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Original Article

Diameter growth and age of jaboticaba trees (*Plinia peruviana* (Poir.) Govaerts) native from Southwest of Paraná, Brazil, based on growth-rings

Crescimento em diâmetro e idade de jaboticabeiras (*Plinia peruviana* (Poir.) Govaerts) nativas do Sudoeste do Paraná, Brasil, com base em anéis de crescimento

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Abstract

The jaboticaba tree (*Plinia peruviana* (Poir.) Govaerts) is a native Brazilian species, and its fruits are very popular in Brazil. The purpose of this study was to model the diameter growth, and determine the age of jaboticaba trees in four natural populations in Southwest of Paraná State, Brazil. The knowledge of the growth dynamics of this species is essential to assist management and conservation strategies and to discover when this species was established in the region. Core samples were collected to obtain complete growth series by measurement of annual growth rings. The series were crossdated, seven growth models were adjusted, and the best model for each site and a general model were selected using statistics rules. The time series spanned periods of ~75 to ~100 years, and growth ranged between 0.27 and 0.37 cm year^{-1}. Chapman-Richards' model showed better adherence for locations individually, and Monomolecular when grouped. Because to the age reached by the jaboticaba trees and the high density of this species in these natural populations, consequently named "jaboticabais", it was inferred that there was an anthropogenic action in the dispersion and formation of the settlements through the indigenous and caboclos that inhabited the region before 1940. Also, this is the first work to register and verify the fusion of trunks for species of the *Plinia* genus using double piths found in samples, a feature that must be considered to avoid overestimating the age of jaboticaba trees based solely on measuring tree diameter.

Keywords: Myrtaceae, dendrochronology, modeling growth, forest management.

Resumo

A jabuticabeira (*Plinia peruviana* (Poir.) Govaerts) é uma espécie nativa brasileira e seus frutos são muito populares no Brasil. O objetivo deste estudo foi modelar o crescimento diamétrico e determinar a idade de jabuticabeiras em quatro populações naturais no Sudoeste do Paraná, Brasil. O conhecimento da dinâmica de crescimento desta espécie é essencial para auxiliar na definição de estratégias de manejo e conservação e descobrir quando esta espécie se estabeleceu na região. Amostras do tronco foram coletadas para obter séries completas de crescimento através da medição dos anéis de crescimento anuais. As séries foram cruzadas, sete modelos de crescimento foram ajustados e o melhor modelo para cada site e um modelo geral foram selecionados usando regras estatísticas. A série temporal abrangeu períodos de ~75 a ~100 anos, e o crescimento variou entre 0,27 e 0,37 cm ano^{-1}. O modelo de Chapman-Richards apresentou melhor aderência para locais individualmente, e o modelo Monomolecular quando agrupados. Devido à idade atingida pelas jabuticabeiras e à alta densidade desta espécie nessas populações naturais, consequentemente denominadas "jaboticabais", inferiu-se que houve uma ação antrópica na dispersão e formação destas populações através dos indígenas e caboclos que habitavam a região antes de 1940. Além disso, este é o primeiro trabalho a registrar a fusão de troncos de espécies do gênero *Plinia*, encontrando medulas duplas em amostras, característica que deve ser considerada para evitar superestimar a idade das jabuticabeiras com base apenas na medição do diâmetro da árvore.

Palavras-chave: Myrtaceae, dendrocronologia, modelagem do crescimento, manejo florestal.

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1. Introduction

The jaboticaba tree (*Plinia peruviana* (Poir.) Govaerts) is a native Brazilian species, occurring in the Atlantic Forest Biome (Stadnik et al., 2020) and its fruits are very popular in Brazil for both fresh and processed consumption. Some studies also showed its importance for medicinal purposes (Fernandes et al., 2022), due to the high total phenolic compounds and anthocyanin levels in the jaboticaba peel (Neves et al., 2021), showing antioxidant, anti-inflammatory, and antitumoral effects (Leite-Legatti et al., 2012; Paula et al., 2023).

Tree rings are an important source of long-term proxy information to provide unique insights into past vegetation dynamics (Egan and Howell, 2001). This is especially true when a large number of trees samples are cross-dated, which permits the identification of rings that were formed contemporaneously with one another among trees. This validation becomes possible to infer about relationship between time series of rings and landscapes built by past human cultures (Egan and Howell, 2001) and develop growth models to explain growth patterns of tree species (Burkhart and Tomé, 2012).

Some studies are available in literature showing fitted growth models of South Brazilian tree species, using growth ring series, although for many species there is a lack of information regarding growth patterns. For example, dynamics of growth of *Podocarpus lambertii* emphasizing the limitation growth of this species under competition at other native forest species (Canetti et al., 2016), in Colombo, Paraná State, Brazil. The species *Araucaria angustifolia* present different growth pattern, when growing in altitudinal gradients in Santa Catarina State (Ricken et al., 2022). Also, the importance to study growth pattern of species in different sites and regions was highlighted by Stepka et al. (2021). These authors studied three species (*A. angustifolia, Cedrela fissilis* and *Ocotea porosa*) in six different sites, in the three South States of Brazil (Paraná, Santa Catarina and Rio Grande do Sul), and they showed that the growth pattern may differ, when the environment differs.

The wood anatomy with growth rings identification in jaboticaba trees are present in a few researches, demonstrating that the wood features were growth rings compact and poorly-defined, marked by a row of thick-walled fibers radially-flattened (Santos et al., 2013; Stange et al., 2018). However, jaboticaba tree growth patterns studies based on growth rings series have not being carried out, and are important to assist management and species conservation strategies.

The purpose of this study was to determine the age and to model the diameter growth pattern of jaboticaba trees (*Plinia peruviana*) in four natural populations in the Southwest of Paraná, using dendrochronological analyzes.

2. Materials and Methods

In the Southwest of Paraná, Brazil, at least 14 Mixed Ombrophilous Forest remnants present 4.036 *Plinia peruviana* trees, which are locally called "jaboticabais" (Danner et al., 2010). This study was carried out on four forest remnants (Figure 1) located in the municipalities of Chopinzinho - CH (25º52'36" S, 52º36'28" W, 859 m a.s.l.), Clevelândia - CL (26°26'17" S, 52°19'20" W, 963 m a.s.l.), Pato Branco - PB (26º06'34" S, 52º38'29" W, 713 m a.s.l.) and Vitorino - VT (26º19'01" S, 52º46'42" W, 818 m a.s.l.). The density of adult jaboticaba trees (*P. peruviana*) in these forest fragments is 59.6 (CH), 75.6 (CL), 40.6 (PB), and 45.8 (VT) trees ha^{-1} and a sample of 10 adult jaboticaba trees from each site had an average of 54, 32, 41, and 45 cm in diameter at the breast height, respectively (Danner et al., 2010).

According to the Köppen climate classification, CL has a Cfb-type climate (temperate oceanic climate or subtropical highland climate, coldest month with temperature averaging above 10 °C, and the warmest month less than 22 ºC, mild summers, and frequent severe frosts in late autumn, winter and early spring seasons). The other three sites have a Cfa-type climate (humid subtropical climate, the coldest month averaging above 10 °C and the warmest month exceeding 22 ºC, hot summers, and frosts occurring frequently, but concentrated in winter). No significant precipitation difference between seasons and no dry months are characteristics of both climate type (Alvares et al., 2013).

In the Southwest of Paraná, the soils where the jaboticaba trees grow up were clayey (59% of granulometry analysis), strongly acidic (pH almost 4.0), with high content of organic matter and iron, aluminum high-saturation, low levels of phosphorus and very low saturation of bases. The most common tree species in this forest with "jaboticabais" are *Araucaria angustifolia* [(Bert.) O. Kuntze], *Nectandra lanceolata* (Nees), *Ocotea porosa* (Nees & Mart), *Ocotea odorifera* [(Vell.) Rohwer], *Apuleia leiocarpa* [(Vog.) Macgr.], *Cedrela fissilis* (Vell.), *Piptocarpha angustifolia* (Duséss.), *Diatenopteryx sorbifolia* (Radlk.), *Vitex montevidensis* (Cham.), *Syagrus romanzoffiana* [(Cham.) Glassm.], *Slonea monosperma* (Vell.) and other Myrtaceae fruit trees such as *Eugenia involucrata* (DC.), *Eugenia uniflora* (L), *Eugenia pyriformis* (Cambess.), *Campomanesia xanthocarpa* (O. Berg), *Myrcianthes pungens* [(O. Berg) D. Legrand], *Myrciaria tenella* [(DC.) O. Berg] and *Campomanesia guazumifolia* [(Cambess.) O. Berg] (Danner et al., 2010).

To determine the age and growth of trees, ten adult jaboticaba individuals, with a diameter at 1.3 m in height (DBH) ≥ 20 cm and only one trunk, were randomly selected in each population. Non-destructive sample collection was carried out using an increment borer of 0.5 cm of diameter, to obtain wood samples from two sections of each trunk at 1.3 m above ground level. The DBH of each tree was measured with a measuring tape. The wood samples were polished with sandpaper of different sizes to make the growth rings more evident.

The growth rings were delimited, counted, and measured using a stereoscopic microscope and a Lintab measurement table, with 0.01 mm precision, and the TSAP-Win software (Rinn, 1996). All measurements were converted in centimeters. Two samples from VT were excluded from the analysis, as they were of insufficient quality for accurate marking and measuring of the rings.

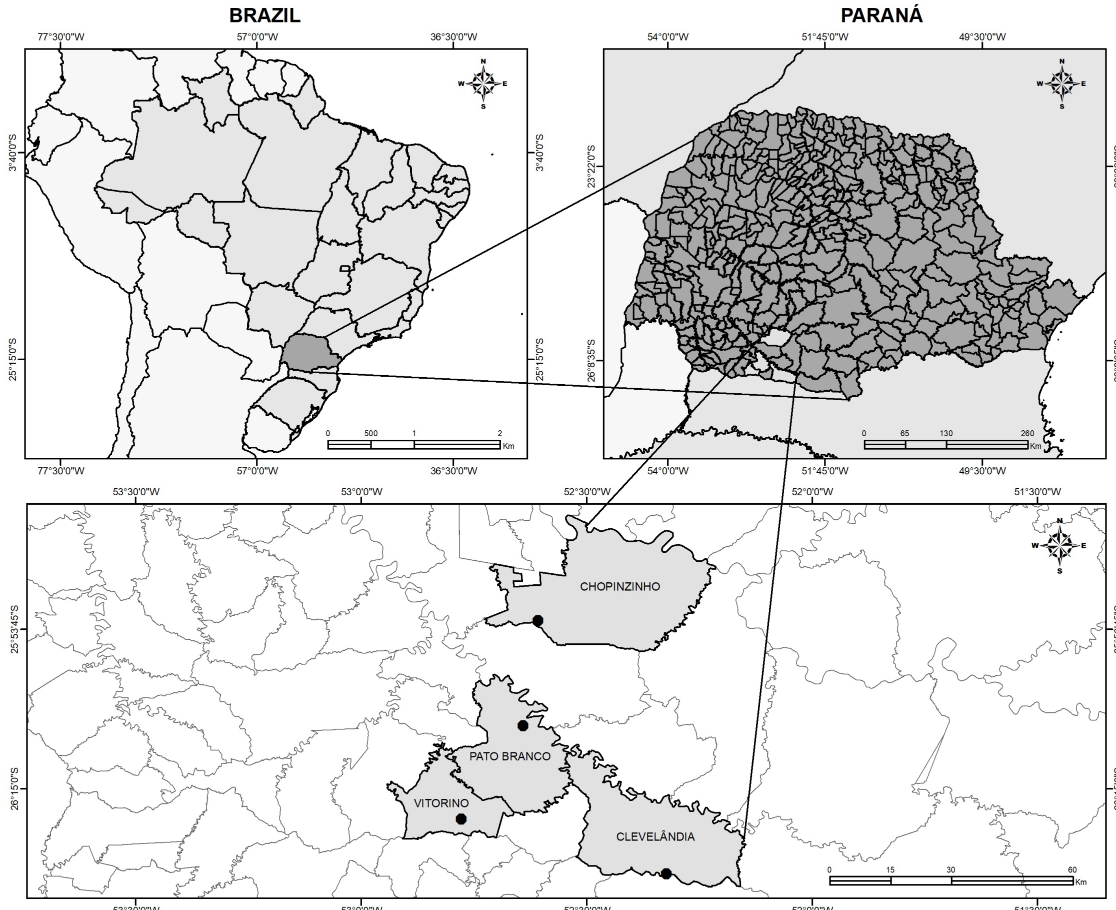

Figure 1. Location of the studied "jaboticabais" in Southwest of Paraná, Brazil.

The growth series were dated between the rays of the same tree and between trees. We used the software Cofecha to synchronize similar patterns between growth series (Holmes, 1983). The series of radial increments were used to calculate diameter increment, multiplying by two. The growth series were generated by the accumulated diameters increment of each tree, calculated for each year. We considered the DBH class interval of 5.0 cm. The passage time between diameter classes were calculate dividing the class DBH interval by the average increment of the same DBH class (Burkhart and Tomé, 2012). The data was submitted to analysis of variance, followed by the Scott-Knott test for means grouping, using ExpDes.pt package (Ferreira et al., 2021) in R plataform (R Development Core Team, 2022).

Seven mathematical models of diametric growth of jaboticaba trees (Supplementary Material Table S1) were tested using non-linear regression, using the PROC NLMIXED process in the SAS® software, as well as Canetti et al. (2021). The equation with the best adjustment to the real data for each study site was selected by the following statistical parameters: standard error of the estimate (Syx%), corrected Akaike's Information Criterion (AICc), Bayesian information criterion (BIC), and root-mean-square error (RMSE). The same procedure was used to construct a growth model with the data set of all the jaboticaba trees, to be used in other sites where there are not growth data available for this species. For each selected growth model, the culmination point of DBH increment was determined, by the identification of the higher current annual increment, calculated as the first derivative of the growth model (Burkhart and Tomé, 2012).

3. Results

The average diametric growth of *Plinia peruviana* was 0.27 cm $year^{-1}$ in site CH, 0.31 cm $year^{-1}$ in CL, 0.37 cm $year^{-1}$ in PB, and 0.32 cm $year^{-1}$ in VT. In all locations, increment growth rates was homogeneous between the diameter classes, except for CL, in which the jaboticaba trees of the class center of 7.5 cm had significantly larger diameter increment (p value < 0.01) than in the other classes. There were no significant differences in passage times between diameter classes (p value > 0.05). Jaboticaba trees had an average passage time of 16 years among diametric classes (CH = 18 years, CL and VT = 16 years, and PB = 14 years).

The average age of jaboticaba trees in the largest diameter class center (32.5 cm) was approximately 100 years in CH, PB, and VT. This average age was 77 years in CL, in which the largest class center was 27.5 cm. With one exception, in all locations tree age significantly increased as the diameter class center of the jaboticaba trees increased. The exception was between classes 27.5 and 32.5 cm in CH in which no significant age difference occurred (Figure 2).

We noticed that the calculated diameter based on the tree-ring measurements was consistently smaller (about half) than the diameters obtained in the field with a measuring tape for several of our samples. It was then verified that these samples contained the union of two trunks with double pith (Figure 3), that is, these samples comprised two fused jaboticaba trees. The jaboticaba trees collected in the field were then revisited, and the trunk fusion at the base was checked visually. It was found to be characterized by deep indentations (Figure 3).

The trunk fusion was observed in the majority of the sampled jaboticaba trees (~66%), ranging from 50% of trees in PB and VT to 80% in CH and CL. For these trees, the diameter referring to only one of the piths was considered in the calculations. There were no significant differences in diametric increase between jaboticaba trees with single and double piths in the different study sites (Figure 4).

Based on statistical parameters and coefficients (Supplementary Material Table S2) comparing the seven models for diametric growth of jaboticaba trees (*Plinia peruviana*), the Chapman-Richards model showed the best fitting to the jaboticaba tree time series in each of the four study sites (Figure 5A). However, the monomolecular model showed the best fitting to the time series when considering all individuals in a single growth curve for the species (Figure 5B).

The culmination point of the diameter increases in jaboticaba trees occurred around 20 years of age in CL, and near 50 years of age in VT. After these points, the growth tended to reduce or stabilize. This point was calculated near 30 years of age in CH and PB (Table 1). Maximum age was near or over 100 years of age for most of the studied sites (CH, PB, and VT), except for CL that was 70 years of age.

When comparing the culmination point of increment in diameter (Table 1), we can observe a bigger value for PB population, an intermediate value for VT and similar and smaller culmination points for the other two sites. Nevertheless, the time for maximization of VT population was much higher than all other three sites (~50 years).

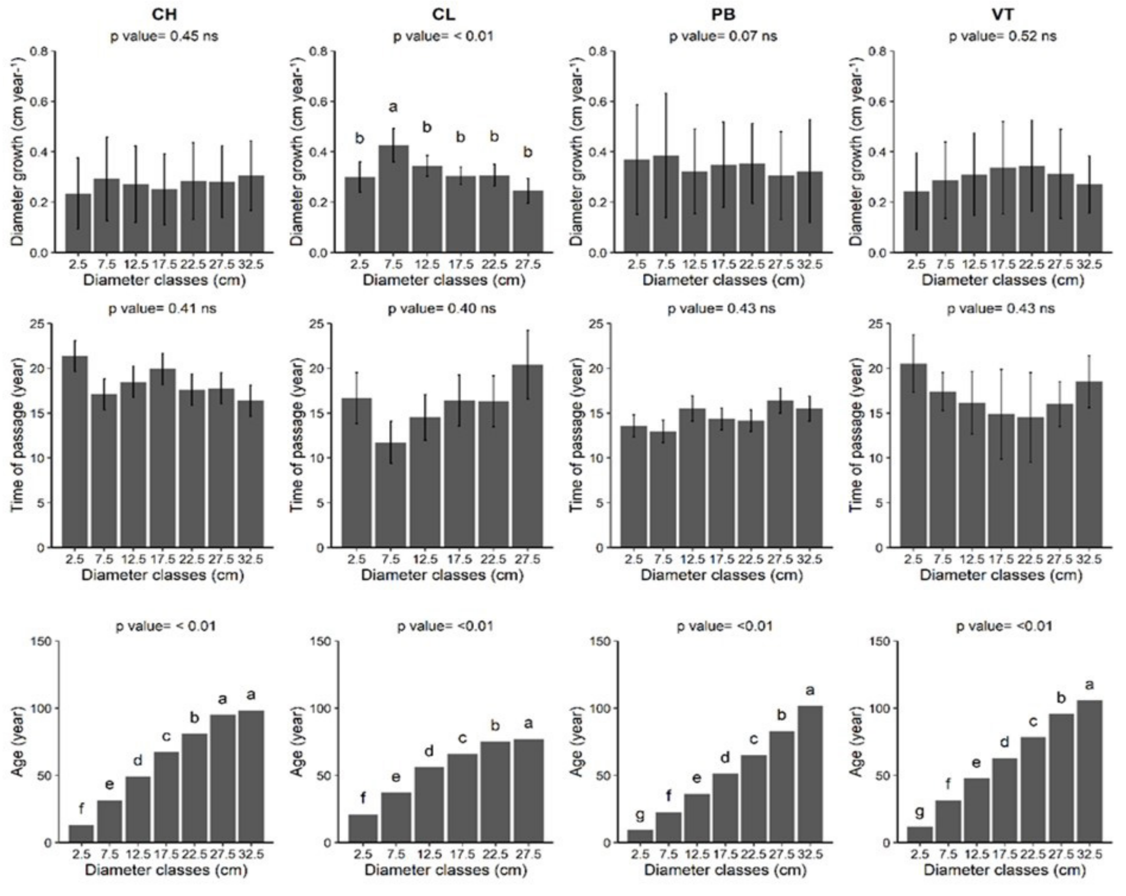

Figure 2. Diametric growth, time of passage and age of jaboticaba trees (*Plinia peruviana*) in the four collection sites. Sites: CH = Chopinzinho, CL = Clevelândia, PB = Pato Branco, VT = Vitorino. Different letters indicate difference between means, using the Scott-Knott test ($p < 0.05$). ns: indicates that there was no difference by the F test ($p < 0.05$) of the analysis of variance. Vertical lines indicate standard deviation.

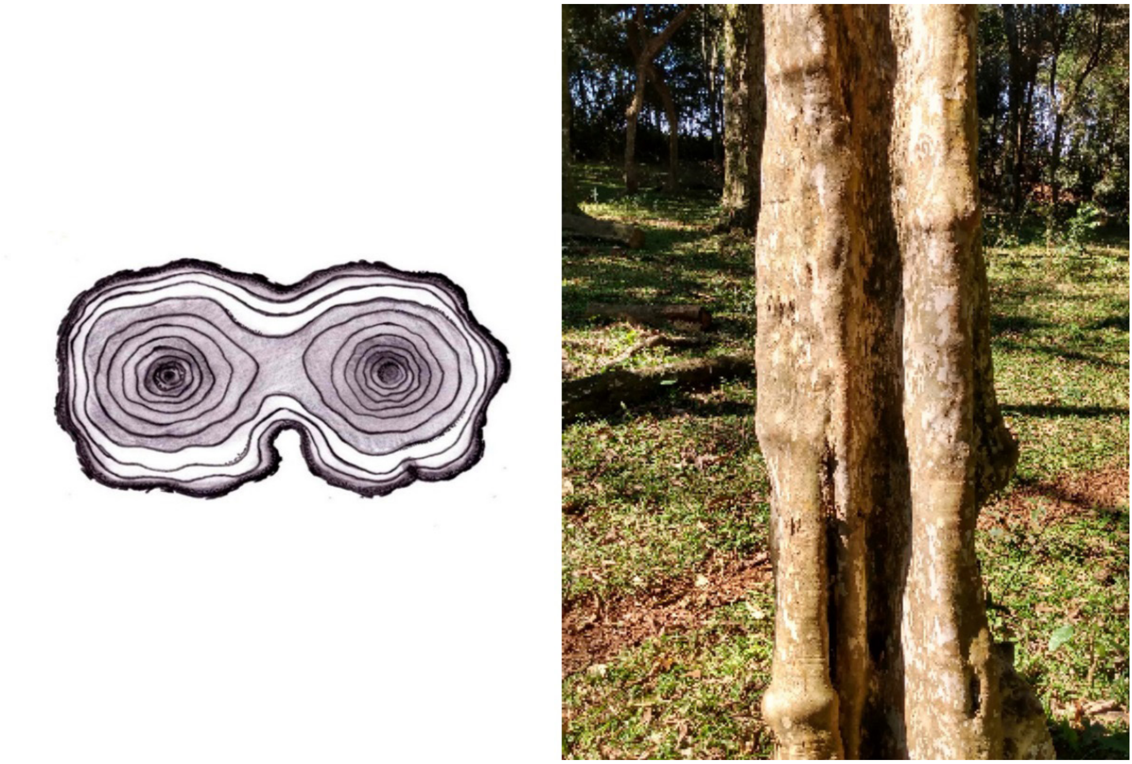

Figure 3. Scheme representing samples with double pith (in the left side) and conformation of the fused trunk of jaboticaba tree (*Plinia peruviana*) in the field (in the right side), which presented a double pith in the dendrochronological analyzes.

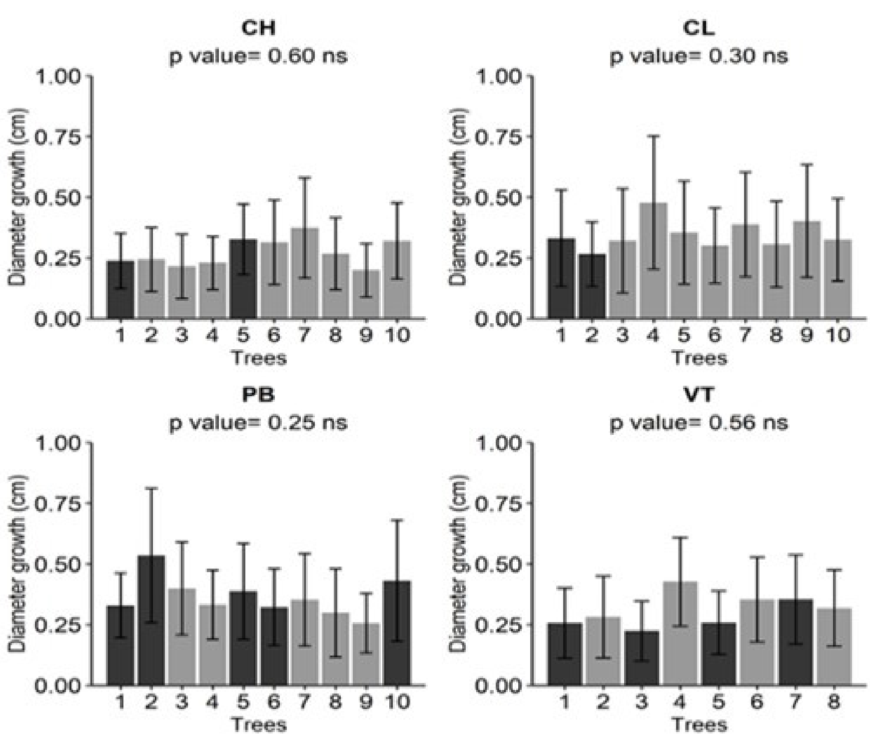

Figure 4. Diametric growth of jaboticaba trees (*Plinia peruviana*) that presented double pith (light gray bars) and simple pith (dark gray bars). Sites: CH = Chopinzinho, CL = Clevelândia, PB = Pato Branco, VT = Vitorino. Vertical lines represent standard deviation among diametric classes.

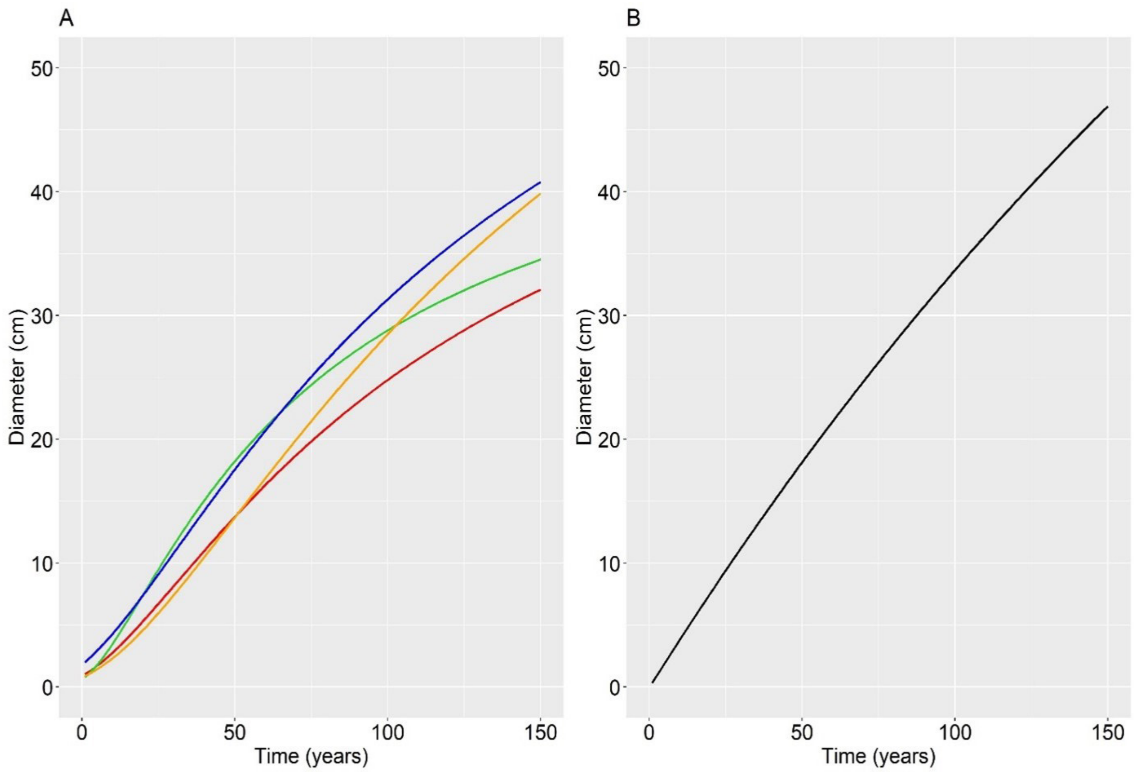

Figure 5. Curves of diametric growth by Chapman-Richards model of jaboticaba trees (*Plinia peruviana*) in the four collection sites (A) and a general growth model (Monomolecular) adjusted for all jaboticaba trees (B). Sites: CH = Chopinzinho (red line, $R^2 = 0.84$). CL = Clevelândia (green line, $R^2 = 0.86$). PB = Pato Branco (blue line, $R^2 = 0.90$). VT = Vitorino (orange line, $R^2 = 0.95$). General model (black line, $R^2 = 0.73$).

Table 1. Culmination point and relations observed in the jaboticaba trees (*Plinia peruviana*) studied samples.

Sites	Diameter at the culmination point (cm)	Time to reach the culmination point (years)	Increment at the culmination point (cm)	Average annual increment until the culmination point (cm)	Maximum age observed (years)
CH	8.4	31	0.29	0.25 c	105
PB	11.5	32	0.34	0.35 a	131
VT	13.4	49	0.32	0.31 b	97
CL	7.5	20	0.41	0.26 c	77

Sites: CH = Chopinzinho. CL = Clevelândia. PB = Pato Branco. VT = Vitorino. Different letters indicate difference between means, using the Scott-Knott test ($p < 0.05$).

4. Discussion

Until our work there had been no growth studies of *Plinia peruviana* based on dendrochronological analysis, although growth rings have been described previously in this species (Santos et al., 2013; Stange et al., 2018). Some studies were carried out with species in the same forest typology (Ombrofilous Mixed Forest), showing annual growth rings in *Araucaria angustifolia*, *Cedrela fissilis, Ocotea porosa*, and *Podocarpus lambertti*, due to the climate sazonality that shows warm summers and cold winters (Canetti et al., 2016; Ricken et al., 2022; Stepka et al., 2021). These authors have been described and applied the growth series to develop growth models. Our work uses such analysis for the first time in *P. peruviana* to enable the recovery of growth series and thereby show all the life stages of these trees.

Our findings have several implications for conservation and management of this species. For example, the diametric growth of *P. peruviana* were slow compared than others Mixed Ombrofilous Forest species (Canetti et al., 2016; Ricken et al., 2022; Stepka et al., 2021), ranged from 0.27 cm $year^{-1}$ in site CH to 0.37 cm $year^{-1}$ in PB, which may imply less competitiveness with other species when establishing in the forest.

We also observed that jaboticaba trees in CL did not reach diameters larger than 40 cm, different from what was observed in other three locations (see Figure 5), indicating that there may be a restriction factor in growth in this site. Higher altitude and, consequently, lower temperature can restrict the growth of trees. Jabuticaba trees that occur in sites with lower altitude and higher average annual temperature are bigger in height and diameter than others from occurrence in sites with higher altitude and lower temperature, such as CL (Danner et al., 2010). CL has a Cfb-type climate with severe winters, annual average of 19 °C, because is located at a higher altitude (963 m) than the other study sites, which have Cfa-type climate with mild winters (Alvares et al., 2013). Instead, the PB site is at the lowest altitude (713 m), annual average of 21 °C, explaining the greater tree rate growth observed. Ricken et al. (2022) also observed that in higher altitudes *Araucaria angustifolia* trees reached growth stagnation stage earlier. Furthermore, the lower jaboticaba tree density (40.6 trees ha^{-1}) were probably partially responsible for the greater growth in PB compared to CH, CL, and VT sites, with 59.6, 75.6, and 45.8 jaboticaba tree ha^{-1}, respectively (Danner et al., 2010).

Furthermore, the union of two trunks were detected in the majority (66%) of the sampled jaboticaba trees, which is not yet documented in the *Plinia* genus species. It is believed that the double piths are caused by the union of two seedlings of the jaboticaba tree. This could happen due to the deposition of many seeds in the same place, because each jaboticaba fruit have two to four seeds, or even by the origin of seedlings of the same seed, since the jaboticaba tree has polyembryonic seeds (Danner et al., 2011).

The tree age estimate using DBH of trees is expected, when growth models are adjusted (Burkhart and Tomé, 2012). We showed that the diameter of *Plinia peruviana* can be used to estimate age, but if the trunk is fused, it should be considered as two trees, and then, this characteristic must be considered in the data analysis to avoid overestimating tree age. Calculating their age from their diameter would yield approximately twice their actual age, leading to an erroneous interpretation of the population age structure. Therefore, this trait of *Plinia peruviana* should be considered in forest inventories, as it is possible to identify the union of two trunks in the field visually (see Figure 3). Previous forest inventories in the region considered *Plinia peruviana* trees presenting only one trunk, when they were not forked bellow 1.3 m above ground level and, consequently, overestimating the diameter of some trees (Danner et al., 2010). This study of the jaboticaba tree may also serve as a model for other tree species that can generate fused trunks.

Initially, we believed that jaboticaba trees with union of two trunks might show slower diametric increase due to competition between them. However, there was no lower growth rates of trees with double piths when compared to single pith ones (see Figure 4). Also, the fusion of trunks by root grafting in *Pinus* has been described as a non-competitive interaction due to the possibility of translocation of water and nutrients between the stems (Bormann, 1966).

The maximum growth series of some jaboticaba trees reached over 100 years of age (see Table 1) at DBH (1.30 m above ground level), in CH, PB, and VT. As these are locations with a high density of the species (> 40 trees ha^{-1}), instead in Irati, other region of Paraná, the density was 1.56 jaboticaba trees ha^{-1} (Roik et al., 2019), this may indicate anthropogenic intervention in establishing these populations. The influence of indigenous people leading to more spread and density of useful and edible fruit species in Brazil has been recently demonstrated (Andrade et al., 2019; Caetano-Andrade et al., 2020; Cruz et al., 2020). Indigenous people's ancient action is associated with 41% of wild fruit species and 71% of commercial fruit species in Latin America (Van Zonneveld et al., 2018).

The historical information reinforces our hypothesis that the "jaboticabais" may have shaped in clusters or stands by the ancient Amerindians in southwest of Paraná. The more than centenary jaboticaba trees would have been established before year 1,900, a time compatible with the Kaingang indigenous population's trajectory from Paraná to the west of Santa Catarina and the Rio Grande do Sul states, located further south of Brazil, passing and settling temporarily in Southwest of Paraná (Wachowicz, 1985). The jaboticaba tree orchard in CL presented trees with a maximum age of fewer than 80 years. This implying that their establishment may have occurred through interventions by other human groups, the "caboclos" that inhabited temporarily in Southwest of Paraná between 1900-1940, before the colonization by the descendants of early European settlers (Wachowicz, 1985). Further deeper studies are necessary to confirm this hypothesis of anthopogenic action in "jaboticabais", such as archaeological analyzes to reach solid conclusions (Cruz et al., 2020).

The general equation adjusted with the data from all "jaboticabais", using the Monomolecular model, showed a good fit, $R^2 = 0.73$ (Supplementary Material Table S2). Since studies aimed at modeling the growth of jaboticaba trees requires laboratory infrastructure, the general equation described in this work can estimate the growth of the jaboticabais that do not have a specifically developed equation. However, it should be emphasized that predicting growth based on a single equation using data from trees with different management histories tends to underestimate the growth in diameter (Kiernan et al., 2008). This reinforces the importance of developing growth models by location, understanding the environmental and human effects on growth dynamics, and planning the commercial use and conservation of these species.

5. Conclusion

The present study provides data to understanding the growth of jaboticaba trees will help in sustainable management plans and should consider the slow growth of the species to guarantee the regeneration and recruitment between diametric classes. Furthermore, growth-rings provided the discovery of jaboticaba trees with fused trunks and double piths, changing the way the population structure, age, and growth rate is interpreted or cause an overestimate of growth, requiring the identification of this characteristic in field diameter measurements.

The possibility that these jaboticabais have an anthropogenic origin, due to our detection of the establishment time, opens opportunities for further studies to confirm this fact.

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Supplementary Material

Supplementary material accompanies this paper.

Table S1. Models tested to adjust the diametric growth of jaboticaba trees (Plinia peruviana) in four sites in Southwest of Paraná.

Table S2. Statistical parameters and coefficients of the models for diametric growth of jaboticaba trees (Plinia peruviana) adjusted by sampling location and together.

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