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Adjustment of Thinning Equations for Forest Management Area in the Western Amazon

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ABSTRACT

Logging in the Amazon using reduced impact methods has high potential. However, one of the problems of forest management is an accurate estimation of the wood stock of a forest. Thinning equations allow for the analysis of the volume and fluctuations in diameter along the trunk of a tree, making it possible to estimate the volume, diameter, or height based on known dimensions of the trunk. Therefore, this study aimed to adjust and evaluate two thinning equations in a forest management area in the Western Amazon, in the municipality of Xapuri, state of Acre, Brazil, comparing them and selecting the one that presented the best performance for the study area. The study involved sampling in the Chico Mendes Extractive Reserve, utilizing 53 work units and employing the Kozak and linearized Demaerschalk models. These models were assessed based on their determination coefficient, standard error percentage, and graphical analysis of residues. The Demaerschalk model exhibited superior performance, with R^2 adj. of 92.88% for commercial height and 95.68% for total height. This research contributes to efficiently estimating tree dimensions, essential for sustainable forest management in the Western Amazon. The application of the Demaerschalk model provides precise measurements, enhancing the accuracy of volume calculations and facilitating effective forest management practices.

1. Introduction

The Amazon rainforest is the largest tropical forest in the world, occupying about 6 million km^2 of South America, and houses a wide biodiversity of species of fauna and flora. However, such a biome is constantly threatened by anthropic actions, especially illegal logging, and sustainable forest management, guided by laws and technical guidelines, is an alternative to mitigate illegal exploitation (Braz et al. 2014; Laurance et al. 2014; Nepstad et al. 2014). Despite the benefits, sustainable forest management still presents problems in the production process; one is high waste, which occurs at all stages of the production chain (Braz et al. 2014). The condition that most contribute to increased waste is the fact that the tree trunk is not a perfect cylinder, making volume measurement a complex activity, which, when carried out inappropriately, can lead to erroneous assessments and estimates of the stock of wood in native forests (Barlow et al. 2016; Gaveau et al. 2014; Môra et al. 2020).

The tree volume is commonly measured from equations that use variables such as diameter at 1.30 m above the ground, the height of the individual, and form factor, which for the Amazon region corresponds to 0.7, with the size form factor used to convert the volume of the cylinder into the actual volume of the tree, considering that there are differences along the diameter of the tree (Clark et al. 2015; Miranda et al. 2015; Mitchell et al. 2019). However, the accuracy of such equations is still the subject of debate (Feldpausch et al. 2012; Lanssanova et al. 2018; Qie et al. 2017). The use of thinning functions is recommended to increase forest measurement accuracy (Berenguer et al. 2018; Chave et al. 2014; Souza et al. 2020).

Thinning functions are statistical instruments that can be used for forest volume estimate because they consider the oscillations in shape along the trunk, thus making it possible to describe the profile and carry out a volumetric estimate between different points of the shaft through integral functions (Jenkins et al. 2015; Johnson et al. 2018; Lanssanova et al. 2018). In addition, it is possible to measure the diameter as a function of a certain height or the height as a function of a specific diameter (Lewis et al. 2015; Malhi et al. 2016; Souza et al. 2020). Despite the demand for techniques to increase the accuracy of the quantification of wood stock and reduce waste, the use of thinning functions in management projects in the Amazon is still limited, with little information available in the literature on the adjustment of such functions for native species (Avitabile et al. 2016; Houghton et al. 2015; Lanssanova et al. 2018).

Thinning operations have been studied across various forest ecosystems but are less thoroughly researched in the Amazon region. For instance, Malhi et al. (2016) have focused on the health benefits of thinning in temperate forests. On the other hand, Gibbs et al. (2015) have evaluated its economic viability in European forests. Concerns regarding how thinning affects forest resilience, especially in the context of climate change, have been raised (Johnson et al. 2018; Lewis et al. 2015).

The potential for sustainability through thinning practices in the Amazon has been discussed, yet there remains a notable gap in species-specific thinning equations (Gaveau et al. 2014; Houghton et al. 2015). The ecological impact of thinning in the Amazon is not yet fully understood, and comparisons with natural disturbances are limited (Avitabile et al. 2016; Laurance et al. 2014). Addressing these gaps may be crucial for implementing effective forest management strategies in the Amazon (Nepstad et al. 2014). Therefore, this study aimed to adjust and evaluate two thinning equations in a forest management area located in the Western Amazon, in the municipality of Xapuri, state of Acre, Brazil, comparing them and selecting the one that presented the best performance for the study area.

2. Materials and Methods

2.1. Study Area

The study was carried out in an area of sustainable community forest management of Amoprex, located in the Chico Mendes Extractive Reserve in Xapuri, Acre, Brazil. The sampling of the trees was carried out in the properties that are part of the first annual operation plan, being 53 work units (UTs), according to the location of each one within the forest typology (**Fig. 1**). It should be noted that the study area is a native forest with a wide diversity of species.

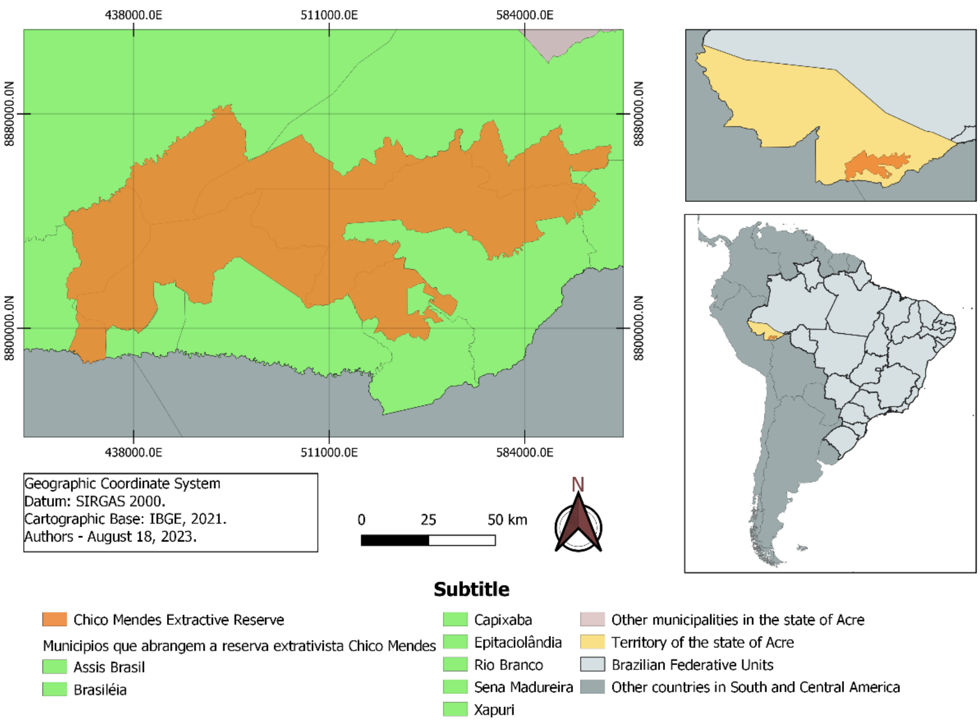

Fig. 1. Location map of the Chico Mendes Extractive Reserve.

The region's climate is type Am, hot and humid tropical, with an average annual temperature varying from 24.5ºC to 32ºC, average accumulated annual precipitation of 2000 mm, with two well-defined seasons, one dry and the other rainy, which in the location of the study area, the dry period lasts three months (Costa et al. 2012).

According to Thaines and Andrade (2011), forest typologies in the area are open forest with bamboo + open forest with palm tree + dense forest (FAB+FAP+FD) and open forest with palm tree in alluvial area (FAP – Alluvial).

2.2. Data Collection

Measurements of diameters at breast height (DBH) and subsequent heights were taken with a spacing of 2 m between measurements, and the commercial height and total height were also measured in each tree/sample. The measurements were carried out with the help of climbers, with the trees still standing.

The trees/samples were distributed in 11 diameter classes with an amplitude of 10.0 cm, in which, in the last class, individuals with DBH ≥ 110 cm were allocated. When the distribution of individuals by diameter classes was performed, one class presented 7 individuals. It should be noted that the number of trees/samples will be the same for all diameter classes, with each class having 7 individuals, totaling 77 trees/sample.

2.3. Data Analysis

For the measurements at the base of the individuals, the initial height measurement of 10 cm was adopted for the models proposed by Kozak et al. (1968) and Demaerschalk (1972), and it was necessary to adopt this measure so as not to annul the basic information in the application of the equation.

In the analysis for commercial height (CH) in the model of Demaerschalk (1972), the top measurements decreased to 10 cm in the last measurement. This alternative was adopted to avoid annulling the top information for calculating the commercial height in applying equations. For the adjustment of the thinning equations, the collected data were processed in an electronic spreadsheet to test two models of adjustment of the equations, one linear and the other linearized. Model 1 (Kozak et al. 1968) was calculated using Equation 1.

$$Y^2 = \beta 0 + \beta 1\ (h/TH) + \beta 2\ (h/TH)^2 + \varepsilon \quad (1)$$

where Y is a formula (d/DBH); d is the diameter at height h, usually with or without shell; DBH is the diameter measured at a height of 1.30 m; h is the distance from the ground to the point where diameter d is obtained; TH is the total height; $\beta 1$ is the regression parameters (i = 0, 1, 2); and ε is the random error. Model 2 (Demaerschauk 1972) was calculated using Equation 2.

$$Di = 10^{\beta 0}\ DBH^{\beta 1}\ L^{\beta 2}\ TH^{\beta 3} \quad (2)$$

The formula was linearized using Equation 3.

$$LnDi = \beta 0Ln10 + \beta 1LnDBH + \beta 2LnL + \beta 3LnTH \quad (3)$$

where Ln is Neperian logarithm; Di is the diameter with shell to be estimated (cm); DBH is the diameter at 1.30 m from the ground, in cm; L is $TH - CH$, distance from the total height to the height at which the diameter Di occurs; TH is the total height (m); CH is the commercial height where the diameter Di is (m); βi is the model coefficients to be estimated (i = 0, 1, 2, 3); and εi is random error.

According to Kvâlseth (1985), the following should be used: (i) adjusted coefficient of determination ($R^2aj.\%$); (ii) standard error of the estimate ($Syx\%$); and graphical analysis of the percentage residues ($E\%$) to avoid personal judgment in the selection of adjusted equations, being calculated using Equation 4.

$$R^2aj.\% = [1 - (n - 1/(n - p - 1)) \times (1 - R^2)] \times 100 \quad (4)$$

where n is the number of observations, p is the number of independent variables, and R^2 is the coefficient of determination.

3. Results and Discussion

Regarding the commercial height variable, the Demaerschalk model provided the best fit to the data, presenting the coefficient of determination adjusted in percentage. However, it presented a standard error of the higher percentage estimate compared to the Kozak model, indicating that the estimated data may vary by 19.02% more or less (**Table 1**).

The Kozak model presented a lower value of the adjusted coefficient of determination when compared to the Demaerschalk model. However, the standard error ($Syx\%$) presented a value of 7.08% lower than the value presented by the Demaerschalk model. When analyzing differences in height estimation as a function of differences in the length of log sections in a hybrid population of *Eucalyptus urophylla x Eucalyptus grandis,* Môra et al. (2020) used the original Demaerschalk model and observed that R^2 oscillated between 92.89% and 94.81%, with the standard error of the estimate ranging between 15.07% and 30.59%.

Table 1. Coefficients and statistics obtained through the adjustment of thinning models, considering the commercial height of the trunk in an area of sustainable forest management in the municipality of Xapuri, Acre, Brazil

Models	Coefficients				Measures of Precision	
	β0	**β1**	**β2**	**β3**	**R^2aj%**	**S_{yx}%**
Kozak et al. (1969)	1.27	-1.96	1.32		63.15	11.94
Demaerschalk (1972)	0.12	0.99	0.15	-0.25	92.88	19.02

The better performance of the model proposed by Demaerschalk compared to that of Kozak was also observed by Lanssanova et al. (2013), who evaluated functions in an area of the Amazonian biome in Mato Grosso. The authors observed that the Demaerschalk model presented higher adjusted R^2 and lower S_{yx}% (0.92 and 8.48%, respectively), compared to the Kozak model, which obtained adjusted R^2 equivalent to 0.89 and S_{yx}% equal to 10.04%. However, the authors point out that both models presented satisfactory results for the adjusted coefficient of determination in percentage. Souza et al. (2020) emphasized that to determine the most appropriate model to be used in a thinning function adjustment, it is suggested that the model should present high R^2aj and low standard error of the estimate (S_{yx}%). The authors also report that because tropical forests present heterogeneous populations, the height and diameter of the shaft tend to present greater variation compared to populations located in planted forests.

Another criterion for evaluating the models was the analysis of the graphical distribution of the percentage residues (**Fig. 2**). From the graphical distribution of the residuals, it is possible to analyze the precision of the adjusted equation and compare the estimated values with the observed values. The Kozak model showed better distribution of residuals, where the values are closer to the axis (X) and are evenly distributed along the line of observed values, indicating precision between the observed and the estimated value.

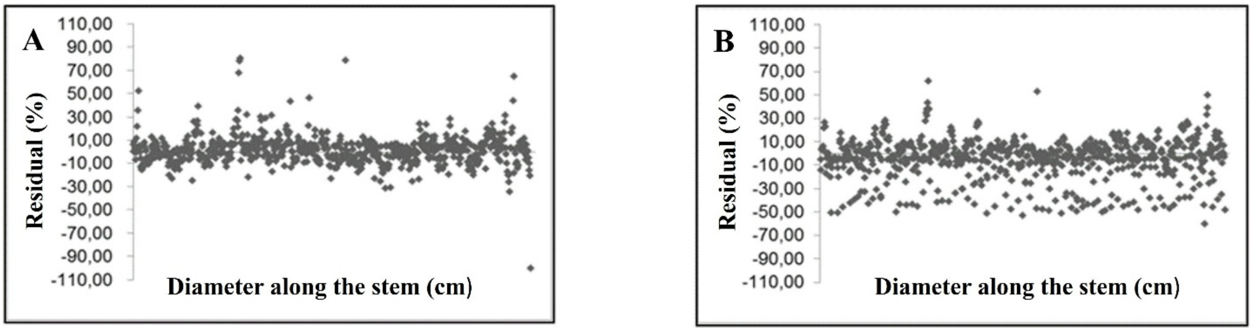

Fig. 2. (A) Distribution of waste for the Kozak model for CH; (B) distribution of waste for the Demaerschalk model for CH.

The graphical distribution of the residuals makes it possible to analyze the amplitude of the deviation of the estimated values in relation to the observed ones, assessing whether there is proportionality between the overestimated and underestimated values (Lanssanova et al. 2018). According to Souza et al. (2020), models with high residual dispersion may indicate limitations in the estimates.

Furthermore, the role of forests as carbon sinks cannot be overlooked, especially in the context of climate change. Muslih et al. (2022) highlighted that urban forests act as effective carbon sinks. Although our study focuses on natural forests, the biomass and carbon stock measurement methods employed by Muslih et al. (2022) may be applicable for assessing the environmental impact of forest management. This tendency suggests incorporating carbon sequestration metrics into forest management practices for a more holistic approach (Muslih et al. 2022).

Regarding the total height, after the analysis of the data of diametric distribution along the total height, through the regression method, the model proposed by Demaerschalk (1972) obtained the best fit to the data, compared to the model of Kozak et al. (1968), when the values of the adjusted determination coefficients were observed, equal to 95.68% and 62.91% respectively (**Table 2**).

Table 2. Coefficients and statistics obtained through the adjustment of thinning models considering the total height of the trunk in an area of sustainable forest management in the municipality of Xapuri, Acre, Brazil

Models	Coefficients				Measures of Precision	
	β0	β1	β2	β3	R^2aj%	S_{yx}%
Kozak et al. (1969)	1.23	-2.39	2.01		62.91	11.74
Demaerschalk (1972)	0.05	0.96	0.34	-0.32	95.68	13.35

However, the standard error of the estimate of the model of Demaerschalk (1972) presented a greater amplitude of variation (13.35%) and inferior performance when compared with the model proposed by Kozak et al. (1968), which presented S_{yx}% 1.61% lower, indicating a variation of 11.74% for more or less, that is lower amplitude.

The variability in the standard error of the estimate among different models has also been observed by Pretzsch et al. (2015), who highlighted the importance of considering forest structure and environmental conditions when selecting a model. This aspect could explain the observed differences between the Demaerschalk and Kozak models in our study. The objective of forest management can also influence the choice of model. As pointed out by Forrester and Tang (2016), the Demaerschalk model may be more suitable for forests with high biodiversity, while the Kozak model may be more effective in monoculture forests.

According to Andrade (2014) in which he tested five thinning models for two species of the genus Eucalyptus, the author reports that the Demaerschalk (1972) is the most used model in Brazil, and it is observed in his study that this model presented the best fit compared to the other models tested.

Regarding the residue distribution plot, the distribution of residues for the equation based on the Kozak model presented better distribution when compared with that originated by the equation from the Demaerschalk model tested for the study area (**Fig. 3**). Môra et al. (2020) point out that it is expected that as an increase of R^2 occurs there will be a reduction in the standard error of the estimate (S_{yx}%), however, in the case of using the Demaerschalk Model, it should be noted that because it is a non-linear model, there may be occasions when this expectation is not observed. It is possible to have situations where R^2 is close to 100% even with a high S_{yx}%.

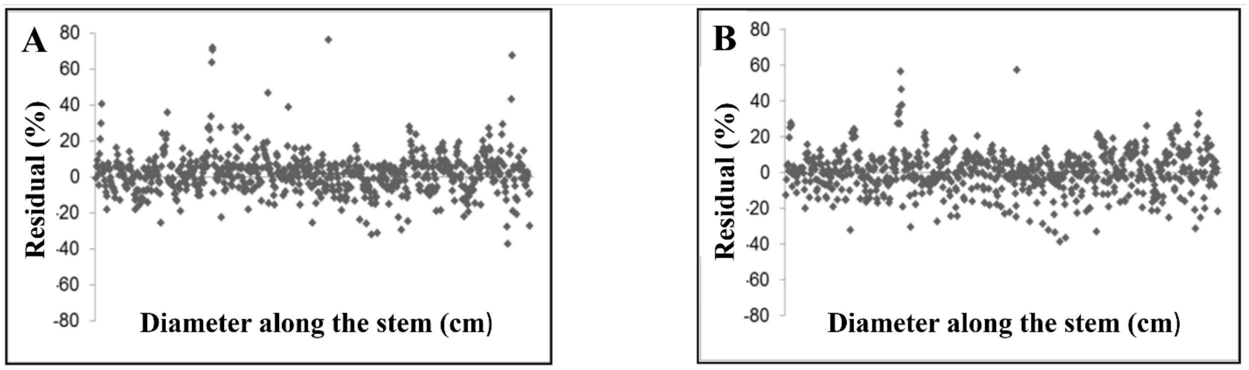

Fig. 3. (A) Distribution of residues for the Kozak model for TH; (B) distribution of waste for the Demaerschalk model for TH.

In regard to the forest structure dynamics following selective timber harvesting, it is crucial to consider the findings of Permata et al. (2023). The study revealed that logged-over forests exhibit different rates of upgrowth, ingrowth, and mortality compared to primary forests. Specifically, the ingrowth and mortality rates were lower in treated areas, which may have significant implications for sustainable forest management. These results corroborate our observations on the changes in forest structure and tree mortality in areas under sustainable forest management (Permata et al. 2023).

4. Conclusions

It was observed that the adjusted equations presented significant values for the two models tested regarding the adjusted coefficient of determination, percentage, standard error of the estimate, and graphical analysis. Considering the evaluation criteria, the Demaerschalk model fitted the data best and presented the best value of the adjusted percentage coefficients of determination for both the analysis of the commercial height and the total height of the stem. It is suggested that studies be carried out to adjust the thinning equations for species of commercial value based on the minimum cutting diameter. It should be noted that areas of native tropical forests have several species, each with a different growth rate. Therefore, adopting equations that can estimate the growth and volume of these species with the greatest possible precision is essential.

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