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Diametric growth and time of passage in an Atlantic Forest fragment under forest recovery

Crescimento diamétrico e tempo de passagem em um fragmento de Mata Atlântica sob recuperação florestal

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RESUMO

Investigações científicas sobre a dinâmica de comunidades vegetais promovem estratégias apropriadas para o manejo de florestas naturais, com fins conservacionistas ou sustentavelmente exploratórios. O objetivo foi avaliar a acurácia de modelos de regressão para projetar o crescimento em diâmetro e calcular o tempo de passagem por classe diamétrica de fustes em um fragmento de Mata Atlântica sob recuperação. O trabalho foi conduzido em um fragmento de 2,53 ha no município de São João Evangelista (MG). O inventário foi realizado aos 80 e 104 meses após início do processo de recuperação. Os dados de incremento periódico anual (IPA) em diâmetro foram utilizados para os cálculos do tempo de passagem e idade relativa. As estimativas temporais para o alcance dos diâmetros mínimos de 5, 10, 20 e 30 cm foram de 5, 9, 15 e 21 anos, respectivamente. Conclui-se que os modelos Logístico e de Curtis, adaptados para a estimativa de IPA, são eficientes para a avaliação do tempo de passagem, fornecendo informações precisas sobre a dinâmica de crescimento no fragmento em estudo. Fragmentos durante a recuperação florestal podem exibir taxas de crescimento semelhantes entre classes de diâmetro.

PALAVRAS-CHAVE: amplitude de classe diamétrica; fuste; incremento periódico anual; modelagem.

ABSTRACT

Scientific investigations on the dynamics of plant communities promote appropriate strategies for management of natural forests, with conservationist or sustainably exploratory purposes. This research aimed to evaluate accuracy of regression models to project diameter growth and calculate passage time by diametric class of stems in an Atlantic Forest fragment under recovery. The work was carried out in a fragment of 2.53 ha in São João Evangelista municipality (MG). Inventory was performed at 80 and 104 months after starting the recovery process. Annual periodic increment (API) in diameter data was used to calculate passage time and relative age. Temporal estimates for reaching the minimum diameters of 5, 10, 20, and 30 cm were 5, 9, 15, and 21 years, respectively. It is concluded that the logistic and Curtis models, adapted for the IPA estimation, are efficient for analysis of passage time, providing accurate information on growth dynamics within the fragment under study. Fragments during forest recovery may exhibit similar growth rates between diameter classes.

KEYWORDS: diameter class amplitude; stem; annual periodic increment; modeling.

INTRODUCTION

Information on the dynamics of natural forests is essential for analyzing the structure of woody formations and defining conservation and sustainable management strategies (SIRAMI et al. 2018, SALES et al. 2021). Growth dynamics forecasting provides crucial insights for the rational management of timber and non-timber resources.

The Atlantic Forest is renowned as one of the world's most biodiverse hotspots for woody plant species. Despite protective legislation and exclusive domain laws (Law No. 11,428, BRAZIL 2006), fragmentation has intensified due to urbanization, illegal logging, fires, climate change, and the establishment of agricultural and mining enterprises (PINTO 2021, FILGUEIRAS et al.). 2019, RODER et al. 2023). Continuous monitoring of this domain is crucial for implementing public policies aimed at conservation and developing management guidelines, particularly for recovering forest fragments where growth dynamics are not yet fully understood.

Growth and yield modeling is a statistical approach for forecasting woody biomass conditions, valuable for establishing protected areas, planning harvest cycles, and enhancing the compatibility of exploitation systems with vegetation types (PIRES et al.). 2021). On the other hand, modeling forest growth dynamics presents a significant challenge for natural forest managers, as the structural complexity of these ecosystems requires flexible and adaptable management systems (DIONISIO et al. 2018, CANETTI et al. 2021).

Understanding plant growth rates aids in making silvicultural decisions for forest maintenance and restoration programs, as well as sustainable management practices (PIRES et al. 2021). However, determining tree age, a crucial factor in biometric modeling, remains challenging in tropical forests. An alternative approach involves estimating the relative age of a species or native population by calculating periodic diameter growth, assuming that tree size is directly proportional to age.

Calculating the relative age gives an estimate of the passage time, which represents the average time interval for all the individuals in a diametric class to grow and reach another class of higher size (GOVEDAR et al. 2021). This methodology provides a concise understanding of the temporal changes in diameter class distribution, facilitating the determination of cutting cycles and offering quantitative insights into sustainable production. Nevertheless, scientific investigations on residence time have been extensively applied to larger forests, with few studies conducted in areas of early woody formation, such as environments undergoing recovery processes (SANTOS et al. 2017).

The ecological services of forests managed under a polycyclic system should be preserved after interventions, with remaining stocks supporting continuous production in sequential harvests (CANETTI et al. 2021, PIRES et al. 2021). The definition of the ideal felling cycle is based on an estimate of the passage of time, the period that the forest requires to replenish the harvested stock close to or similar to the original one, prior to the environmental intervention (DIONISIO et al. 2018). It is important to emphasize that forest management should be conducted with caution, considering the floristic composition and structural aspects of the forest, such as density, dominance, sociological position, diameter distribution, growth, mortality, and regeneration (CANETTI et al. 2021, HOUÉNON et al. 2022).

Research on sustainable management advances the development of improved techniques and protocols that meet the needs of producers, society, and the environment, providing guidance for managing the ecological and commercial potential of vegetation based on growth rates, species, environment, or region (PINTO 2021). This study aimed to assess the accuracy of regression models for projecting diameter growth and calculating the time required for stems to transition between diameter classes in a recovering Atlantic Forest fragment.

MATERIAL AND METHODS

The study was conducted in an Atlantic Forest fragment located in São João Evangelista, Minas Gerais, Brazil, within the grounds of the Federal Institute of Education, Science, and Technology of Minas Gerais. The site is situated at coordinates 18°33'5.05" S and 42°45'50.40" W (Datum SIRGAS 2000). The region's climate is classified as Cwa (humid subtropical) according to the Köppen climate classification system, characterized by wet summers and dry winters. The average annual temperature and rainfall are 21.2 ºC and 1,000 mm, respectively (CLIMATE-DATA.ORG 2023).

The Atlantic Forest fragment, spanning 2.53 hectares, has been undergoing forest restoration since November 2013. The land use history includes successive monoculture cultivation of *Coffea arabica* L. for approximately a decade. The predominant soil type is dystrophic Red-Yellow Latosol with a prominent A horizon, sandy texture, undulating relief, at an elevation of 690 m.

Forest inventory was conducted at 80 and 104 months after the initiation of the Atlantic Forest fragment restoration process. The sampling involved the establishment of nine 20 × 20 m (400 m^2) square plots, representing a sampling intensity of 14.23%. All tree stems with a circumference at breast height (1.30 m above ground level) of 10 cm or greater were measured using a measuring tape. The corresponding diameter at breast height (DBH, cm) was calculated by dividing the circumference by π (3.141592654...).

The annual periodic increment (API, cm $year^{-1}$) data from the two-year inventory period were analyzed using boxplots and tested for normality using the Shapiro-Wilk test. The median IPA distribution was calculated for each diameter class. Two diameter class widths (3 and 5 cm) and seven regression models were evaluated to establish functional relationships for estimating the median PAI, resulting in a total of 14 adjustment combinations. The determination of diameter classes was based on predefined regular class intervals, empirically established, taking into account the total range of sampled diameters and analytical information applied to native vegetation in forest recovery (CAMPOS & LEITE 2017, SANTOS et al. 2017).

The modeling encompassed the full spectrum of species diversity within the forest fragment. Five linear regression models and two nonlinear models (Table 1), commonly used in the forestry sector for biometric modeling, were tested (CAMPOS & LEITE 2017). The regression model parameters were estimated using ordinary least squares (OLS). The convergence of the non-linear regression parameters was based on the Levenberg-Marquardt iterative method.

Table 1. Models tested to estimate the median of annual periodic increment in diameter (API, cm $year^{-1}$) as a function of the diameter class center (CC, cm) for a fragment of Atlantic Forest under forest recovery.

Model	Form of adjustment	Features
	------------------------- Linear models -------------------------	
(1)	$IPA = \beta_0 + \beta_1 CC + \varepsilon$	Simple linear
(2)	$IPA = \beta_0 + \beta_1 CD + \beta_2 CC^2 + \varepsilon$	Linear quadratic
(3)	$Ln(IPA) = \beta_0 + \beta_1 \frac{1}{CC} + \varepsilon$	Adaptation of the Curtis Hypsometric Model.
(4)	$IPA = \beta_0 + \beta_1 Ln(CC) + \varepsilon$	Adaptation of Henricksen's hypsometric model.
(5)	$Ln(IPA) = \beta_0 + \beta_1 Ln(CC) + \varepsilon$	Adaptation of the Stoffels and Soest hypsometric model.
	----------------------- Non-linear models -----------------------	
(6)	$IPA = \beta_0 e^{-e^{\beta_1 - \beta_2 CC}} + \varepsilon$	Gompertz
(7)	$IPA = \beta_0 / \left(1 + \beta_1 e^{-\beta_2 CC}\right) + \varepsilon$	Logistics

β_0, β_1 and β_2 = regression model parameters and ε = random error.

The quality of the fits was assessed using the weighted value of statistical scores (WV), derived from the Mean Absolute Deviation (MAD), Root Mean Square Error (RMSE), and Akaike Information Criterion (AIC). The WV is a weighted sum calculated by assigning weights to accuracy measures, with a weight of 1 for the most efficient equation, 2 for the second, and so on, following the methodology proposed by THIERSCH (1997). Lower values of WV, MAD, RMSE, and AIC indicate superior predictive performance. Three equations were chosen for subsequent graphical analyses.

The initial PAI for the smallest diameter class was calculated using the minimum DBH of the measured stems. Subsequent diameters were determined by adding the estimated annual increment to the previous diameter at breast height. The initial relative age was determined by dividing the smallest measured DBH by the first estimated PAI. This age represented the minimum age required for a tree stem to enter the first diameter class. The calculation of subsequent relative ages was based on adding one year for each estimated IPA, using the first relative age as a baseline. The transition time between diameter classes was determined by calculating the difference between the minimum relative ages of two consecutive diameter classes.

For statistical significance, a 5% probability level was used. Statistical analyses were carried out using the R software version 4.1.3 (R CORE TEAM 2022), using the "Metrics" packages (HAMNER & FRASCO 2018), "minpack.lm" (ELZHOV et al. 2022) and "stats" (R CORE TEAM 2022).

RESULTS

The forest inventory encompassed 595 stems ha^{-1} and 464 trees ha^{-1}, sampled on two separate occasions. The minimum and maximum DBH per stem ranged from 3.18 cm (approximately 10 cm in circumference) to 24.16 cm in the initial measurement, and from 3.18 cm to 30.24 cm in the subsequent measurement. Annual periodic diameter increments are presented by diameter class in Figure 1, revealing upper outliers in the 6-9 cm DBH range (midpoint of 7.5 cm class).

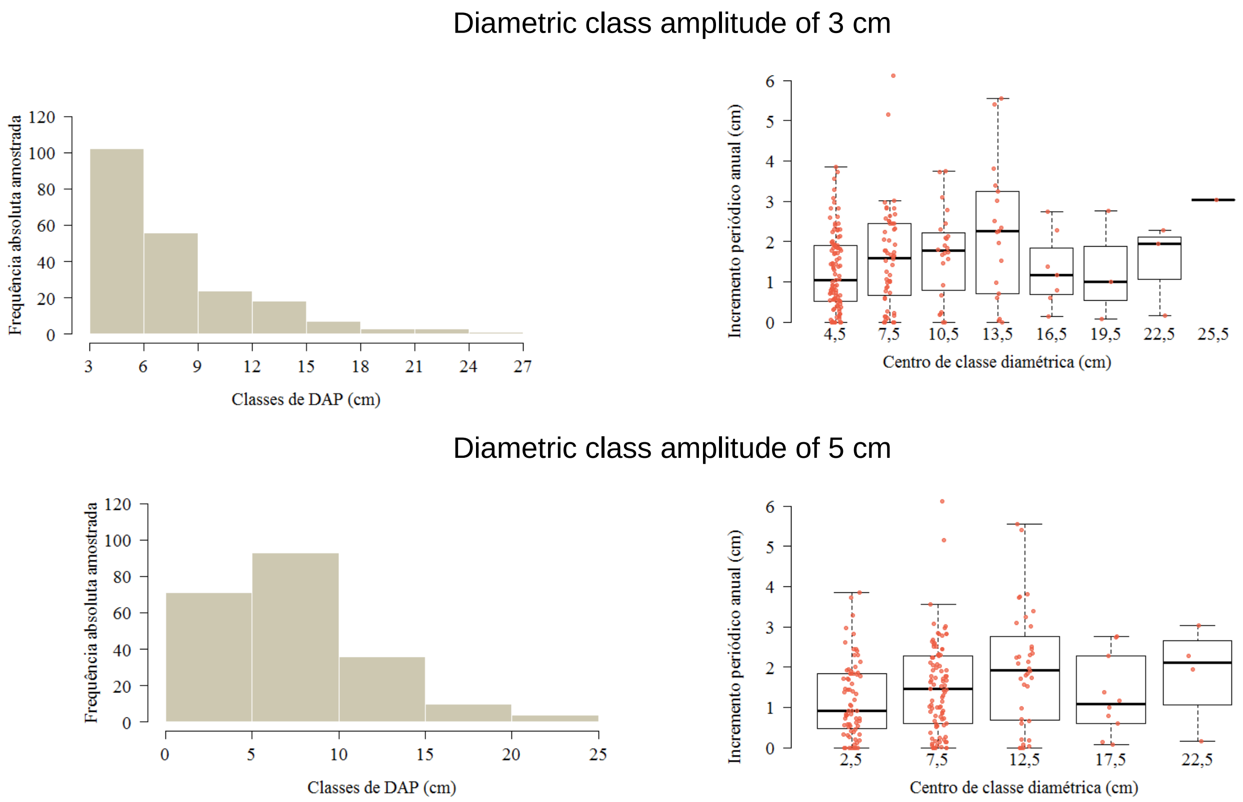

Figure 1. Diameter distribution of sampled stems in the year 2020 in a fragment of Atlantic Forest under forest recovery process on the left, and Boxplot of their periodic annual increments up to 2022 on the right.

The Shapiro-Wilk test ($p \leq 0.01$) revealed non-normality for the entire increment dataset and, when analyzed by diameter class, for the 3 cm (class centers of 4.5 and 10.5 cm) and 5 cm diameter ranges (class centers of 2.5, 7.5, and 12.5 cm). Thus, modeling was conducted to estimate the median periodic increment as a function of the diameter class center for the studied Atlantic Forest fragment undergoing forest recovery (Table 2).

The goodness of fit improved as the diameter class intervals widened. When comparing amplitudes of 3 and 5 cm, MAD, RMSE, and AIC statistics decreased by approximately 38.32%, 36.00%, and 45.62%, respectively. Equations (5-3), (5-4), and (5-7), corresponding to adjusted models (3), (4), and (7), exhibited the smallest deviations (low weighted values of statistical scores). These equations were chosen for subsequent graphical analyses (Figure 2).

Table 2. Coefficients and fit quality of the equations obtained to estimate the median of annual periodic increment in diameter (API, cm year^{-1}) as a function of the diameter class center (CC, cm) for a fragment of Atlantic Forest under forest recovery.

Equation	β_0	β_1	β_2	MAD	RQEM	AIC	WV
-------- Diametric classes with amplitude of 3 cm --------							
(3-1)	0,989698	0,049010	-	0,4744	0,5556	19,3011	33
(3-2)	1,781138	-0,084567	0,004453	0,4744	0,5244	20,3758	34
(3-3)	0,732663	-2,840109	-	0,4561	0,5881	10,9072	28
(3-4)	0,268302	0,565674	-	0,4507	0,5694	19,6925	31
(3-5)	-0,281168	0,294412	-	0,4685	0,5775	10,9317	30
(3-6)	376,686200	1,774341	0,005760	0,4764	0,5471	21,0518	38
(3-7)	-0,000051	-1,000049	0,000001	0,4662	0,5241	20,3660	30
-------- Diametric classes with an amplitude of 5 cm --------							
(5-1)	0,992331	0,040425	-	0,3215	0,3662	10,1441	18
(5-2)	0,881207	0,066572	-0,001046	0,3110	0,3636	12,0722	21
(5-3)	0,599343	-1,723694	-	0,2707	0,3511	5,5134	8
(5-4)	0,600196	0,392496	-	0,2776	0,3502	9,6976	10
(5-5)	-0,289245	0,280830	-	0,3030	0,3564	5,8867	12
(5-6)	1,708577	0,368961	0,327570	0,2655	0,3500	11,6898	11
(5-7)	1,703865	2,358996	0,388844	0,2657	0,3497	11,6819	10

Equation (i-j) = i represents the diameter class amplitude, and j denotes the regression model presented in Table 1. MAD stands for Mean Absolute Deviation, RQEM for Root Mean Square Error, and AIC for Akaike Information Criterion. WV represents the weighted value of statistical scores, while β_0, β_1, and β_2 are parameters of the regression models.

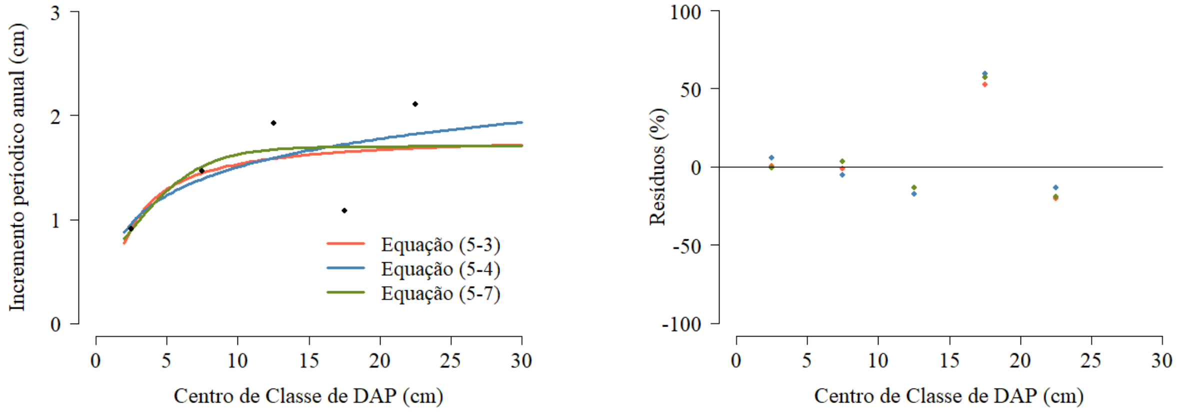

Figure 2. Annual periodic increment curves and percentage residue distribution of equations selected for the analysis of passage time in a fragment of Atlantic Forest under forest recovery on the left and right, respectively.

The asymptotic behavior was observed in all curves generated using the selected equations, with respect to the 5 cm diameter class interval. Smaller dispersions of percentage residuals were observed in equations (5-3) and (5-7). The relative age and time spent in each diameter class were calculated for both equations (Table 3). For the forest fragment undergoing regeneration, the application of equations revealed a trend towards stabilization among diameter classes ranging from 5 to 25 cm. This table contains information on the trend of passage time beyond the inventoried diameter range, assuming minimal variation in ecological interactions within the community.

Table 3. Estimates of relative age and passage time per diametric class for a fragment of Atlantic Forest under forest recovery, assuming a class width of 5 cm.

Centro de Classe (cm)	IPA (cm year^{-1})	Minimum age	Maximum age	Passing time (years)
		------- (months) -------		
------------------------ Equation (5-3) ------------------------				
7,5	1,3276	60	96	4
12,5	1,5611	108	132	3
17,5	1,6345	144	168	3
22,5	1,6768	180	204	3
27,5	1,7040	216	240	3
32,5	1,7228	252	276	3
37,5	1,7364	288	312	3
42,5	1,7469	324	336	2
47,5	1,7525	348	372	3
------------------------ Equation (5-7) ------------------------				
7,5	1,4827	62	98	4
12,5	1,6746	110	134	3
17,5	1,6997	146	170	3
22,5	1,7033	182	206	3
27,5	1,7038	218	242	3
32,5	1,7039	254	266	2
37,5	1,7039	278	302	3
42,5	1,7039	314	338	3
47,5	1,7039	350	374	3

DISCUSSION

The recovering Atlantic Forest fragment exhibited an inverse J-shaped diameter distribution, characteristic of tropical forests. This is a common trend in forests without intensive disturbance, with a higher frequency of stems in the smaller diameter classes (Figure 1). This is an indication that the density of smaller trees supports the community of larger trees (REIS et al. 2018).

The modeling performance for estimating PAI was not compromised by the presence of upper outliers within the 6 to 9 cm DBH range (Figure 1), as the dependent variables specified in the regression models represented median increment information for each diameter class (Table 1). It is worth noting that the median, as a measure of central tendency unaffected by extreme values, proves particularly useful in biometric distributions that deviate from normality—a trend also observed in the increment data according to the Shapiro-Wilk test ($p \leq 0.01$). The observed similarity between increment distributions for 3 and 5 cm diameter class widths was more pronounced in smaller size classes, potentially attributable to asymmetries in annual periodic increment dispersion within each biometric interval.

The regressions for diameter increment estimates were generally deemed satisfactory, considering the inherent species richness of the natural ecosystem, the complexity of ecological processes, and growth variability in uneven-aged environments (GOVEDAR et al. 2021). Fourteen functional relationships were established for estimating the median annual periodic increment as a function of the diametric class center (Table 1). The utilization of weighted statistical scores proved crucial in guiding equation selection.

The adoption of 5 cm intervals for diameter classes enhanced the goodness of fit of the regression models (Table 2). The higher concentration of stems in the 5 cm range likely enhanced size class representation, thereby improving the quality of fit (Figure 1). The best predictive performance was found in equations (5-3) and (5-7). The biological consistency of both equations was demonstrated through their coefficients and confirmed by graphical analysis (Figure 1). The negative slope coefficient in equation (5-3) and the positive asymptote (represented by β_0) in equation (5-7) indicated an ascending trend in annual periodic increment with increasing stem diameter.

The median estimate of annual periodic increment in stem growth showed minimal variation across increasing diameter classes. The similarity in passage time among these classes may be attributed to the recovery state of the fragment, given that greater incremental differences between size classes are expected as competition intensifies due to canopy closure and advancement of the regeneration stage (TAIZ & ZEIGER 2013).

No threshold diameter was identified beyond which growth rates declined. This likely resulted from the prevalence of juvenile and/or maturing individuals in the recovering forest fragment. Research has shown reductions in plant growth rates as the senescence phase approaches, reducing diametric increment (SCOLFORO et al. 1996, PIRES et al. 2021). Therefore, caution is necessary when applying periodic diameter increment modeling. It is advisable to test multiple regression models and select the most suitable one based on a thorough evaluation using a set of accuracy statistics.

Although a floristic survey was not conducted in this study, the rapid progression through smaller diameter classes (approximately every three to four years) indicated accelerated initial growth rates (exceeding 1.4 cm year^{-1}) compared to larger woody formations in more advanced stages of regeneration. It is emphasized that younger individuals distributed in mature forests are expected to have lower periodic diameter increments due to increased competition for light inherent to forest understory conditions (PIRES et al. 2021). The following annual diameter increments of up to 10 cm have been observed for these Amazonian forest species: less than 0.7 cm year^{-1} for *Erisma uncinatum* Warm., *Hymenolobium excelsum* Ducke, and *Trattinnickia burserifolia* Mart. (CANETTI et al. 2021); < 0.5 cm year^{-1} for *Carapa guianensis* Aubl. and *Tetragastris* altissima (Aubl.) Swart (PIRES et al. 2021) and; < 0.2 cm year^{-1} for *Minquartia guianensis* Aubl. (ANDRADE et al. 2017).

Future projections of tree diameter growth inform strategic decision-making for natural forest management, balancing conservation goals with sustainable resource utilization. The fragment reached the minimum diameter threshold for classification as medium-stage regeneration (10 cm, CONAMA 2007) at approximately nine years of age. This information holds significant technical relevance for developing management strategies, as interventions in Atlantic Forest domains are increasingly restricted due to advancing regeneration stages, regulated by Law 11.428 (BRAZIL 2006).

The mean stem diameters for trees with DBH greater than 5 cm, the minimum threshold for environmental intervention requests in Minas Gerais (Joint Resolution No. 3,102; SEMAD & IEF 2021), were 9.24 ± 4.09 cm and 10.79 ± 9.03 cm in 2020 and 2022, respectively. These dimensions indicate that the fragment is in an intermediate stage of regeneration, according to the National Environmental Council's Resolution No. 392 (CONAMA 2007). It should be noted that this ordinance is based on a set of quantitative and qualitative aspects for classifying stages of regeneration in Minas Gerais.

Although economic feasibility analysis was not the primary focus of this study, the implementation of the management regime must comply with Law 11.428 (BRAZIL 2006), which restricts management in the Atlantic Forest to pioneer tree species and fragments in early or intermediate stages of regeneration, where pioneer species comprise over 60% of the ecological groups present. For sustainable forest management operations aimed at timber production, cutting cycles were estimated at 15 years for a minimum marketable diameter (MMD) of 20 cm, and 18, 21, and 32 years for diameters of 25, 30, and 50 cm, respectively. To maintain the forest fragment under the management conditions imposed by this law, it may be necessary to reduce the minimum cutting diameter and intensify exploitation with shorter cutting cycles.

The findings offer valuable insights for developing conservation strategies that preserve native vegetation and promote sustainable management practices in the study area. It should be noted that the presented results do not imply recommendations for timber forest management, as further research on technical and economic feasibility in accordance with current legislation is necessary.

CONCLUSION

The Logistic and Curtis models, adapted for estimating annual periodic increment, are effective for calculations related to plant passage time in forest fragments undergoing recovery. The 5 cm diameter class range is suitable for calculating the passage time of fragments undergoing forest recovery for over six years.

Forest fragments undergoing recovery may exhibit comparable growth rates across diameter classes. For the Atlantic Forest fragment under recovery in this study, the estimated annual periodic increment ranged from 1.5 to 1.7 cm year^{-1} (with a three-year passage time across 5 cm intervals) for trees with diameters between 10 and 25 cm. The relative age for stems to reach 5 cm in diameter was approximately five years.

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