077
		D_{tab}	0.193	0.183	0.166	0.170	0.178	0.169

Area = sampled forest compartment; Dcalc. = maximum absolute value between fitted PDF and observed values in each compartment; Dtab. = critical value of Kolmogorov–Smirnov test ($\alpha = 0.05$); *the PDF did not fit to the observed values (Dtab. ≤ Dcalc.)

Table 5 Description of time series obtained by dendrochronology and growth models adjusted by species in each study area

Species	Number of tree rings measured	Samples dbh range (cm)	Samples estimated age range (years)	Growth model	Equation statistics				Equation parameters			Parameter's confidence intervals			
					Syx%	RMSE	AICC	BIC	β0	β1	β2	β1 (lower)	β1 (upper)	β2 (lower)	β2 (upper)
Apuleia leiocarpa	1843	41.1–76.2	126–267	Gompertz	27.24	8.84	1,320,000	1,320,000	160	3.051	0.005	3.045	3.057	0.005	0.005
				Johnson-Schumacher	**25.32**	**7.89**	**1,270,000**	**1,270,000**	**160**	**270.180**	**59.708**	**269.570**	**270.780**	**59.326**	**60.090**
				Lundqvist-Korf	25.36	7.94	1,270,000	1,270,000	160	29.229	0.626	28.985	29.474	0.624	0.628
				Logistic	28.86	9.73	1,350,000	1,350,000	160	13.599	0.010	13.540	13.658	0.010	0.010
				Monomolecular	25.42	7.94	1,270,000	1,270,000	160	1.016	0.002	1.015	1.016	0.002	0.002
				Schumacher	27.24	9.99	1,370,000	1,370,000	160	187.770		187.570	187.980		
Erisma uncinatum	1678	52.1–126.8	114–219	**Gompertz**	**30.77**	**10.18**	**1,170,000**	**1,170,000**	**190**	**3.733**	**0.008**	**3.725**	**3.741**	**0.008**	**0.008**
				Johnson-Schumacher	34.39	11.32	1,180,000	1,180,000	190	206.510	31.238	206.020	207.000	30.926	31.550
				Lundqvist-Korf	35.26	11.71	1,200,000	1,200,000	190	55.571	0.776	54.936	56.206	0.774	0.779
				Logistic	30.39	10.3	1,190,000	1,190,000	190	22.610	0.016	22.505	22.715	0.016	0.016
				Monomolecular	35.4	11.76	1,200,000	1,200,000	190	1.038	0.003	1.038	1.039	0.003	0.003
				Schumacher	30.76	11.56	1,220,000	1,220,000	190	161.940		161.800	162.090		
Hymenolobium excelsum	2065	44.3–67.6	135–205	Gompertz	22.49	6.64	1,340,000	1,340,000	210	3.470	0.006	3.466	3.475	0.006	0.006
				Johnson-Schumacher	**19.81**	**5.53**	**1,260,000**	**1,260,000**	**210**	**298.950**	**65.318**	**298.490**	**299.420**	**65.072**	**65.564**
				Lundqvist-Korf	19.41	5.44	1,270,000	1,270,000	210	21.654	0.544	21.546	21.763	0.543	0.545
				Logistic	24.77	7.67	1,400,000	1,400,000	210	21.087	0.013	21.016	21.158	0.013	0.013
				Monomolecular	19.64	5.5	1,270,000	1,270,000	210	1.014	0.002	1.014	1.014	0.002	0.002
				Schumacher	22.49	9.42	1,500,000	1,500,000	210	189.260		189.110	189.420		
Trattinnickia burserifolia	1285	41.2–119.8	94–175	**Gompertz**	**30.38**	**7.99**	**859,390**	**859,419**	**190**	**3.981**	**0.010**	**3.972**	**3.989**	**0.010**	**0.010**
				Johnson-Schumacher	35.7	9.25	857,039	857,068	190	174.500	25.567	174.030	174.960	25.305	25.829
				Lundqvist-Korf	37.18	9.69	865,244	865,273	190	42.040	0.741	41.581	42.499	0.739	0.744
				Logistic	29.19	8.03	880,594	880,623	190	28.187	0.022	28.038	28.337	0.022	0.022
				Monomolecular	37.79	9.95	874,054	874,083	190	1.038	0.003	1.038	1.039	0.003	0.003
				Schumacher	30.37	9.35	895,158	895,178	190	133.400		133.270	133.530		

$S_{yx}\%$ = relative residual standard error (%); *RMSE* root mean square error; *AICC* corrected Akaike information criteria; *BIC* Bayesian information criteria; β_0 = parameter fixed at the upper limit of the largest diameter class recorded in the complete census used; β_1 and β_2 = parameters of the equations adjusted by nonlinear regression. The equations with the best fits for each species are highlighted in bold

Fig. 9 Accumulated diameter growth equations fitted for *Apuleia leiocarpa* (**A**), *Erisma uncinatum* (**B**), *Hymenolobium excelsum* (**C**), and *Trattinnickia burserifolia* (**D**) and measured data obtained by dendrochronology. The growth equations were fitted for the ages represented by three or more samples. Dbh = diameter at 1.30 m above ground level; t = time (years); $S_{yx\%}$ = relative residual standard error (%)

$$Dbh = 160.00e^{\frac{270.18}{t+59.70}}$$

$$Dbh = 190.00e^{-3.73e^{-0.008t}}$$

$$Dbh = 210.00e^{-\frac{298.95}{t+65.32}}$$

$$Dbh = 190.00e^{-3.98e^{-0.010t}}$$

Data and materials availability The data that support the findings of this study are available from Embrapa Florestas and Elabore Projetos e Consultoria Florestal but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of Embrapa Florestas and Elabore Projetos e Consultoria Florestal.

Declarations

Ethics approval The authors declare that they follow the rules of good scientific practice.

Consent to participate The authors declare that the data collection was obtained from forest compartments with Sustainable Forest Management Plans approved by Secretaria Estadual do Meio Ambiente (SEMA-MT).

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