



## A 20-year tree liberation experiment in the Amazon: Highlights for diameter growth rates and species-specific management

Hassan C. David<sup>a,\*</sup>, João O.P. Carvalho<sup>a</sup>, Iran Paz Pires<sup>b</sup>, Luana S. Santos<sup>a</sup>, Eglison S. Barbosa<sup>a</sup>, Nathalia S. Braga<sup>a</sup>

<sup>a</sup>Rural Federal University of Amazonia, Pau Amarelo Avenue, 68650-000 Capitão Poço, PA, Brazil

<sup>b</sup>Instituto Floresta Tropical, São Pedro St. 566, Batista Campos, Belém, PA 66023-570, Brazil

### ARTICLE INFO

#### Keywords:

Terra firme forest  
Minimum cutting diameter  
Cutting cycle  
Individual-tree growth  
Non-age-explicit growth model

### ABSTRACT

We address tree diameter growth, linking it to a species-specific approach to managing *terra firme* forests in the Amazon, based on a long-term forest experiment testing the effect of tree liberation on diameter growth. Five species were selected for diameter growth modeling: *Astronium lecointei*, *Chrysophyllum lucentifolium*, *Lecythis lurida*, *Manilkara paraensis*, and *Manilkara elata*. The aims were to (i) investigate the tree diameter growth rates with and without liberation and (ii) determine species-specific minimum cutting diameters (MCDs) and cutting cycles (CCs). Individual tree non-age-explicit growth models were tested with calibration data from trees of  $\geq 35$  cm dbh whose growth was monitored over 20 years. The diameter growth was projected to 100 years. We found that liberation can reduce the time necessary for trees of 35 cm to attain an MCD of 50 cm by up to 70 years and can accelerate diameter growth even after growth stagnation. Its effect may be strong on both small and large trees, depending on the species. Both the diameter growth and the liberation effect depend on the species, thus reinforcing the need for more discussion of specific-species management in the Amazon. *M. elata* had the fastest diameter growth rate among the studied species. *A. lecointei* can grow under liberation as fast as *M. elata*. An MCD of 50 cm is suitable for both species because trees reach this dbh while still growing quickly. The number and length of the CCs for *A. lecointei* and *M. elata* should allow trees to reach a dbh between 60 and 70 cm. The species *C. lucentifolium* and *L. lurida* experienced growth stagnation at dbhs of 40–50 cm; however, liberation accelerated the slowed growth of trees in that diameter range. Similar studies in the Amazon are encouraged in order to confirm the slow growth of *C. lucentifolium* and *L. lurida* at other sites and then recommend reducing their MCD with a species-specific regulation. The number and length of the CCs for these two species should allow trees to reach a dbh no larger than the MCD. *M. paraensis* was the only species for which the effect of the liberation increased with tree size. An MCD of 50 cm is suitable for this species. CCs should allow *M. paraensis* trees to reach a dbh no larger than 60 cm without liberation and 70 cm with liberation.

### 1. Introduction

In the Amazon, logging plays an important social and economic role by generating income and employment. Private companies and the region's people have logged the Amazon's forests in Brazil, and management has been increased by the Brazilian forest concession system (Azevedo-Ramos et al., 2015). Illegal logging still represents a significant part of the total timber exploited in the Amazon, but the focus of this paper is sustainable practices. Approximately 80 commercial tree species are exploited in the region and sold in the local market and in the rest of Brazil, as well as being exported to countries around the world as raw logs or processed wood. Because it provides beautiful

woods and lumber, logging in the Amazon is a subject of interest worldwide.

As forests take some time to recover after exploitation, it is necessary to understand how long forests take to regain a structure and wood availability that is close to the original conditions. That period of recovery relates to the interval between sequential exploitations, and here it concerns the cutting cycle (CC). The current Brazilian regulation for sustainable management in the Amazon fixes a CC between 25 and 35 years for logging. Another important regulation is the minimum cutting diameter (MCD) of 50 cm, i.e., trees can be harvested if they are  $\geq 50$  cm dbh. Both CC and MCD are general rules that are common to all tree species and applied throughout the Brazilian Amazon. Other

\* Corresponding author.

E-mail address: [hassan.david@ufra.edu.br](mailto:hassan.david@ufra.edu.br) (H.C. David).

Amazonian countries have also established their own CCs and MCDs, but these are also general rules (López et al., 2013).

The generality of these criteria that rule forest management in the Amazon has increasingly been contested. Many authors (Andrade et al., 2019; Miranda et al., 2018; Araújo, 2016; Rosa et al., 2016; López et al., 2013; Braz et al., 2012; Macpherson et al., 2010; Schöngart, 2008) argue that the current legislation overestimates the capability of forest recovery, suggesting that the CC and MCD are inappropriate and unbalanced for many species, given that general criteria do not distinguish growth and dynamics at the species level. An unbalanced exploitation affects, in addition to the environment, the economic side, since the deficient recovery may decrease wood availability and the stock of species of interest for subsequent logging (Andrade et al., 2019; Avila et al., 2017; Schöngart, 2008). In this context, recent discussions over species-specific approaches to forest management claim that growth and recovery at the species level should be incorporated into logging planning. This is a more modern model than the current one, and it suggests that species-specific MCDs and CCs could be used rather than the general criteria (Andrade et al., 2019).

Through silvicultural treatments, such as thinning and cutting lianas, the growth of species can be boosted, and the CC of forests is then shortened (Peña-Claros et al., 2008; Dauber et al., 2005). Often, both practices are successfully adopted in the management of tropical forests (Avila et al., 2017). Experiments conducted to test their effect are, unfortunately, less common, given the long time necessary to obtain results. However, research has shown that the thinning of competitor trees can accelerate the diameter growth of the remaining trees by more than 50% (Taffarel et al., 2014a, 2014b; Rozendaal et al., 2010; Schulze et al., 2008; Azevedo et al., 2007). Cutting lianas, in turn, also stimulates the diameter growth because it liberates crown growth. Vidal et al. (2002), for example, observed two times faster growth in diameter because of that practice. By providing faster diameter growth, these silvicultural treatments can therefore shorten CC.

We have conducted an experiment with post logging liberation in an Amazonian *terra firme* dense forest. The tree liberation consisted of thinning competitor trees and cutting lianas over the crowns of liberated trees. Individual tree growth was monitored over 20 years. Here, we selected five tree species aiming to (i) investigate their diameter growth with and without liberation. Based on the growth and yield of the selected species, we also aimed to (ii) investigate whether the fixed MCD of 50 cm was appropriate for the species (i.e., species-specific MCD) and (iii) indicate how much the species should grow in diameter (i.e., species-specific CC).

## 2. Materials and methods

### 2.1. Study area

The study area is located in the eastern Amazonia, Brazil, in a Forest Management Unit 'Fazenda Cauaxi', where various forest experiments have been conducted. The area is situated 20 km southwest of the town of Paragominas, state of Pará (Wadsworth and Zweede, 2006). The local altitude averages 150 m, and the terrain ranges from flat to slightly undulating. The regional climate according to the Koppen classification (Alvares et al., 2013) is 'Am - monsoon', with a short dry season under the influence of monsoons.

Submontane and Lowland Dense Rainforests, also known as *terra firme* dense forests, dominate regional vegetation. These types of tropical forests, when well-preserved or in their original conditions, have a diameter distribution shaped as a reverse J-curve (Silva et al., 2015), a density of trees with a diameter at breast height (dbh)  $\geq 5$  cm reaching, in general,  $\sim 1200$  trees  $\text{ha}^{-1}$  and a basal area of  $\sim 30$  to  $\text{m}^2 \text{ha}^{-1}$  (Silva et al., 2015; Souza et al., 2006). Fig. 1 illustrates the location of the experimental area and vegetation classes surrounding the study area.

### 2.2. Forest experiment and tree species

As our dataset comes from long-term collection of field data, in addition to reporting the applied methods, we briefly report how the experiment started. In 1996, a certain remnant of *terra firme* dense forest located in 'Fazenda Cauaxi' was logged, and a timber volume of  $\sim 25 \text{ m}^3 \text{ha}^{-1}$  from more than 50 tree species was removed. An average of 17 trees  $\text{ha}^{-1}$  with dbh  $\geq 35$  cm and acceptable stem quality were removed of a total of approximately 24 trees  $\text{ha}^{-1}$  (Wadsworth and Zweede, 2006). The logging followed the techniques of Reduced-Impact Logging (RIL), based on the principles of sustainable forest management. This logging model suggests that the managed area be denominated as a Forest Management Unit, being split into Annual Production Units, which in turn were split into smaller 100-ha Work Units.

Two years after logging (i.e., in 1998), the forest researcher Johan C. Zweede implemented an experiment aiming at testing the effect of liberation thinning on the diameter growth of potential crop trees (PCT). A certain Work Unit was selected for the experiment, and it was 100% inventoried, including trees with dbh  $\geq 35$  cm. Two 20-ha ( $200 \text{ m} \times 1000 \text{ m}$ ) experimental plots were installed in that logged Work Unit; one plot was used for liberation thinning treatment (application of thinning and cutting lianas), and the other plot was installed for the control, in which no silvicultural intervention was performed.

In both plots, all trees with dbh  $\geq 35$  cm were tagged and identified at the species level, and all trees in the treatment plot were categorized as either liberated or competitor trees. Liberated trees were those individuals of commercial species with very good stem quality and dbh  $\geq 35$  cm that would benefit from the liberation thinning. Note that these conditions assign trees with 'dbh  $< 35$  cm' or 'low stem quality' as unbenefited trees, even if they are a commercial species. Competitor trees were split into three classes: (i) suppressed competitor, if it is an unbenefited tree with dbh  $\geq 10$  cm within 2 m of a competitor tree; (ii) dominant competitor, if it is an unbenefited tree of any dbh that overlaps the crown of a liberated tree, regardless of the distance between them; and (iii) codominant competitor, if it is an unbenefited tree with a crown that shares a canopy with a liberated tree and fits certain criteria of dbh and distance to a liberated tree. Table 1 summarizes the criteria for categorizing competitor trees. The density of competitor trees of each species is shown in Wadsworth and Zweede (2006).

The liberated trees, present only in the treatment plot, had their growth favored by the thinning of competitor trees, as well as by the cutting of lianas over their crown. The thinning of the competitor trees consisted of girdling them at breast height, removing slices (approximately  $5 \times 10$  cm) of bark, including part of the secondary phloem (inner bark), and applying herbicide where the bark was removed; one exception is that herbicide was not applied to competitor trees of commercial species. The cuts were interleaved along the stem circumference in a chessboard pattern, leaving 20–25% of the secondary phloem undamaged, thus facilitating the flux of the herbicide. This method provides a slow and gradual death and fall of the thinned trees, causing a low impact in the forest.

For this study, five commercial tree species existent in the experiment and widely harvested in Amazon were selected for modeling diameter growth: *Astronium lecointei* Ducke (muiracatiara), *Chrysophyllum lucentifolium* Cronquist (abiu-goiabão), *Lecythis lurida* (Miers) S.A. Mori (jarana), *Manilkara elata* (Allemão ex Miq.) Monach (maçaranduba), and *Manilkara paraensis* (Ducke) Standl. (maparajuba). Further information regarding species richness and dominance is presented in Wadsworth and Zweede (2006).

### 2.3. Calibration dataset and growth models

Our long-term dataset covers trees with dbh  $\geq 35$  cm in the treatment and control plots. The dbh of these trees was measured annually from 1998 to 2010, and from 2010, the dbh was measured biannually,

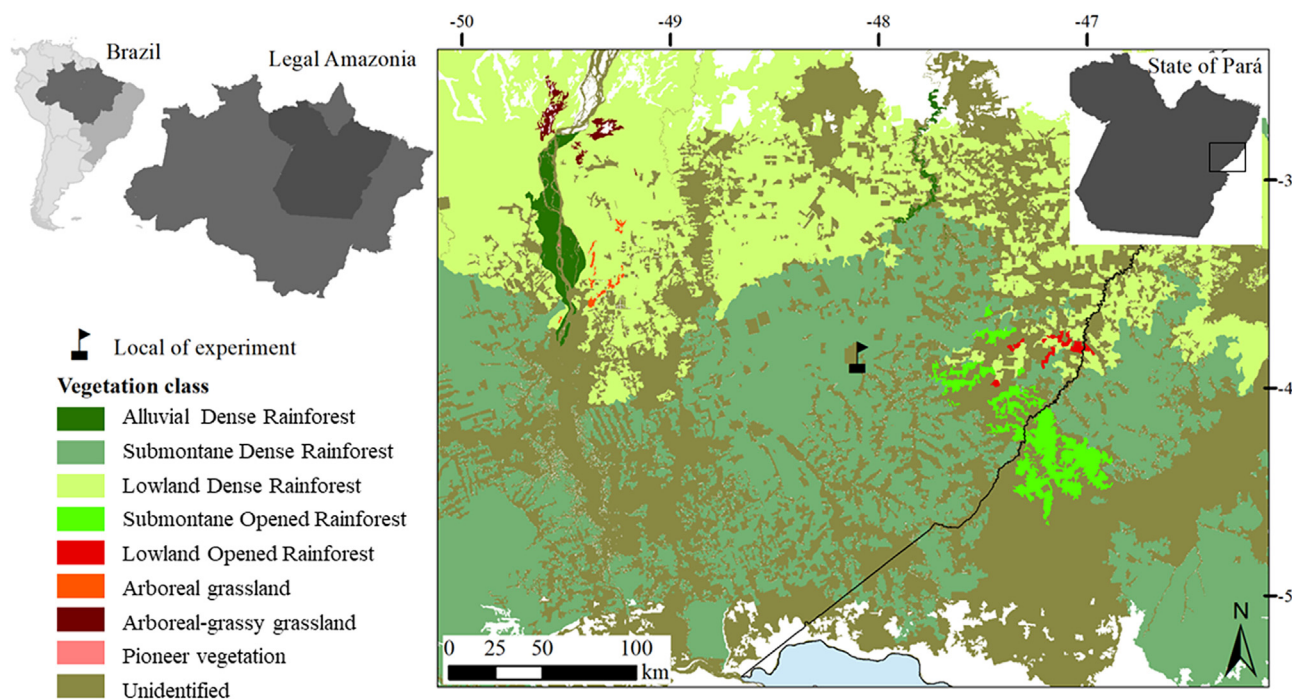


Fig. 1. Location of the study area and types of vegetation surrounding the study area. Data for classification of vegetation are sourced from Project RadamBrasil following guidelines from Veloso et al. (1991).

Table 1  
Criteria for classifying competitor trees in the experiment.

Category of competitor trees	Dbh	Distance to the closest liberated tree
Suppressed competitor	≥ 10 cm	≤ 2 m
Dominant competitor	Any	Any
Co-dominant competitor	20–39 cm	≤ 3 m
	40–59 cm	≤ 5 m
	60–79 cm	≤ 7 m
	80–99 cm	≤ 8 m
	> 99 cm	≤ 9 m

except in 2014, when collection could not be performed. Field data were always collected in the Amazonian drought season, i.e., between July and November. The five selected species are present in both treatment and control plots, allowing us to assess their diameter growth in both competition environments (with and without liberation thinning). Box-plots of the variable dbh observed in our datasets are shown in Fig. 2.

The ten datasets (5 species × 2 plots) shown in Fig. 2 were used to calibrate the growth models (GMs). The age of the trees is an unavailable variable in our dataset, as no tree-ring analysis was performed. As an alternative, we predicted the individual-tree diameter growth of the studied species by means of GMs in which age (here

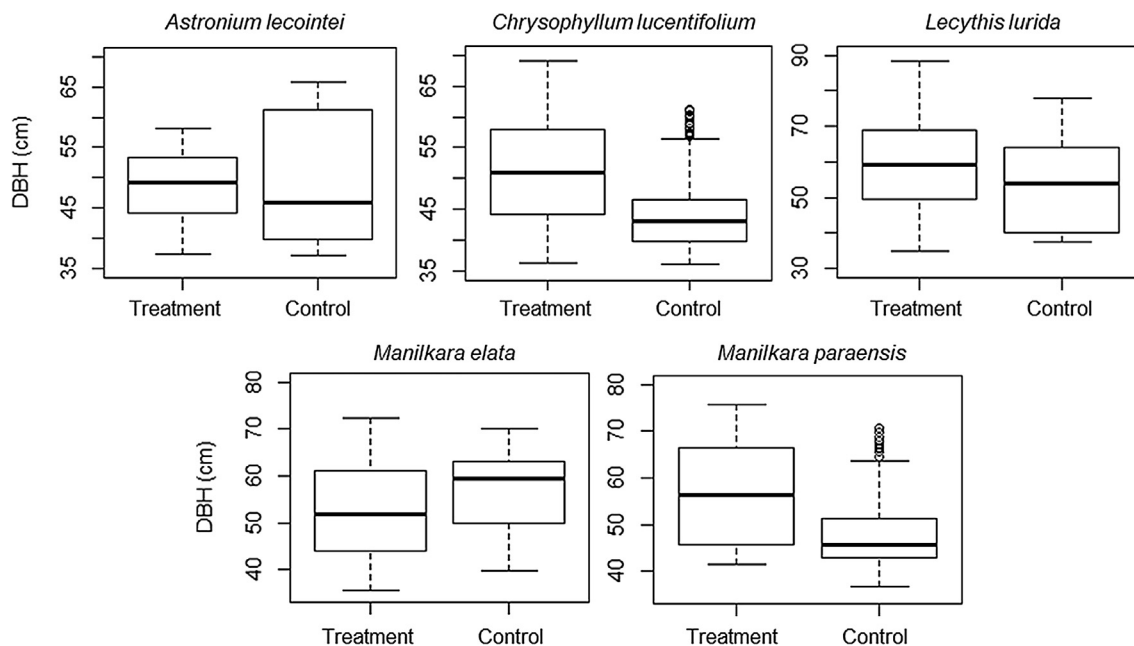


Fig. 2. Box-plot of the dbh datasets for growth model calibration. Bold lines are the median. Empty circles are outliers.

**Table 2**  
Growth models tested to estimate the diameter growth of commercial tree species.

Author	Original Growth Model	Non-age-explicit growth model
Lundqvist-Korf	$Y = Ae^{-k\frac{1}{t^m}}$	$Y_{t+a} = Ae^{-k\frac{1}{\left(\left[\frac{-k}{\ln(Y_t/A)}\right]^{\frac{1}{m}} + a\right)^m}}$ (1)
Richards	$Y = A(1 - ce^{-kt})^{\frac{1}{1-m}}$	$Y_{t+a} = A\left(1 - e^{-ka}\left(1 - \left(\frac{Y_t}{A}\right)^{1-m}\right)\right)^{\frac{1}{1-m}}$ (2)
Hossfeld IV	$Y = A\frac{t^k}{Ac + t^k}$	$Y_{t+a} = A\frac{\left(\left(\frac{cY_t}{A - Y_t}\right)^{\frac{1}{k}} + a\right)^k}{c + \left(\left(\frac{cY_t}{A - Y_t}\right)^{\frac{1}{k}} + a\right)^k}$ (3)

$Y_t$ : Dbh, in cm.  $Y_{t+a}$ : Dbh projected to the future, in cm.  $A$ : asymptote.  $k$ : parameter of slope.  $m$ : parameter of shape.  $t$ : age.  $a$ : projection length. Sourced from Burkhardt and Tomé (2012).

called  $t$ ) is not explicit. This type of GM can be obtained by isolating  $t$  from the original GM and substituting for  $t$  in the original GM with the isolated expression  $t + a$ , in which ‘ $a$ ’ is the projection length (PL), as explained in Burkhardt and Tomé (2012). Table 2 shows three original GMs and their underlying derivative formulation without age explicit that were fit to predict diameter growth.

We used the GRG (Generalized Reduced Gradient) nonlinear method (Schiestl-Aalto et al., 2015) to fit the GMs, taking initial parameters  $k$ ,  $m$ , and  $c$  from Burkhardt and Tomé (2012), while the initial parameter  $A$  was set for each species according to the maximum dbh observed in data. The goodness-of-fit of the models was assessed through the statistics root mean square error (RMSE) (4) and coefficient of determination ( $R^2$ ) (5). For each dataset, we selected GM with smallest RMSE and the largest  $R^2$ .

$$RMSE\% = 100 \left/ \bar{Y} \left[ \frac{\sum_{i=1}^n (Y_i - \hat{Y}_i)^2}{n - p} \right]^{1/2} \right. \quad (4)$$

$$R^2 = 1 - \frac{\sum_{i=1}^n (Y_i - \hat{Y}_i)^2}{\sum_{i=1}^n (Y_i - \bar{Y})^2} \quad (5)$$

where  $Y_i$ : observed dbh, in cm.  $\hat{Y}_i$ : estimated dbh, in cm.  $\bar{Y}$ : mean observed dbh, in cm.  $n$ : number of observations.  $p$ : number of model parameters.

The GMs were projected to a PL of 100 years considering initial dbhs of 35, 50, 60, and 70 cm for all studied species. Based on estimates of the fitted GMs, periodic annual increments (PAIs) in diameter were estimated by species and initial dbh at the years of growth of 1, 10, 20, and so on, until 100 years. We computed the PAI in diameter as shown in (6), as well as the extra PAI provided by the treatment in relation to the control, as shown in (7).

$$PAI = \frac{Dbh_{later} - Dbh_{early}}{PL} \quad (6)$$

$$ExtraPAI = PAI_{treatment} - PAI_{control} \quad (7)$$

where PAI is the periodic annual increment in  $cm\ year^{-1}$ . dbh: diameter at breast height, in cm; PL: projection length, in years.

### 3. Results

#### 3.1. Growth model performance

Table 3 provides goodness-of-fit statistics of the GMs selected for each species and plot (treatment and control). The RMSE reached a maximum value of 5.41%, and the  $R^2$  was larger than 91%, indicating a great performance of the GRG nonlinear method and the selected GMs. We noted that the same model for each species was better fitted to both

the treatment and control plots, allowing us to more fairly compare the growth curves observed in the two experimental plots. The Hossfeld IV model (3) presented the worst performance of all tested models and therefore does not appear in Table 3.

Table 3 also shows the coefficients of the GMs. Parameter  $A$ , related to the asymptote of the growth curves, expectedly converged in larger coefficients for the treatment plot than for the control plot, except in the species *M. elata* (Table 3). We also found little variation in parameters  $k$  and  $m$  between plots, as well as a certain similarity of these parameters among the species that used the same GM.

In the selected models, the Lundqvist-Korf model (1) and the Richards model (2), the asymptote is designated by the  $A$  parameter. The parameters  $k$  and  $m$  interact with each other and are related to the slope and shape of the curve, respectively. In the Lundqvist-Korf model,  $k$  is inversely proportional and  $m$  is directly proportional to the growth rate, while in the Richards model,  $k$  is directly and  $m$  is inversely proportional to the growth rate (Burkhardt and Tomé, 2012). The parameters  $A$  and  $k$  (Table 3) from fittings of *M. elata* had little difference between the control and treatment plots, revealing that the species reaches equivalent maximum diameters and growth rates both with and without liberation thinning, i.e., the species had low or no response to the treatment. For the other species, we obtained expected values for the model parameters (Table 3) whose results indicated larger asymptotes and faster growth rates in the treatment plots than in the control plots.

Fig. 3 shows plots that relate observed dbhs and their estimates from the selected GMs to each species and experimental plot. Fig. 3 also shows differences between the average trend (black line) and the expected trend (red line); the expected trend indicates an ideal unbiased fit. The fits for the species *A. lecointei* and *L. lurida* presented the most unbiased residuals, followed by *M. elata*, *M. paraensis*, and *C. lucentifolium*.

#### 3.2. Diameter growth curves and increments

Fig. 4 illustrates the diameter growth curves for each species in the treatment (left) and control (right) plots. The curves were drawn for the initial diameters of 35 (lowest curve), 50, 60, and 70 cm (highest curve) growing for a PL of 100 years; a curve with an initial diameter of 70 cm was not drawn for the species *A. lecointei* or *M. paraensis* in the control plot because no tree with  $\geq 70$  cm was found in these datasets.

Table 4 and Fig. 5 relate the extra PAI provided by the treatment as a function of the PL for initial dbhs of 35, 50, 60, and 70 cm. As in Fig. 4, the extra PAIs for an initial diameter of 70 cm were not drawn for the species *A. lecointei* and *M. paraensis* because no tree with  $\geq 70$  cm was found in the control plot.

*A. lecointei*. At a PL of 100 years, the treatment added, compared to the dbhs found in the control, an extra periodic annual increment (PAI)

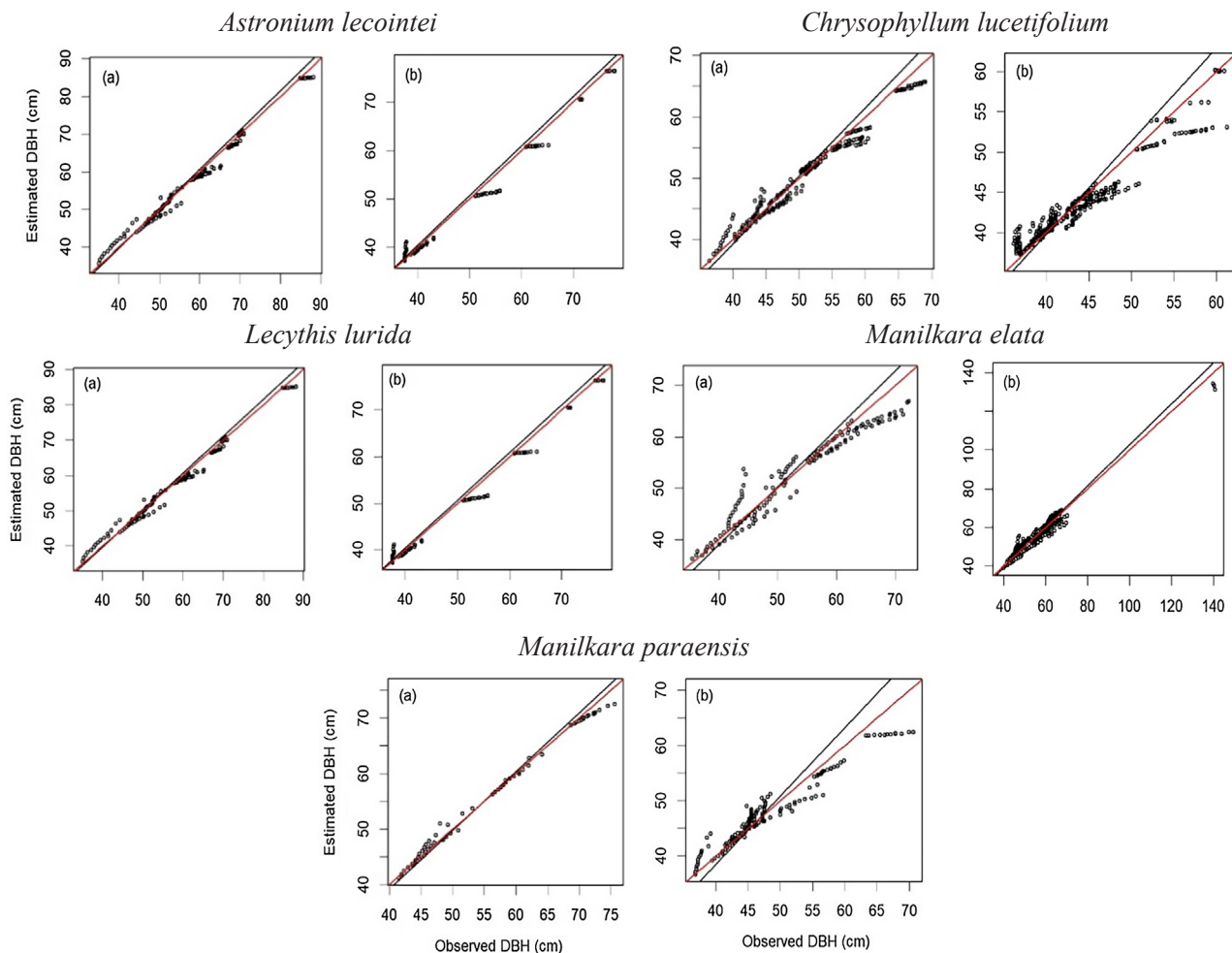
**Table 3**  
Coefficients and goodness-of-fit statistics of selected GMs for commercial tree species.

Species	Growth Model	Experimental plot	Model coefficients			Goodness of fit	
			A	K	m	R <sup>2</sup>	RMSE
<i>Astronium lecointei</i>	Richards	Treatment	79.94	0.02	0.04	0.97	2.09%
		Control	69.11	0.02	0.60	0.98	3.43%
<i>Chrysophyllum lucetifolium</i>	Lundqvist-Korf	Treatment	104.93	3.08	0.34	0.97	3.03%
		Control	91.55	3.47	0.34	0.92	4.03%
<i>Lecythis lurida</i>	Lundqvist-Korf	Treatment	121.04	3.06	0.33	0.99	2.47%
		Control	91.57	3.14	0.33	0.99	3.07%
<i>Manilkara elata</i>	Richards	Treatment	81.37	0.02	0.44	0.92	5.41%
		Control	82.19	0.02	0.15	0.95	4.38%
<i>Manilkara paraensis</i>	Richards	Treatment	80.94	0.02	0.60	0.99	1.82%
		Control	64.14	0.02	0.60	0.91	4.90%

A: asymptote. k: parameter of slope. m: parameter of shape. R<sup>2</sup>: coefficient of determination. RMSE: root mean square error.

in diameter of ~0.10 cm year<sup>-1</sup> for dbhs starting from 35, 50, 60, and 70 cm (Table 4, Fig. 5). Considering the minimum and maximum CC established in law, a tree with a dbh of 35 cm reaches 46.8 cm in 25 years and 50.4 cm in 35 years in natural conditions of competition. If liberation thinning is applied, the same tree reaches 52.5 cm and 57.4 cm in these same periods. The GMs estimate that a tree with a dbh of 35 cm takes 34 years to reach the MCD of 50 cm in natural conditions of competition; however, this growth time falls to 21 years if liberation thinning is applied. These growth rates correspond to PAIs of

approximately 0.44 and 0.71 cm year<sup>-1</sup>, respectively. For a tree to attain a dbh of 60 cm starting from 35 cm, it would take 74 years in natural conditions, compared to 41 years in a reduced-competition environment. To attain a dbh of 70 cm would take longer than the PL of 100 years, but it would take 76 years with liberation thinning. In 100 years, trees with dbhs of 35, 50 and 60 cm reach 63.7, 66.3 and 67.8 cm dbh, respectively, in natural conditions of competition. With liberation thinning, trees with dbhs of 35, 50, 60, and 70 cm can reach 73.8, 75.9, 77.2, and 78.6 cm, respectively, in 100 years. Liberation



**Fig. 3.** Relationship between observed and estimated dbh of commercial tree species. (a) Treatment with liberation thinning. (b) Control. Black line: average trend. Red line: expected trend. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

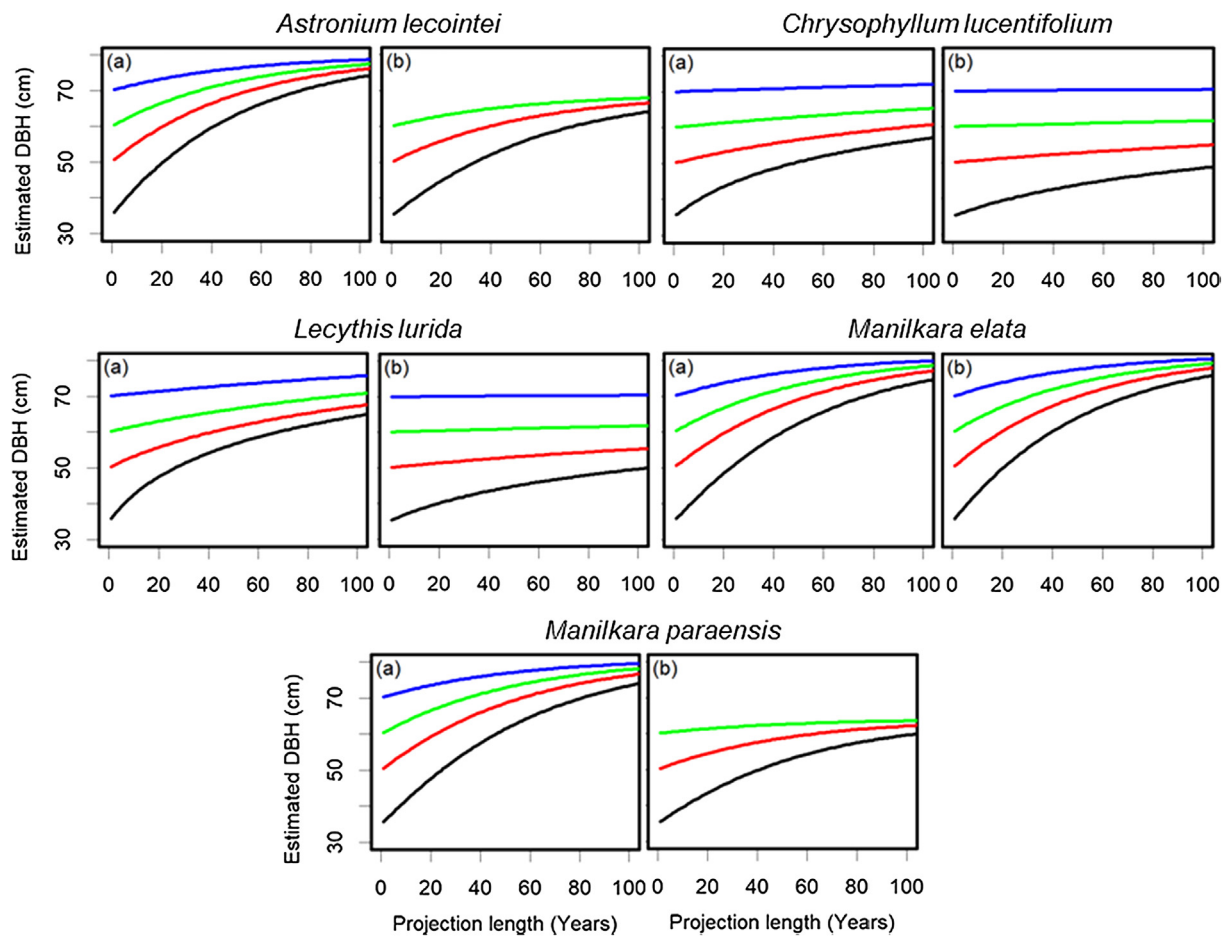


Fig. 4. Diameter growth curves of commercial tree species. (a) Treatment with liberation thinning. (b) Control. Black line: initial dbh of 35 cm, red line: 60 cm, green line: 50 cm, blue line: 35 cm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4

Extra periodic annual increment (PAI,  $\text{cm year}^{-1}$ ) in diameter provided by liberation thinning in relation to the control plot.

Initial dbh (cm)	Projection length (Years)										
	1	10	20	30	40	50	60	70	80	90	100
<i>Astronium lecoitei</i>											
35	0.33	0.29	0.25	0.21	0.19	0.17	0.15	0.13	0.12	0.11	0.10
50	0.24	0.22	0.20	0.18	0.16	0.14	0.13	0.12	0.11	0.10	0.10
60	0.22	0.20	0.18	0.17	0.15	0.14	0.13	0.12	0.11	0.10	0.09
70	-	-	-	-	-	-	-	-	-	-	-
<i>Chrysophyllum lucentifolium</i>											
35	0.32	0.25	0.20	0.17	0.15	0.13	0.12	0.11	0.10	0.09	0.08
50	0.12	0.11	0.10	0.09	0.08	0.08	0.07	0.07	0.07	0.06	0.06
60	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04
70	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
<i>Lecythis lurida</i>											
35	0.62	0.47	0.37	0.31	0.27	0.23	0.21	0.19	0.17	0.16	0.15
50	0.28	0.25	0.22	0.20	0.18	0.17	0.15	0.14	0.13	0.13	0.12
60	0.15	0.14	0.13	0.12	0.12	0.11	0.10	0.10	0.10	0.09	0.09
70	0.07	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.05
<i>Manilkara elata</i>											
35	-0.12	-0.09	-0.07	-0.06	-0.05	-0.04	-0.03	-0.02	-0.02	-0.02	-0.01
50	-0.06	-0.05	-0.04	-0.03	-0.02	-0.02	-0.02	-0.01	-0.01	-0.01	-0.01
60	-0.03	-0.03	-0.02	-0.02	-0.02	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
70	-0.02	-0.02	-0.02	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
<i>Manilkara paraensis</i>											
35	0.22	0.22	0.21	0.20	0.19	0.18	0.17	0.16	0.16	0.15	0.14
50	0.27	0.25	0.24	0.22	0.21	0.20	0.18	0.17	0.16	0.15	0.14
60	0.30	0.28	0.26	0.24	0.22	0.20	0.19	0.18	0.16	0.15	0.14
70	-	-	-	-	-	-	-	-	-	-	-

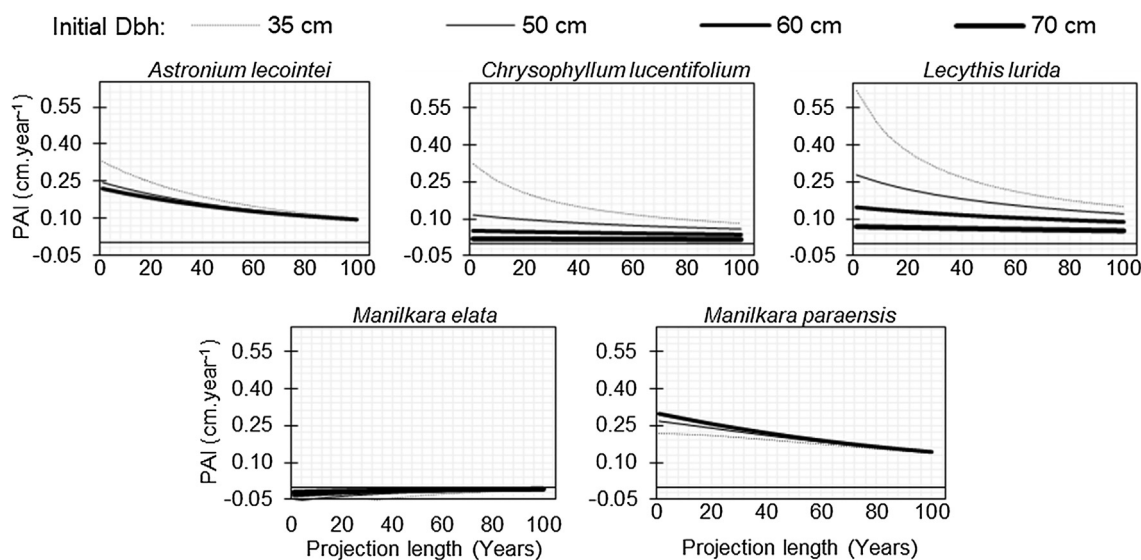


Fig. 5. Extra periodic annual increment (PAI) in diameter provided by liberation thinning in relation to the control plot.

thinning added  $\sim 10$  cm to the initial dbhs.

*C. lucentifolium*. At a PL of 100 years, the extra PAI in diameter provided by the treatment, compared to that found in the control, was larger ( $0.08 \text{ cm year}^{-1}$ ) for trees with a dbh starting at 35 cm, followed by trees starting at 50 cm ( $0.06 \text{ cm year}^{-1}$ ), 60 cm ( $0.04 \text{ cm year}^{-1}$ ), and 70 cm ( $0.02 \text{ cm year}^{-1}$ ) dbh (Table 4, Fig. 5). Under natural conditions of competition, a tree of 35 cm reaches 40.3 cm in the minimum CC of 25 years, and a slightly larger dbh of 41.8 cm is reached in the maximum CC of 35 years, i.e., a very small extra PAI in diameter of 1.5 cm would be gained in 10 additional years of growth. With liberation thinning, the dbh would be 45.0 cm and 47.4 cm in this same period, i.e., the reduced competition contributes slightly more than 5 cm more in 10 years. With liberation, a tree with a dbh of 35 cm takes 48 years to reach the MCD of 50 cm ( $\text{PAI} = -0.31 \text{ cm year}^{-1}$ ), but it would not reach that dbh in less than 100 years without the treatment ( $\text{PAI} < 0.15 \text{ cm year}^{-1}$ ). With or without liberation thinning, a tree with a dbh of 35 cm takes more than 100 years to reach 60 cm or 70 cm. At a PL of 100 years and in natural conditions of competition, trees with dbhs of 35, 50, 60, and 70 cm reach 48.5, 54.7, 61.6, and 70.4 cm, respectively. With liberation thinning, they reach 56.8, 60.6, 65.3, and 72.0 cm, respectively. Liberation thinning added  $\sim 8$ ,  $\sim 6$ ,  $\sim 4$ , and  $\sim 2$  cm, respectively, to these initial dbhs.

*L. lurida*. As observed in the species *C. lucentifolium*, the liberation thinning added, in relation to the control PAIs, an extra PAI (average of 100 years) inversely proportional to the tree size. The extra PAI was largest ( $0.15 \text{ cm year}^{-1}$ ) for trees with a dbh starting at 35 cm, followed by trees starting at 50 cm ( $0.12 \text{ cm year}^{-1}$ ), 60 cm ( $0.09 \text{ cm year}^{-1}$ ), and 70 cm ( $0.05 \text{ cm year}^{-1}$ ) dbh (Table 4, Fig. 5). Under natural conditions of competition, a tree of 35 cm reaches 41.0 cm in the minimum CC of 25 years and 42.7 cm in the maximum CC of 35 years. With liberation thinning, the dbh would be 49.4 cm to 52.7 cm, i.e., the thinning contributes an additional 8.4 cm in 25 years and 10.0 cm in 35 years. A tree of 35 cm dbh takes  $\sim 105$  years ( $\text{PAI} = \sim 0.14 \text{ cm year}^{-1}$ ) to attain the MCD of 50 cm without liberation thinning, but it would take only 27 years ( $\text{PAI} = \sim 0.56 \text{ cm year}^{-1}$ ) with liberation, i.e., an reduction of almost 80 years. To attain a dbh of 60 cm, this same tree would take 68 years with liberation thinning. To attain a dbh of 70 cm would take longer than the PL of 100 years, even with liberation thinning. In 100 years, trees with dbhs of 35, 50, 60, and 70 cm reach 49.6, 55.2, 61.8, and 70.4 cm, respectively, under natural conditions of competition. With liberation thinning, they would reach 64.5, 67.2, 70.6, and 75.6 cm in 100 years, respectively. For these initial dbhs, the liberation thinning added  $\sim 15$ ,  $\sim 12$ ,  $\sim 9$ , and  $\sim 5$  cm

plus, respectively.

*M. elata*. Liberation thinning had no significant ( $\alpha > 0.05$ ) effect on this species; a tiny negative extra increment was observed compared to that in the control plot (Table 4, Fig. 5). With or without liberation thinning, a tree of 35 cm reaches  $\sim 52$  cm and  $\sim 57$  cm, respectively, in the minimum and maximum CC of 25 and 35 years, i.e., the PAI is  $0.68$  and  $0.63 \text{ cm year}^{-1}$ , respectively. A tree with a dbh of 35 cm takes from 21 to 23 years to reach the MCD of 50 cm ( $\text{PAI} = 0.65\text{--}0.71 \text{ cm year}^{-1}$ ); from 40 to 44 years to reach a dbh of 60 cm; and from 70 to 74 years to reach a dbh of 70 cm. In 100 years, trees with dbhs of 35, 50, 60, and 70 cm reach 75.5, 77.7, 79.1, and 80.5 cm, respectively.

*M. paraensis*. At a PL of 100 years, the treatment added, compared to that in the control, an extra PAI in diameter of  $\sim 0.14 \text{ cm year}^{-1}$  for dbhs starting from 35, 50, 60, and 70 cm (Table 4, Fig. 5). Considering the CCs of 25 and 35 years, a tree a dbh of 35 cm can reach, under natural conditions of competition, 45.2 cm in 25 years and 48.4 cm in 35 years. If liberation thinning is applied, that tree can reach 50.4 cm and 55.3 cm, respectively, in 25 and 35 years. The GMs estimate that a tree with a dbh of 35 cm takes 41 years to reach the MCD of 50 cm ( $\text{PAI} = \sim 0.37 \text{ cm year}^{-1}$ ) under natural conditions of competition; this time of growth falls to 25 years ( $\text{PAI} = \sim 0.60 \text{ cm year}^{-1}$ ) if liberation thinning is applied. A tree with 35 cm takes more than 100 years to attain 60 cm without liberation thinning, compared to 47 years with liberation thinning. To reach a dbh of 70 cm would take 81 years with liberation thinning. In 100 years, trees with dbhs of 35, 50 and 60 cm reach 59.6, 62.1, and 63.6 cm, respectively, under natural conditions of competition. With liberation thinning, trees with dbhs of 35, 50, 60, and 70 cm reach, respectively, 73.4, 76.2, 77.9, and 79.4 cm in 100 years. Liberation thinning added  $\sim 14$  cm to these initial dbhs.

## 4. Discussion

### 4.1. Minimum cutting diameter

Our GMs suggest that the MCD of 50 cm is too general if the different diameter growth rates observed among the studied species are taken into account. Similarly, Rozendaal et al. (2010) simulated the diameter growth of three tree species in a Bolivian Amazon Rainforest, where they obtained substantially different diameter growth rates among species. In addition, the authors found differences among within-species individuals, as well as within-species diameter classes. Unfortunately, the lack of studies addressing species-specific diameter GMs and the time of growth necessary to attain the MCD is an

important deadlock preventing comparison of our results.

*A. lecointei* had the second-fastest diameter growth rate (Fig. 4), and it was the species most positively affected by liberation thinning. In a post-logging natural condition, our findings suggest that an MCD of 50 cm is suitable for this species because its diameter growth remains relatively active even in large trees ( $\text{dbh} \geq 35$  cm). Rozendaal et al. (2010) also observed a general increase in diameter PAI (i.e., biological activity) from small (5–10 cm) to large trees (50–60 cm) for their studied species. These results illustrate that many tropical tree species take longer than temperate species to stagnate their growth and thus reach large diameters. Schulze et al. (2008), for example, reported a dbh of 187 cm for *A. lecointei* when investigating four post-logging forests across the Brazilian Amazon. Schulze et al. computed a mean PAI (PL of 8 years) of  $0.42 \text{ cm year}^{-1}$  ( $\text{dbh} \geq 5$  cm) without silvicultural interventions. As our predictions cover only  $\text{dbh} \geq 35$  cm and longer PLs, we cannot fairly compare our results to Schulze et al.'s estimates, although we obtained a similar PAI of  $0.44 \text{ cm year}^{-1}$  for trees growing from 35 to 50 cm under the same conditions of competition assessed by these authors. These PAIs are twice as large as the PAI (PL of 4 years) reported by Poorter et al. (2001) for *A. lecointei* in a Bolivian Amazon forest, although their different PL and inclusion criterion of  $\text{dbh} \geq 10$  cm prevent us from fairly comparing the increments.

*C. lucentifolium* had the slowest diameter growth rate, especially for diameters from 40 to 50 cm (Fig. 4), suggesting that this range includes the point of growth stagnation for this species. The treatment increased the PAI; however, it exerted the smallest effect in the range of 40–50 cm among the studied species (except *M. elata*). Taffarel et al. (2014b) studied *C. lucentifolium* in a *terra firme* Amazonian forest subjected to five treatments (T1–T5) with post-logging thinning and liana cutting, differing in their thinning intensities. The treatments T1 to T5 were compared to controls of a logged plot with no silvicultural intervention (T6) and an unlogged plot (T7). Taffarel et al. monitored the diameter growth of trees larger than 35 cm 5 years after logging and 4 years after silvicultural interventions, observing PAIs in diameter ranging from approximately  $\sim 0.15$  to  $\sim 0.25 \text{ cm year}^{-1}$  for T1 to T5,  $\sim 0.27 \text{ cm year}^{-1}$  for T6, and  $\sim 0.13 \text{ cm year}^{-1}$  for T7. The authors found no significant difference ( $\alpha = 5\%$ ) of PAIs in diameter among the treatments or between them in relation to the controls; the result was associated with the short time (4 years) during which the treatments exerted their effect. We, however, monitored this effect over a longer time period (20 years) and noted that the diameter growth rate of the species had already stagnated before attaining an MCD of 50 cm, even when the treatment was applied, based on the extra PAIs shown in Table 4. We recommend a more appropriate MCD for *C. lucentifolium* of 40–45 cm for sites in the condition of our study, based on the species' slower biological activity for trees with  $\text{dbh} \geq 40$  cm.

*L. lurida*, like *C. lucentifolium*, had a slow growth rate. In the control plot, *L. lurida*'s rates were slightly faster than those of *C. lucentifolium*, with stagnation of growth between 40 and 50 cm. The treatment exerted twice as large of an effect on the growth of *L. lurida* as on that of *C. lucentifolium*, and this effect for both species was substantially weaker for trees with diameters over 50 cm (Fig. 5, Table 4). Azevedo et al. (2007) monitored a post-logging forest over 20 years, measuring the diameter of trees ( $n = 8$ ) of *L. lurida* with  $\text{dbh} \geq 20$  cm in and finding a PAI in diameter of  $0.42 \text{ cm year}^{-1}$ . For any initial dbh and PL we assessed, our PAIs estimated for the control plot were smaller than the PAI found by Azevedo et al., although most PAIs in the treatment plot were larger. After three years of logging of an eastern Amazon *terra firme* forest, Vidal et al. (2002) obtained PAIs ranging from 0.00 to  $0.40 \text{ cm year}^{-1}$  and an average of  $0.14 \text{ cm year}^{-1}$  for *L. lurida*, one of the species with the slowest growth rates among 14 species studied by the authors, as we noted. Taffarel et al. (2014a) studied the growth of *L. lurida* in the same study area and the methods from Taffarel et al. (2014b) previously cited. Taffarel et al. (2014a) obtained statistically equal ( $\alpha = 5\%$ ) growth of *L. lurida* among the treatments with liberation thinning. Taffarel et al. (2014a) obtained PAIs in diameter ranging

from  $\sim 0.25$  to  $\sim 0.45 \text{ cm year}^{-1}$  for T1 to T5;  $\sim 0.35 \text{ cm year}^{-1}$  for T6; and  $\sim 0.13 \text{ cm year}^{-1}$  for T7. Our estimated PAIs for the control plot were somewhat similar to estimates from Vidal et al. (2002) and in Taffarel et al. (2014a) in T6. However, our treatment slightly increased the diameter growth compared to that found in Taffarel et al. (2014a) considering any initial dbh and a short PL of 5 years as the authors did. Our results and from these cited authors reveal the slow growth rate of the species in western Amazonia; we thus suggest that the MCD for *L. lurida* should be reduced to 40–45 cm for sites in the condition of our study. Otherwise, liberation thinning should be applied to boost the growth of 40–50 cm trees once their growth has stagnated.

*M. elata* had the fastest diameter growth rate, but it was the only species negatively affected by the treatment, although the extra PAIs (Fig. 5, Table 4) were statistically insignificant ( $\alpha = 5\%$ ). As the species had a very fast growth rate, the findings suggest that liberation thinning is insufficient to accelerate its growth. Thus, we believe that the unexpectedly negative extra PAIs may result from conditions other than competition that might have hampered growth in the treatment plot, such as soil attributes, tree injuries, and crown shape (consequently, crown illumination); Souza et al. (2014), Costa et al. (2007), and Silva et al. (1996) showed that such conditions can exert an important effect on tree growth rate. Azevedo et al. (2007), authors mentioned previously, also studied the growth of *M. elata* trees with  $\text{dbh} \geq 20$  cm (the authors used its former scientific name, *Manilkara huberi*) and observed a PAI in diameter of  $0.42 \text{ cm year}^{-1}$  ( $n = 256$ ), i.e., a value smaller than our PAIs in the two plots (treatment and control). Costa et al. (2007) presented results from a long-term (16 years) experiment to assess the effect of crown illumination and liana cutting on the diameter growth in a post-logging forest located in the eastern Amazon. In their experiment, the authors categorized trees of *M. elata* (authors used its former scientific name, *M. huberi*) with  $\text{DAP} \geq 10$  cm into groups with total, partial and low solar illumination, having PAIs of 0.67, 0.58 and  $0.26 \text{ cm year}^{-1}$ , respectively. These two first values are close to our PAIs, but as we have no information about solar illumination in our experiment, we cannot state that such a similarity is due to the same light conditions. Costa et al. also assessed the groups with and without liana cutting in their crown, which had PAIs of 0.60 and  $0.45 \text{ cm year}^{-1}$ . Liana cutting was also applied in our treatment; we, on the other hand, found no effect of this silvicultural practice (along with thinning) on the diameter growth of *M. elata*. Silva et al. (1996) monitored the growth of several tree species in two logged Amazon forests; *M. elata* (presented as *M. huberi*) had PAIs ranging from 0.4 and  $0.5 \text{ cm year}^{-1}$  when no silvicultural intervention was performed. Souza et al. (2014) studied the diameter growth of *M. huberi* (trees with  $\text{dbh} \geq 35$  cm) in the same experimental area and treatments (T1–T7) as Taffarel et al. (2014a, 2014b), with T1–T5 as treatments with post-logging thinning and liana cutting at five different thinning intensities, and control plots T6 and T7 with and without logging, respectively. Souza et al. also found no significant difference ( $\alpha = 5\%$ ) in the PAIs among T1 to T5, but T1 and T3 were significantly different from the control T7, meaning that the diameter growth of the species was positively affected by the thinning along with liana cutting compared to its growth in an unlogged forest. From 2005 to 2009, the average PAIs ranged from  $0.41 \text{ cm year}^{-1}$  (T7) to  $0.59 \text{ cm year}^{-1}$  (T3). With no lianas in the trees, the authors reported a maximum PAI (PL from 2007 to 2009) of  $0.66 \text{ cm year}^{-1}$ . When the tree crowns were entirely exposed to solar light, the maximum PAI (PL from 2007 to 2009) was  $0.61 \text{ cm year}^{-1}$ . In spite of the fact that the cited research presented different responses to thinning (i.e., some having an effect and others having no effect), the species *M. elata* had somewhat fast growth rates in all cases, as we noted. Thus, we suggest that the MCD of 50 cm is suitable for *M. elata* due to its diameter growth being well active even in large trees ( $\text{dbh} \geq 35$  cm).

*M. paraensis* had the median diameter growth rate among the studied species, as well as the second-largest PAI increase provided by the treatment. The biological activity of *M. paraensis* trees with



dbh  $\geq$  35 cm is relatively fast until they reach 50 cm, even without liberation thinning; therefore, we suggest that the MCD established in law is suitable. The species' diameter growth stagnation starts at dbhs from 50 cm. A unique response was detected in these larger trees: the larger the dbh, the larger the extra PAIs provided by the liberation thinning, in contrast to those found for the other species (Table 4). It is difficult to state that this species is prone to having this response to liberation thinning due to the lack of studies of this species with liberation thinning that consider PAI by diameter class. In the previously cited research from Souza et al. (2014), the authors also monitored the growth of *M. paraensis* (dbh  $\geq$  35 cm) in the same experiment reported in the discussion of *M. elata*. In general, Souza et al. obtained similar growth rates and extra PAIs. In the T1-T3 treatments with liberation thinning, the authors found PAIs  $\sim 0.10$  cm year $^{-1}$  extra (though statistically equal) compared to that of the control with no liberation (T6) and  $\sim 0.15$  cm year $^{-1}$  extra compared to that of the unlogged forest (T7). In the case with no lianas in the trees, the authors reported a maximum PAI (PL from 2007 to 2009) of 0.58 cm year $^{-1}$ . When the tree crowns were entirely exposed to solar light, the maximum PAI (PL from 2007 to 2009) was 0.59 cm year $^{-1}$ .

#### 4.2. Cutting cycle

Variation in diameter growth rates among species is expected; Schöngart (2008), for example, observed some tree species growing 10 times faster than others. In addition, we observed within-species variation in growth rates based on tree size, noted through the initial dbhs of 35, 50, 60 and 70 cm. Authors such as Andrade et al. (2019), d'Oliveira and Ribas (2011), Dionisio et al. (2018), Rozendaal et al. (2010), Schulze et al. (2008), and Vidal et al. (2002) studied Amazon tree species and noted that some species increased in diameter faster than other others; in some cases, research shows that trees with larger dbh grow faster than smaller trees, as Dionisio et al. (2018) concluded. Understanding species-specific growth rates helps to predict the time (i.e., number and length of CC) necessary for the tree species to provide their maximum yield. A commercial tree species that initially grows at slow rates, for example, might be harvested too early without the knowledge that it could grow into a larger, more valuable tree. If this species' growth rate accelerates when it reaches a medium diameter, the maximum yield would not be attained because such species should be left to a late harvest. Here, we note the species that should be left to reach a certain dbh in future CCs. The number and length of the CCs necessary to reach such dbhs will depend, of course, on the size of trees left in the last logging.

Our recommendation for *A. lecointei* and *M. elata* is that they should be left to reach dbhs between 60 and 70 cm. This is because a large tree of 70 cm would grow, at most, 10 cm more in a period equivalent to four CCs of 25 years (i.e., 100 years), even with liberation. Having smaller trees with dbhs from 30 to 35 cm left in the logged forest and with no post-logging liberation, these species could be harvested at subsequent CCs, even at the shortest length of 25 years. Through liberation to benefit the species *A. lecointei*, a tree with an initial dbh of 35 cm would yield an extra diameter of  $\sim 7$  cm in 25 years. A period equivalent to two or more CCs would be necessary to harvest such species if only trees with dbh  $<$  25–30 cm were left in the last logging.

The species *C. lucentifolium* and *L. lurida* should not be left to reach dbhs  $>$  50 cm if no liberation is applied. A tree of 50 cm dbh grows no more than 5 cm more in 100 years. With liberation, they could be left to reach up to approximately 55 cm. If only trees with dbh  $\leq$  35 cm were left after a certain forest logging and no post-logging liberation was applied, one CC of 25–35 years would be too short for trees of *C. lucentifolium*, *L. lurida*, and *M. paraensis* to reach the MCD of 50 cm; these species could be harvested at every future CC if trees with dbh  $>$   $\sim 40$  cm were left standing. With liberation, the minimum dbh of  $\sim 40$  cm necessary for successive harvests falls to  $\sim 35$  cm.

The species *M. paraensis* should be left to reach dbhs no larger than

60 cm without liberation and no larger than 70 cm with liberation due to its low growth rates when the trees reach these sizes. With liberation and leaving trees of  $>$  35 cm dbh in the last logging, the species could be harvested at subsequent CCs of 25 years. With no liberation, to have trees reach the MCD size, the CC must be the longest (35 years).

#### 4.3. Implications for forest management

The current law applied to sustainable forest management in the Brazilian Amazon, including MCD and CC, provides standards valid for the entire forest community. As these are general rules, much recent research (e.g., Andrade et al., 2019; Castro and Carvalho, 2014; Cunha et al., 2016; Rosa et al., 2016; Rozendaal et al., 2010; Schöngart, 2008) has driven forest management toward a species-specific approach, although Schöngart (2008) comments that this practice is still rare in tropical forests. To Andrade et al. (2019), there is enough scientific evidence to promote more sustainable, species-specific management system for timber purposes. However, we suggest that further important commercial species still need to be studied, mainly considering their growth rate with variations in region (site) and tree size. Although we did not assess the effect of site, Rosa et al. (2016), Dauber et al. (2005) and others note that site is an important issue to be considered in the assessment of species growth in the Amazon, where several types of vegetation (see classes surrounding our study area in Fig. 1) and climate (Alvares et al., 2013) are found. In relation to tree size, we present PAIs for different initial dbhs (Figs. 4 and 5), which allowed us to detect the diameter range of the point of growth stagnation. One limitation of this study is that our GMs were calibrated to data with dbh  $\geq$  35 cm; therefore, we have no data to forecast how long the species would take to reach 35 cm dbh. As a consequence, this lack of data prevents us from forecasting the number of CCs necessary for trees  $<$  35 cm to reach the MCD.

As species-specific discussion has increased, it is necessary to clarify that species-specific management is not a model in which the species are logged one at a time, because it would be unfeasible in all aspects (economic, environmental, technical, etc.). To implement such a model, species-specific growth, recruitment and mortality rates need to be guidelines incorporated into logging planning. The fixed MCD should be replaced by a species-specific MCD. The fixed length of the CC remains; however, every single species should preferably be left until it attains its maximum specific growth rate or its specific MCD. Therefore, a tree should be harvested after a certain number of CCs that depends on its size and species, as our models suggest. Although recruitment and mortality rates were not the target of our study, it is important to highlight that the variation in the species-specific growth rates shows that forest management could be better planned based on a species-level approach. Species-specific management plays an important role in the sustainability of the forest and its species. It could prevent future degradation of available timber resources provoked by the current unspecific rules, in addition to allowing more income when the maximum yield for a given species is known (Andrade et al., 2019; Cunha et al., 2016; Dauber et al., 2005; Schöngart, 2008). As reported by López et al. (2013), ignoring the effect of species growth rate on forest management might lead to commercial species being harvested before attaining their maximum yield. In this context, a species-specific approach suggests that the maximum yield of the species should be an important indicator to define species-specific MCDs and CCs. In our study, for example, *A. lecointei* and *M. elata* had the fastest growth even as larger trees; therefore, they should be left to grow more and longer than the other species studied.

The post-logging liberation exerted, in general, an expected positive effect on diameter growth, meaning that the CC may greatly reduce under liberation. The liberation effects varied by species; more accelerated diameter growth rates were noted for *A. lecointei*, *M. elata* and *M. paraensis* than for the other species. In addition, the effects of liberation change according to tree size; the diameter growth rate of *C.*

*lucentifolium* and *L. lurida*, for example, was much higher for smaller (< 45 cm) tree diameters. Although recruitment and mortality of the forest community were not the target of our survey, researchers such as Martins et al. (2018), Avila et al. (2017) and Free et al. (2014) have shown that our silvicultural interventions favor recruitment and reduce the mortality of remaining trees; this is an expected result due to the greater light availability and reduction in competition.

## Acknowledgements

We are thankful to the *Instituto Floresta Tropical* for providing the data used in this study.

## References

- Alvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalves, J.L.M., Sparovek, G., 2013. Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift* 22, 711–728.
- Andrade, V.H.F., Machado, S.A., Filho, A.F., Botosso, P.C., Miranda, B.P., Schongart, J., 2019. Growth models for two commercial tree species in upland forests of the Southern Brazilian Amazon. *For. Ecol. Manage.* 438, 215–223. <https://doi.org/10.1016/j.foreco.2019.02.030>.
- Araújo, H.J.B., 2016. Crescimento de espécies madeireiras em uma floresta acreana e compatibilidade com a legislação florestal. *Rev. Cienc. Agrárias* 59, 113–123. <https://doi.org/10.4322/rca.2227>.
- Avila, A.L., Schuartz, G., Ruschel, A.R., Lopes, J.C., Silva, J.N.M., Carvalho, J.O.P., Dormann, C.F., Mazzei, L., Soares, M.H.M., Bauhus, J., 2017. Recruitment, growth and recovery of commercial tree species over 30 years following logging and thinning in a tropical rain forest. *For. Ecol. Manage.* 385, 225–235. <https://doi.org/10.1016/j.foreco.2016.11.039>.
- Azevedo, C.P., Sanquetta, C.R., Silva, J.N.M., Machado, S.A., 2007. Efeito da exploração de madeira e dos tratamentos silviculturais no agrupamento ecológico de espécies. *Flor* 38, 53–69.
- Azevedo-Ramos, C., Silva, J.N.M., Merry, F., 2015. The evolution of Brazilian forest concessions. *Elem.: Sci. Anthropol.* 3, 1–8.
- Braz, M.E., Scheneider, P.R., Mattos, P.P., Selle, G.L., Thaines, F., Ribas, L.A., Vuaden, E., 2012. Taxa de corte sustentável para manejo das florestas tropicais. *Ci. Fl.* 22, 137–145.
- Burkhardt, H.E., Tomé, M., 2012. *Modeling Forest Trees and Stands*. Springer Science & Business Media.
- Castro, T.C., Carvalho, J.O.P., 2014. Dinâmica da população de *Manilkara huberi* (DUCKE) A. Chev. durante 26 anos após a exploração florestal em uma área de terra firme na Amazônia brasileira. *Cienc. Flor.* 24, 161–169.
- Costa, D.H.M., Carvalho, J.O.P., Van Den Berg, E., 2007. Crescimento diamétrico de maçaranduba (*Manilkara huberi* Chevalier) após a colheita da madeira. *Amaz. Cie. Desenv.* 3, 65–76.
- Cunha, T.A., Finger, C.A.G., Hasenauer, H., 2016. Tree basal area increment models for Cedrela, Amburana, Copaifera and Swietenia growing in the Amazonian rain forests. *For. Ecol. Manage.* 365, 174–183. <https://doi.org/10.1016/j.foreco.2015.12.031>.
- Dauber, E., Fredericksen, T.S., Peña, M., 2005. Sustainability of timber harvesting in Bolivian tropical forests. *For. Ecol. and Manage.* 214, 294–304. <https://doi.org/10.1016/j.foreco.2005.04.019>.
- Dionisio, L.F.S., Schuartz, G., Lopes, J.C., Oliveira, F.A., 2018. Growth, mortality, and recruitment of tree species in an Amazonian rainforest over 13 years of reduced impact logging. *For. Ecol. Manage.* 430, 150–156. <https://doi.org/10.1016/j.foreco.2018.08.024>.
- d'Oliveira, M.V.N., Ribas, L.A., 2011. Forest regeneration in artificial gaps twelve years after canopy opening in Acre State Western Amazon. *For. Ecol. Manage.* 261, 1722–1731. <https://doi.org/10.1016/j.foreco.2011.01.020>.
- Free, C.M., Landis, R.M., Grogan, J., Schulze, M.D., Lentini, M., Dunisch, O., 2014. Management implications of long-term tree growth and mortality rates: a modeling study of big-leaf mahogany (*Swietenia macrophylla*) in the Brazilian Amazon. *For. Ecol. Manage.* 330, 46–54. <https://doi.org/10.1016/j.foreco.2014.05.057>.
- López, P.L., Villalba, R., Bravo, F., 2013. Cumulative diameter growth and biological rotation age for seven tree species in the Cerrado biogeographical province of Bolivia. *For. Ecol. Manage.* 292, 49–55. <https://doi.org/10.1016/j.foreco.2012.12.011>.
- Macpherson, A.J., Schulze, M.D., Carter, D.R., Vidal, E., 2010. A model for comparing reduced impact logging with conventional logging for an Eastern Amazon Forest. *For. Ecol. Manage.* 260, 2002–2011. <https://doi.org/10.1016/j.foreco.2010.08.050>.
- Martins, W.B.R., Pinto, A.R.G., Da Costa, J.S., Carvalho, J.O.P., Castro, T.C., Ruschel, A.R., 2018. Dinâmica da população de *Lecythis idatimon* Aubl. no período de trinta anos em uma floresta de terra firme manejada na Amazônia brasileira. *Sci. For.* 46, 690–700. <https://doi.org/10.18671/scifor.v46n120.17>.
- Miranda, D.L.C., Higuchi, N., Trumbore, S.E., Latorraca, J.V.F., Do Carmo, J.F., Lima, A.J.N., 2018. Using radiocarbon-calibrated dendrochronology to improve tree-cutting cycle estimates for timber management in southern Amazon forests. *Trees* 32, 587–602. <https://doi.org/10.1007/s00468-018-1658-3>.
- Peña-Claros, M., Fredericksen, T.S., Alarcón, A., Blate, G.M., Choque, U., Leano, C., Licona, J.C., Mostacedo, B., Pariona, W., Villegas, Z., Putz, F.E., 2008. Beyond reduced-impact logging: Silvicultural treatments to increase growth rates of tropical trees. *For. Ecol. Manage.* 256, 1458–1467.
- Poorter, L., Boot, R.G.A., Hayashida-Oliver, Y., Leigue-Gomez, J., Peña-Claros, M., Zuidema, P.A., 2001. Dinâmica de espécies arbóreas em un bosque húmedo tropical en el norte de la amazonía boliviana. In: Mostacedo, B.Y., Fredericksen, T.S. (Eds.), *Regeneración y Silvicultura de Bosques Tropicales en Bolivia*. El País, Santa Cruz, pp. 53–76.
- Rosa, S.A., Barbosa, A.C.M.C., Junk, W.J., Da Cunha, C.N., Piedade, M.T.F., Scabin, A.B., Ceccantini, G.C.T., Schongart, J., 2016. Growth models based on tree-ring data for the Neotropical tree species *Calophyllum brasiliense* across different Brazilian wetlands: implications for conservation and management. *Trees*. <https://doi.org/10.1007/s00468-016-1503-5>.
- Rozendaal, D.M.A., Soliz-Gamboa, C.C., Zuidema, P.A., 2010. Timber yield projections for tropical tree species: the influence of fast juvenile growth on timber volume recovery. *For. Ecol. Manage.* 259, 2292–2300.
- Schiestl-Aalto, P., Kulmala, L., Makinen, H., Nikinmaa, E., Makela, A., 2015. CASSIA—a dynamic model for predicting intra-annual sink demand and interannual growth variation in Scots pine. *New Phytol.* 206, 647–659. <https://doi.org/10.1111/nph.13275>.
- Schöngart, J., 2008. Growth-Oriented Logging (GOL): a new concept towards sustainable forest management in Central Amazonian várzea floodplains. *For. Ecol. Manage.* 256, 46–58.
- Schulze, M., Grogan, J., Landis, R.M., Vidal, E., 2008. How rare is too rare to harvest? Management challenges posed by timber species occurring at low densities in the Brazilian Amazon. *For. Ecol. Manage.* 256, 1443–1457. <https://doi.org/10.1016/j.foreco.2008.02.051>.
- Silva, J.N.M., Carvalho, J.O.P., Lopes, J.C.A., Oliveira, R.P., Oliveira, L.C., 1996. Growth and yield studies in the Tapajós region, Central Brazilian Amazon. *Comm. For. Rev.* 75, 325–329.
- Silva, K.E., Souza, C.R., Azevedo, C.P., Rossi, L.M.B., 2015. Dinâmica florestal, estoque de carbono e fitossociologia de uma floresta densa de terra-firme na Amazônia Central. *Embrapa Amazônia Ocidental*.
- Souza, D.R., Souza, A.L., Leite, H.G., Yared, J.A.G., 2006. Análise estrutural em floresta ombrófila densa de terra firme não explorada, Amazônia oriental. *Rev. Árv.* 30, 75–87.
- Souza, D.V., Carvalho, J.O.P., Mendes, F.S., Melo, L.O., Silva, J.N.M., Jardim, F.C.S., 2014. Growth of *Manilkara huberi* and *Manilkara paraensis* after logging and silvicultural treatments in the municipality of Paragominas, Pará, Brazil. *Flor* 44, 485–496.
- Taffarel, M., Carvalho, J.O.P., Melo, L.O., Silva, M.G., Gomes, J.M., Ferreira, J.E.R., 2014a. Effect of the post-harvesting silviculture on a *Lecythis lurida* (Miers) Mori population in a 'terra firme' forest in Brazil's Amazon forest. *For. Sci.* 24, 889–898.
- Taffarel, M., Gomes, J.M., Carvalho, J.O.P., Melo, L.O., Ferreira, J.E.R., 2014b. Efeito da silvicultura pós-colheita na população de *Chrysophyllum lucentifolium* Cronquist (goiabão) em uma floresta de terra firme na Amazônia brasileira. *Rev. Árv.* 38 (6).
- Veloso, H.P., Rangel-Filho, A.L.R., Lima, J.C.A., 1991. Classificação da vegetação brasileira, adaptada a um sistema universal. IBGE, Rio de Janeiro, pp. 123.
- Vidal, E., Viana, V.M., Batista, J.L.F., 2002. Crescimento de floresta tropical três anos após colheita de madeira com e sem manejo florestal na Amazônia oriental. *Sci. For.* 61, 133–143.
- Wadsworth, F.H., Zweede, J.C., 2006. Liberation: acceptable production of tropical forest timber. *For. Ecol. Manage.* 233, 45–51. <https://doi.org/10.1016/j.foreco.2006.05.072>.