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Dendrochronology Applied to Three Forest Species in the Brazilian Amazon

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Abstract
Sustainable forest management is a legal alternative to combat deforestation and preserve natural resources in the long term. However, the lack of information on the growth and productivity of forests and individual species compromises its effectiveness. To obtain this information, dendrochronological techniques can be used. The aim of the study was to evaluate the dendrochronological potential of three tree species found in terra firme tropical rainforests: *Astronium graveolens* Jacquin, *Hevea brasiliensis* (Willd. ex A.Juss.) Müll.Arg., and *Inga cylindrica* (Vell.) Mart. The method involved collecting disks from the base of the trees (cross-dating), preparing the disks through polishing and scanning, and analyzing the growth rings based on anatomical characteristics. This technique is essential for understanding forest growth patterns, assessing tree responses to environmental changes, and supporting sustainable forest management practices. The three species showed distinct and visible growth rings to the naked eye. *H. brasiliensis* was classified as distinct, while *A. graveolens* and *I. cylindrica* were classified as less distinct. The dendrochronological analysis indicated that the three species presented a correlation between the growth ring series, with *A. graveolens* and *H. brasiliensis* showing an average correlation of 0.568 and 0.575, respectively, and *I. cylindrica* 0.3281. By analyzing the Master series, high growth peaks were identified for *H. brasiliensis* in 2012, 2013, 2016, 2017, and 2021, for *A. graveolens* in 1996, 1982, 2011, 2020, and 2005, and for *I. cylindrica* in 1989, 2001, 2008, 2010, 2014, 2016, and 2017. The species have dendrochronological potential and can contribute to the study of the cycle and minimum cutting diameter in forest management.

Keywords
Forest management — Growth and Production — Tropical Species — Growth Rings

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1. Introduction

The Legal Amazon occupies 5,015,168.18 km², corresponding to about 58.9% of the Brazilian territory (8,519,295.914 km²) (IBGE, 2021), and has vast areas covered by tropical forests. Its extreme diversity in terms of plant, animal, and microorganism species places it among the most complex ecosystems in the world. The tropical forest of Brazil faces serious challenges, such as deforestation, mainly driven by the expansion of agriculture, illegal logging, and illegal mining, becoming a major concern. The habitat loss resulting from deforestation threatens biodiversity and interferes with climate change (Marengo and Souza Jr., 2018).

For these reasons, the government established Law Nº. 12,561/2012, known as the new Brazilian Forest Code, which aims to reconcile environmental preservation with sustainable development, establishing rules for the use and preservation of natural resources. To this end, forest management is considered one of the best options to conserve the forest and ensure the continuous supply of timber without compromising environmental services and functions (Groenendijk et al., 2014). However, there is still a lack of information that can improve the use of timber resources in terms of quantity and quality without affecting the forest's ecological functions.

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Forest management encompasses a set of principles, techniques, and guidelines aimed at coordinating the activities necessary to plan and regulate the use of forest resources, seeking to maximize productivity and efficiency to achieve specific goals (Higuchi, 1994). The Normative Instruction IN 05 of 12/11/2006 currently regulates forest management; however, it does not consider variations in the growth of different species. It establishes a minimum cutting diameter (MCD) of 50 cm for all species, adopts a polycyclic system with cutting cycles (CC) of 25 to 35 years, and allows the removal of up to 30 m^3 per hectare (Miranda, 2017).

An important tool used to enhance results in forest studies is dendrochronology, as it contributes to the understanding of ecological processes, aiding in decision-making regarding sustainable forest management. By analyzing the growth rings of tree species, growth patterns can be identified, and the annual growth rate of forests can be determined, especially in tropical forests, which pose challenges in obtaining accurate and reliable data on tree growth (Rosa et al. 2017). Based on this information, it is possible to define cutting periods and extraction volumes that do not compromise the forest's regeneration capacity.

In the Amazon region, the formation of growth rings in trees is more influenced by variations in precipitation than by changes in temperature and seasons (Worbes, 1985). Some species have difficulties in distinguishing growth layers at a macroscopic level, considering factors such as the homogeneous distribution of vessels in trees, with no clearly identifiable layer through characteristics like lumen, parenchyma, and the growth layers not being continuous, which complicates the precise marking of growth rings, even when a layer delineated by fiber and parenchyma is present (Tanaka, 2005). Due to this difficulty, there is a scarcity of research in this area, as most studies focus on temperate forests, where the distinction of growth layers is clearer and more accessible. Therefore, it is crucial to direct more attention and resources to the dendrochronological study of tropical forests, focusing on species important for forest management.

In this research, three tree species from terra firme tropical rainforests were evaluated: *Astronium graveolens* Jacquin (Guaritá), *Hevea brasiliensis* (Willd. ex A.Juss.) Müll.Arg. (Rubber Tree), and *Inga cylindrica* (Vell.) Mart (Cerrado Inga), considering the analysis of growth rings. This study was conducted with the objective of estimating the dendrochronological potential of these species, which are considered important in forest management. The results may subsequently contribute to the study of growth and the evaluation of cutting cycles and minimum cutting diameter.

2. Material and Methods

2.1 Study Area Characterization

The area where the samples for this study were collected is situated in a terra firme tropical rainforest, described as Evergreen Seasonal Forest (IBGE, 2012), located in the state of Mato Grosso. It is located between the geographical coordinates -11º15'10''S and -55º11'57''W at an altitude of 283 meters (Figure 1). According to the Köppen classification, the region's climate is Aw type, tropical, hot, and humid, with monsoon-type rains (Alvares et al., 2014). The average annual precipitation is approximately 1970 mm per year, with an average annual temperature of 24.7℃ and a rainy season from October to April with an extremely dry winter (Souza et al., 2013).

The study was conducted with the species *Astronium graveolens* Jacquin, *Hevea brasiliensis* (Willd. ex A.Juss.) Müll.Arg., and *Inga cylindrica* (Vell.) Mart. A disk approximately 10 cm thick was collected from the base of each sampled tree (four individuals per species) in a tropical rainforest located near the municipality of Sinop, MT. Before the analyses, the disks were prepared by polishing their cross-sections with different grits (from 80 to 600 grains/mm^2) using an electric sander, providing better contrast of the rings for improved visualization, and scanning the cross-section of the disks.

The analysis of the growth rings was conducted based on the macroscopic anatomical characteristics observed around the circumference of the disk, noting when the growth layers were distinct: (A) Presence of porous rings, (B) Presence of semi-porous rings, (C) Fibrous zone, (D) Marginal axial parenchyma (Botosso, 2009). This stage of the analysis was carried out with the aid of a bench magnifying glass, a 10x loupe, and relevant literature.

After delineation, the width of the rings was determined using four radii for the species *Hevea brasiliensis* and *Inga cylindrica*, and three radii for the species *Astronium graveolens* (Figure 2). These radii were drawn around the circumference of the disks, avoiding areas with cracks, and the analysis was performed using the image analysis software Image-Pro Plus. Subsequently, cross-dating was conducted for these samples. This dating consisted of obtaining matching patterns of ring width from different trees and assigning a common calendar to each analyzed growth ring (Douglas, 1941).

Após as delimitações, a largura dos anéis foi determinada usando quatro raios para as espécies de *Hevea brasiliensis* e *Inga cylindrica*, e três raios para a espécie *Astronium graveolens* (Figura 2). Esses raios foram traçados ao redor da circunferência dos discos, evitando áreas com rachaduras, e a análise foi realizada uti-

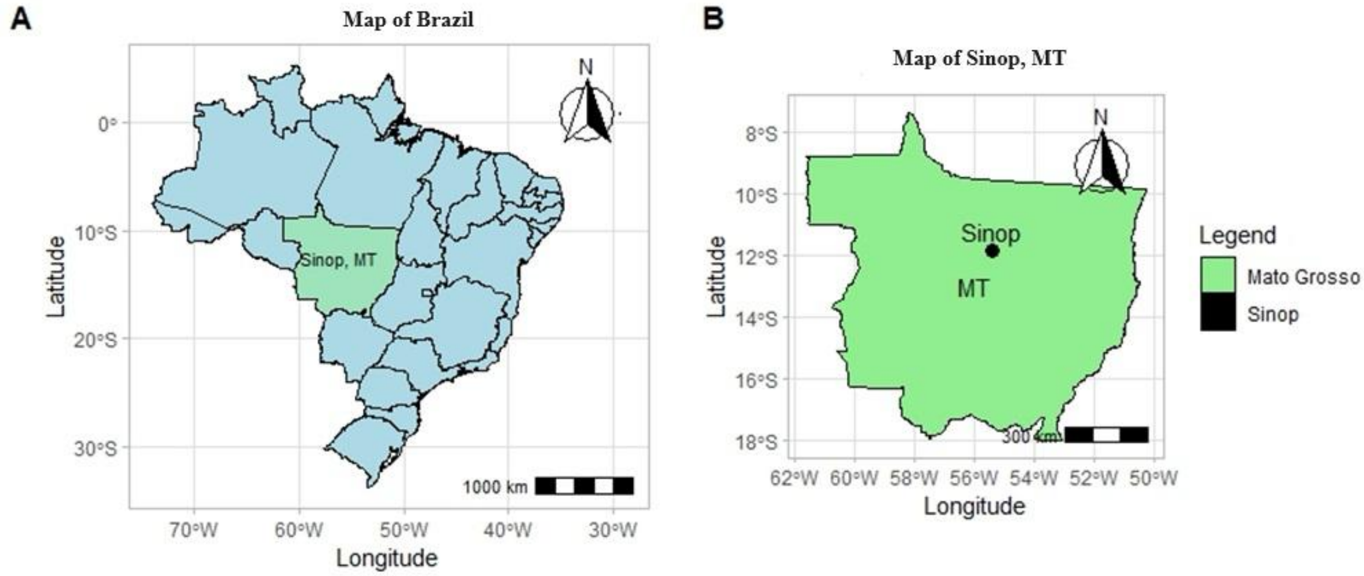

Figure 1. Location Map.

lizando o software de análise de imagens Image-Pro Plus. Em seguida, foi realizada a datação cruzada para estas amostras. Essa datação consistiu em obter padrões de correspondência de largura dos anéis de diferentes árvores e atribuir um calendário comum para cada anel de crescimento analisado (DOUGLAS, 1941).

The data from the radii of each species were recorded in spreadsheets using Microsoft Excel® 2021. Cross-dating was used to verify the correspondence of ring width patterns between samples from the same tree and between different trees, infer where rings might be missing, and carefully examine the growth ring structure (Fritts, 1976). Statistically, cross-dating was performed using the COFECHA program for control and verification of the synchronization of the series (radii) between trees (Holmes, 1983) using a 50-year window with a 25-year overlap and a critical R-value of 0.3281 (Miranda et al., 2017).

Next, a table was created to compare the demarcations of the growth rings of the species, based on the criteria described by Miranda (2017), classified into three levels: easy visualization, medium visualization, and difficult visualization. The last classification requires the analysis of the entire circumference of the disk to delineate the rings and mark locally absent rings or false rings.

3. Results

3.1 Macroscopic Anatomical Characterization

3.1.1. Guaritá (*Astronium graveolens)*

In the anatomical characterization carried out in the laboratory, it was possible to identify the visible rings under magnification, the growth layers that mark the beginning and end of tree growth, which were classified as distinct and visible to the naked eye (Figure 3-A). Regarding the visibility degree of the rings, it was classified in the second category of medium visibility. The species exhibited ring boundaries visible to the naked eye, although at times, the use of a magnifying glass was necessary to clarify the demarcation of a ring around the disk to confirm the true ring, which were marked as semi-porous rings.

3.1.2. Seringueira (*Hevea brasiliensis)*

Visible rays under magnification, growth layers marking the beginning and end of tree growth, classified as distinct and visible to the naked eye (Figure 3-B). Regarding the visibility degree of the rings, it was classified in the first category of easy visualization, as it was not necessary to use a bench magnifying glass for ring counting, these being marked as semi-porous rings.

3.1.3. Ingá (*Inga cylindrica)*

Visible rays under magnification, the growth layers marking the beginning and end of tree growth, classified as distinct and visible to the naked eye (Figure 3-C). Re-

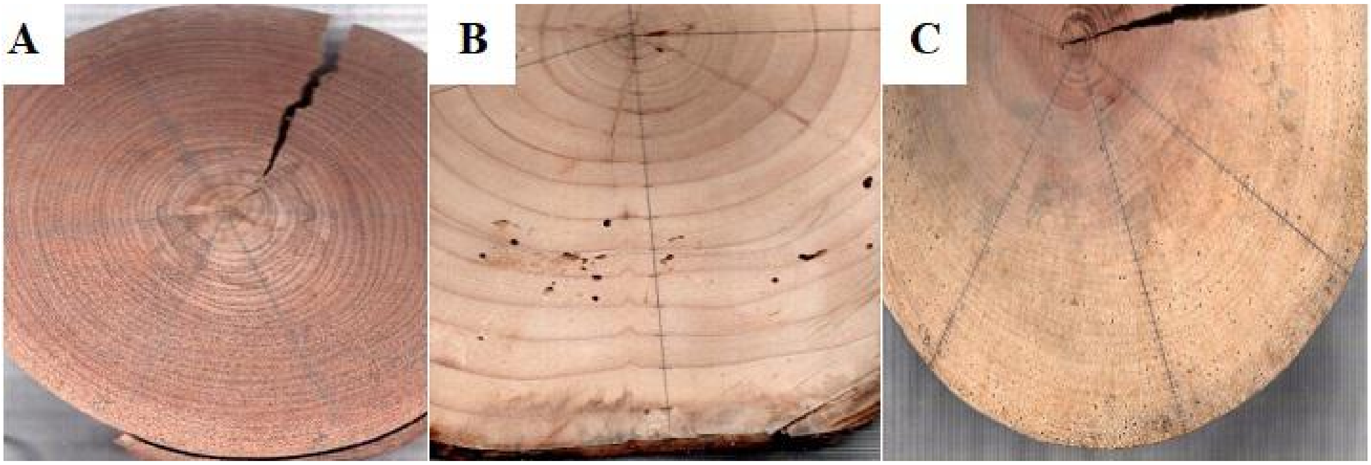

Figure 2. Disks of the species (A) *Inga cylindrica* (Vell.) Mart; (B) *Hevea brasiliensis* (Willd. ex A.Juss.) Müll.Arg.; and (C) *Astronium graveolens* Jacquin.

garding the visibility degree of the rings, it was classified in the first category of easy visualization, as it was not necessary to use a bench magnifying glass for ring counting, being possible to verify with the naked eye, these being marked by the fibrous zone.

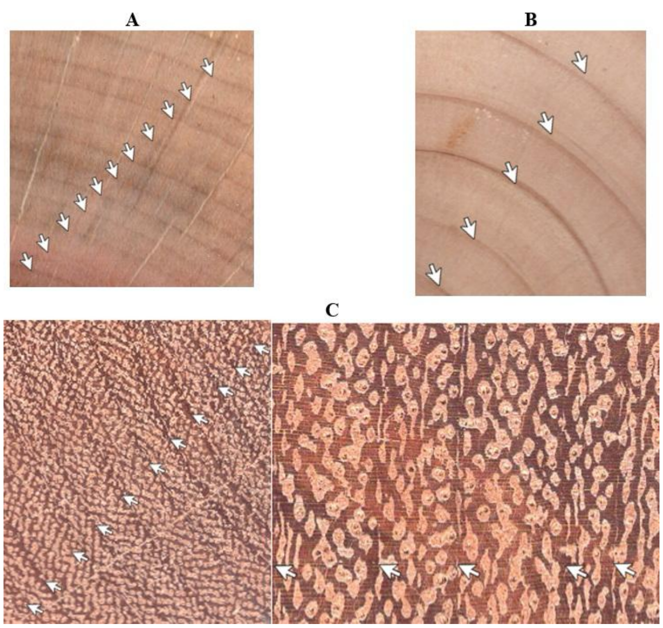

Figure 3. A: Growth rings of *Astronium graveolens* species; B: Growth rings of *Hevea brasiliensis* species; e C: Growth Rings of *Inga cylindrica* (Vell.) Mart species.

3.2. Dendrocronology

The width of the growth rings enabled the synchronization of the chronological series of the 3 analyzed species, indicating the quality of the cross-dating. The species *A. graveolens* and *H. brasiliensis* showed the highest average correlation values of 0.568 and 0.575, respectively. *I. cylindrica* also showed a good average correlation above the critical correlation limit value of 0.3281 set by the program. Thus, a satisfactory adjustment between the growth ring series of each individual tree was achieved (Table 1).

Figures 4-A, B, and C depict the Master chronologies obtained from analyses in the COFECHA software for the studied species.

Upon observing the Master series, it is noticeable that there were significant growth fluctuations in the early years for the species *A. graveolens* from 1970 to 1987, and for *I. cylindrica* from 1991 to 1995, except for *H. brasiliensis*, which shows a more homogeneous growth pattern in its indices.

The peaks of high growth for *H. brasiliensis* were observed in the years 2012, 2013, 2016, 2017, and 2021, with notable peaks in 2017 and 2021. For *A. graveolens*, the peaks were in 1996, 1982, 2011, 2020, and 2005, with notable peaks in 2005 and 2020. For *I. cylindrica*, the peaks were in the years 1989, 2001, 2008, 2010, 2014, 2016, and 2017, with notable peaks in 1989 and 2017. These growth patterns highlight specific periods when the trees exhibited more vigorous growth and can provide insights into the environmental and climatic factors that influenced these patterns.

4. Discussion

The anatomical structure of the species presents distinct growth rings, identified as a fibrous zone in the Inga species and as semi-porous rings in the *Hevea brasiliensis* and *Astronium graveolens* species. Additionally, false

Table 1. Dendrochronology of *Astronium graveolens*, *Hevea brasiliensis*, and *Inga cylindrica* through descriptive statistics obtained by the COFECHA program in the adjustment of master series.

Description	Chronology		
	Astronium graveolens	*Hevea brasiliensis*	*Inga cylindrica*
Master Series	1970-2022	2007-2022	1987-2022
Series Included in the Master	53	16	36
Series Dated in the Master	3	4	4
Average Correlation	0.568	0.575	0.366
Number of Rings Observed	159	64	144
Average Sensitivity	0.312	0.219	0.345

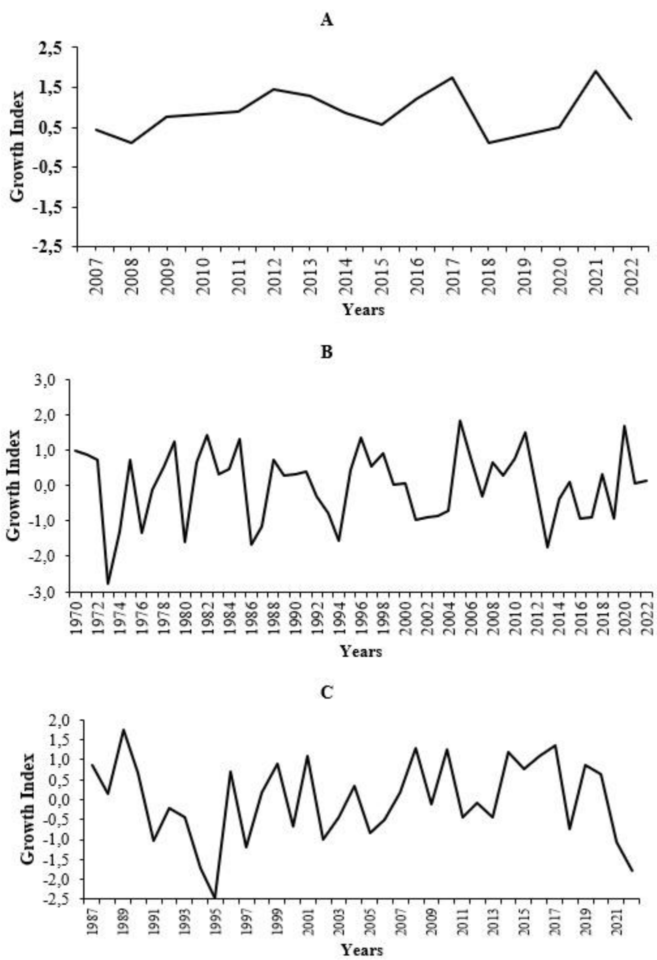

Figure 4. A- Growth Ring Width Indices for *Hevea brasiliensis* in the Master Series; B- Growth ring width indices for *Astronium graveolens* in the Master series; e C- Growth ring width indices for *Inga cylindrica* in the Master series..

growth rings occur similarly in the wood of the *Astronium graveolens* species. In a dendrochronology study conducted by Alvarado (2009) on mahogany trees (*Swietenia macrophylla* King), the author emphasizes the importance of caution when analyzing the presence of false rings, noting that it does not necessarily mean that the species do not form annual growth rings.

Regarding the visibility of the rings, the *Astronium graveolens* species was classified in the second category (medium visibility) due to the ring boundaries being visible to the naked eye. The Hevea brasiliensis and Inga species were classified in the first category (easy visibility), as found in a study by Miranda (2017), since it was not necessary to confirm the ring count using a bench magnifier. It was possible to verify the rings with the naked eye, confirming them as true and excluding the false rings from the count.

In a study investigating the climatic responses to the growth of *Cedrela fissilis* over a period of 55 to 124 years, using a master series adjusted by 9 trees, an intercorrelation between the series of 0.313 was found (Marcon et al. 2019). On the other hand, in a dendrochronological analysis of five species, intercorrelation values ranging from 0.389 to 0.754 were obtained (Chagas, 2009). The use of master series adjusted by the COFECHA software is crucial for dendrochronological studies, as evidenced by the mentioned findings. The intercorrelation between growth ring series provides a measure of data reliability, allowing for more accurate analyses of climatic responses and growth patterns of the investigated species. This, in turn, contributes to a deeper understanding of the relationships between trees and their environment.

It is important to note that the threshold correlation value of the COFECHA program can vary depending on the specific settings and criteria established by the user. However, a correlation value above 0.25 or 0.3 is considered significant for the synchronization of tree ring chronologies. This value may vary based on the characteristics of the samples analyzed and the requirements of the study in question.

The species *H. brasiliensis* demonstrated the highest correlation compared to the other species studied. This high correlation can be explained by the quality and good preparation of the collected disc sample, which facilitated the visualization of the rings both to the naked eye and in the software. Furthermore, the sample did not show eccentricity, which is an important factor for the vectorization and correlation of the rays. Anholetto Júnior (2019) mentions that a species of the same genus, *Hevea spruceana* (Benth.) Müll. Arg., obtained a correlation of 0.480, a value considered positive in relation to the critical point established by the software. This finding further reinforces the dendrochronological potential of the species *H. brasiliensis*.

However, it is important to highlight that the species *A. graveolens* and *I. cylindrica* also demonstrated a good average correlation, above the threshold value established by the program. This means that there was a satisfactory adjustment between the growth ring series of each individual tree of these species. These results indicate that the three analyzed species have good dendrochronological potential and show consistency in the growth patterns of these species. These findings are important as they provide valuable information about the ecology and growth history of the studied species (Palermo, 2012). Additionally, they can contribute to future studies related to climate, environmental impacts, and forest management.

The growth patterns highlight specific periods when the trees exhibited more vigorous growth. These variations can provide a better understanding of the environmental and climatic factors that influenced these patterns (Webb et al, 2022). For instance, specific climatic events, such as years with higher rainfall or temperature variations, may have impacted the trees' growth during these periods. Previous studies emphasize the importance of dendrochronology in understanding forest dynamics and how growth rings can reveal valuable information about the ecology of the studied species (Mattos, 2011). Therefore, these fluctuations in growth can be explored to investigate the relationship between environmental factors, such as climate, and the growth patterns of these species. Consequently, studying the growth of these species could also allow for more precise estimation of minimum cutting diameters and cutting cycles in forest management.

5. Conclusion

Dendrochronological studies play a crucial role in forest management, offering various practical applications. These studies enable the estimation of tree age, analysis of growth increment, understanding of mortality and forest dynamics, and construction of growth and yield models. They are essential for understanding forests and facilitate the sustainable management of forest resources, significantly contributing to the conservation of tropical forests.

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Author Statements

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✓ There is no evidence of plagiarism in this article.

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