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Growth, volume evolution and assortment of a *Pinus elliottii* Engelm. stand at an advanced age

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FOREST MANAGEMENT

ABSTRACT

Background: This study aimed to recover the silvicultural history of a 58-year-old *Pinus elliottii* stand, monitor its growth rate and volume evolution of assortments, especially in the older tree ages. Methods: The study area is located in the Três Barras National Forest, SC, Brazil, and composed of four stands established in 1963, totaling an area of 8.95 ha. The studied stand was subjected to 4 mixed thinnings at 6, 14, 23 and 36 years of age, with the latter in 1999, and since then they have not undergone any further intervention. A census of the stands was conducted in 2013 and 2021; increment cores of 33 trees were collected in the four stands in 2021. A retrospective analysis and estimation of DBHs were performed in the years in which thinning was performed, hypsometric estimates were made, volume and assortment were calculated at the ages of the interventions using equations available in the literature.

Results: A reduction in diameter growth and stabilized height growth of trees was observed after 36 years, the date of the last thinning. Even so, it was found that 78% of the volumes at 50 years were of the most valuable assortment and 83% at 58 years.

Conclusion: There is a need for an economic, sensitivity and risk assessment to assess and identify the viability of long-term planting, especially the optimal age to balance wood production and proportion from the most valuable assortments in the shortest time.

Keywords: Long rotation forest management; Forest modeling; Multiproducts.

HIGHLIGHTS

The development of *Pinus elliottii* was evaluated over 58 years.
A reduction in diameter growth and stabilization of height growth of trees was observed after 36 years.
78% of volumes at 50 years are of more valuable assortment and 83% at 58 years.

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INTRODUCTION

Despite a history marked by the irrational exploitation of its natural resources, most of Brazil's territory is covered by forests, mostly native ones, which are suffering from increasing deforestation rates, causing severe consequences for the climate and the maintenance of species. Given the need to conserve native forests and the increased demand for timber products, planted forests are a very efficient alternative for combining production and preservation. The *Pinus* genus, which was introduced into the country in the 1940s and has excellent growth in the southern region, is one of the most planted species in Brazil, accounting for 19% of a total of 10.2 million hectares of planted forests in the country (Ibá, 2024). Pine wood is versatile, serving as a raw material for manufacturing various by-products, such as sawn timber, panels, plywood, energy biomass, paper and pulp, and can have a much wider range of applications (Ibá, 2024).

There is an increase in the productivity of Brazilian planted forests, driven by both technological development and the favorable soil and climate conditions available in the country. Demand for materials from forests is growing, both in domestic and foreign markets, which makes the development of forest plantations attractive in terms of investment (Moreira et al., 2014). There is also a requirement for improved wood quality so that wood products can gain market share (Pereira and Tomaselli, 2004). Along with the development of silvicultural techniques, longer rotations enable the production of higher-quality logs, suitable for multiple uses (Dobner Júnior et al., 2012).

Quantifying timber potential using information from forest inventories is an important activity in terms of forest production planning (Nakajima et al., 2011). In addition to knowing the stock, it is necessary that forest management be appropriate to the final use objectives of the wood or other by-products from the time of its establishment. Furthermore, performing the correct cultural treatments during its cycle and determining the most appropriate technical rotation time for the final objective, as well as quantifying the potential evolution of the assortments and financial yield over the years, is essential (Dobner Júnior and Quadros, 2019).

The *Pinus* spp. plantations in the Três Barras National Forest were established in the 1960s and were mostly managed through selective and systematic thinning until the end of the 1990s, with no further interventions since then. There are currently approximately 150 to 200 trees per hectare in many stands, with many trees measuring over 40 m in height and over 50 cm in diameter (ICMBio, 2016).

The objective of this study is to evaluate the stock volume production and evolution of assortments in a *Pinus elliottii* Engelm. stand established in 1963 and subjected to four thinnings until the end of the 1990s and has remained unmanaged since then. The basal area development, the most valuable assortments, the individual volume, volume per hectare and evolution of the standing stock over the years were evaluated. The forest analyzed is 58 years old and it was possible to survey the history of interventions throughout the entire production cycle, making it a rare and valuable database for managing forest plantations, as it tracks various tree development phases far beyond the typical ages managed by most forestry companies in Brazil. The proposed hypothesis is that, despite its advanced age, the forest still exhibits growth and gradually increases the proportion of high-value timber assortments over time.

MATERIALS AND METHODS

Study area

The present study was conducted in the Três Barras National Forest (FLONA), currently managed by the Chico Mendes Institute for Biodiversity Conservation (ICMBio**)**. The Três Barras FLONA is located in the Northern Plateau of Santa Catarina, in a Mixed Ombrophilous Forest region, with altitudes ranging from 730 to 800 meters, occupying an area of 4,459 ha, with vegetation cover consisting of Mixed Ombrophilous Montane Forest, riparian forests, floodplains, and reforestation fragments of *Pinus spp.*, *Araucaria angustifolia* (Bert.) O. Ktze, *Eucalyptus spp.*, and *Ilex paraguariensis* St. Hil. (Kloc et al., 2019).

The data used were obtained from four *Pinus elliottii* Engelm. stands planted with an initial spacing of 2 × 2 m (2,500 trees per hectare). The total planting area of the species is 8.95 hectares, divided as follows: stand 55 with an area of 3.72 ha; stand 52 with an area of 2.48 ha; stand 51 with an area of 1.33 ha; and stand 50 with an area of 1.42 ha (Figure 1). These stands are part of FLONA's base project for exploring exotic species, as approved in its management plan, and are designated as priority areas for clear-cutting and the future installation of experiments.

Stand history

According to the history obtained from the conservation unit's management files, the stands were established in 1963 and underwent four thinnings: the first in 1969, the second in 1977, the third in 1986, and the last thinning in 1999, when the forest was 36 years old and had not undergone any other intervention since then. These thinnings were performed in a mixed manner, meaning both selectively and systematically, with an intensity of approximately 50% of the trees.

A census of the individuals present in the stands was conducted in 2013, measuring all DBHs (diameters measured at 1.30 m from the ground) and tagging the trees with metal plates. In addition, the heights of approximately 10% of the total number of trees were measured, and rigorous cubing was performed using the relative Hohenadl method, with 10 sections of 23 individuals selected in proportion to the diameter distribution of the forest.

The second census, carried out in 2021, followed the same procedures as in 2013, with the addition of eight more trees in the cubing. In addition to measuring dendrometric variables and subsequently extrapolating the averages per hectare for each stand**,** the basal area, number of trees per unit area, mean diameter, quadratic mean diameter, annual periodic increment (for all variables studied), and mortality rate of individuals were estimated.

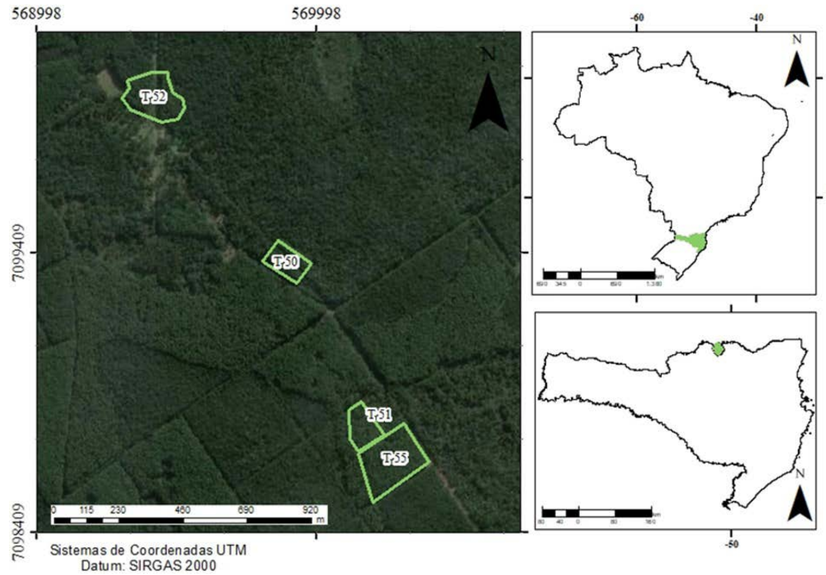


Figure 1: Location map of the study area in the northern plateau of Santa Catarina and delimitation of the four studied stands.

Then, increment cores were collected from 30 trees in stand 55 in 2021, with the individuals sampled in proportion to the diameter distribution of the forest. The diameter distribution was constructed using 5-centimeter class intervals, with the smallest class center at 37.5 cm and the largest at 102.5 cm. The highest number of trees from which increment cores were taken was in the class centers of 57.5 cm and 62.5 cm (central classes), with eight trees in each. In the class centers of 52.5 cm and 67.5 cm, five trees were sampled in each, and in the class centers of 42.5 cm, 72.5 cm, and 102.5 cm, one tree was sampled in each.

In addition to these, one tree with average quadratic diameter was sampled from each of the other three inventoried stands, totaling a sample of 33 trees. Increment cores were collected to perform partial trunk analysis using a Pressler borer, removing 3 increment cores from their circumference. The increment cores are small, non-destructive samples in which it is possible to visualize the growth rings, thus reconstructing past growth and inferring future growth trends of these individuals.

Next, the increment core samples were fixed to wooden supports and sanded with 100 and 180 grit/cm^2 abrasive paper. The samples were subsequently scanned with a professional scanner at 1200 dpi resolution and measured using the IMAGE PRO PLUS application. The software assists in counting the growth rings of the increment cores, measuring the thickness of spring and autumn growth rings by calculating the distances in centimeters.

Data modeling

DBH reconstitution

Estimates of the diameters for the ages at which the thinnings were performed (6, 14, 23 and 36 years) and the censuses (50 and 58 years) were made from the data obtained through partial trunk analysis, based on the diameter's averages reconstructed for each age during the partial trunk analysis.

Hypsometric estimation

Estimates of the total heights of the trees were made from the average diameters determined for each age of interest based on equations available in the literature, seeking equal or similar ages, preferably for *Pinus elliottii*, or in its absence, for other species of the *Pinus* genus. The Assmann hypsometric equation was used for the age of 6 years, fitted by Nicoletti et al. (2016) in their study with *P. taeda* in a commercial stand with different ages located in Ponte Alta do Norte, SC, Brazil, with the equation in question developed for 7 years.

The estimate for the age of 14 years was made using an equation developed by Souza et al. (2018) for a 15-year-old *Pinus elliottii* forest located in the municipality of Cerro Negro, SC, Brazil. The equation used for ages 23 and 36 was developed by Lavrini et al. (2022) in their study of *Pinus taeda* in three different locations: Cambará do Sul, RS; Otacílio Costa, SC; and São Francisco de Paula, RS (all in Brazil). Finally, the equation used for ages 50 and 58 was derived from the census conducted in the same population in 2021, at age 58. Table 1 describes the models used to estimate heights at each age, as well as their parameters.

Volume and tapering

Estimates of the number of logs and total volumes for calculating the assortments were made using volume equations or integrated taper functions organized by Figueiredo Filho et al. (2014). Only the total volume estimate was made for the age of 6 years, since there is still little differentiation among the assortments at this stage of development. The volumetric model chosen was the Modified Meyer model (1), developed by Wendling (1978) for a *Pinus elliottii* stand in the municipality of Curitibanos, SC, Brazil:

$$v = \beta_0 + \beta_1 DBH + \beta_2 DBH^2 + \beta_3 (DBH.h) + \beta_4 (DBH^2.h) \quad (1)$$

The tapering model used at the ages of 15 and 23 years was the Kozak 2nd Degree Polynomial (2) fitted by TÉO et al. (2013) in a *P. elliottii* population aged 18 years in the municipality of Caçador, SC, Brazil:

$$\left(\frac{di}{DBH}\right)^2 = \beta_0 + \beta_1\left(\frac{hi}{h}\right) + \beta_2\left(\frac{hi}{h}\right)^2 \quad (2)$$

The model used at the age of 36 was the Fifth Degree Polynomial (3) fitted by Vivian et al. (2022) in a 43-year-old *P. taeda* plantation, located in the municipality of Correia Pinto, SC, Brazil:

$$\frac{di}{DBH} = \beta_0 + \beta_1\left(\frac{hi}{h}\right) + \beta_2\left(\frac{hi}{h}\right)^2 + \beta_3\left(\frac{hi}{h}\right)^3 + +\beta_4\left(\frac{hi}{h}\right)^4 + \beta_5\left(\frac{hi}{h}\right)^5 \quad (3)$$

Next, data from cubing performed in 2013 and 2021 were used for ages 50 and 58 to fit the Kozak second-degree taper function (2). Table 2 describes the parameters and coefficients of the equations.

The number of logs and volume generated in each of the classes, the stump height as 10 centimeters and the length of each log as 2.6 m were considered for the assortment analysis. Their classification was considered based on the diameter at the thin end as follows: Class I - diameter at the thin end greater than 35 cm; Class II - diameter at the thin end between 25 and 34.9 cm; Class III - diameter at the thin end between 18 and 24.9 cm; and Class IV - diameter at the thin end from 8 to 17.9 cm.

The Bartlett test for homogeneity of variances and analysis of variance (ANOVA) were performed for the variables N, G, V, and dg obtained at ages 50 and 58, aiming to verify whether the analyzed variables are statistically equal with 95% confidence.

RESULTS

Diametric and hypsometric estimates

The values of these variables can be generated for each age of interest from reconstructing the diameter by trunk analysis and hypsometric estimates (Figure 2).

In their study with *P. taeda* in Ponte Alta do Norte, Brazil, Nicoletti et al. (2016) obtained average values of 18.1 cm in diameter for the age of 7 years, with a maximum of 25.2 cm and a minimum value of 8.9 cm. The average for the age of 6 years in the present study was below that of the studies cited, with 12.5 cm, which can be justified by the high density of individuals in the forest, thus hindering diameter development and growth.

Table 1: Models, coefficients and statistical indicators of goodness-of-fit are presented for each estimated age. For age 6, data were obtained from Nicoletti et al. (2016); for age 14, from Souza et al. (2018); for ages 23 and 36, from Lavrini et al. (2022); and for ages 50 and 58, from the equation fitted to the population census data.

Age (years)	Model	β_0	β_1	β_2	Syx%	R² Adjusted
6	$h = \beta_0 + \beta_1 \frac{1}{DBH}$	15.76	-86.51	-	8.05	0.431
14	$h = \beta_0 + \beta_1 DAP + \beta_2 DBH^2$	14.96	0.22	-0.001	6.66	0.962
23 and 36	$lnh = \beta_0 + \beta_1 lnln(DBH)$	-0.35	0.95	-	6.01	0.828
50 and 58	$h = \beta_0 + \beta_1 DBH$	35.24	0.07	-	8.47	0.408

In which: h = Total height, in meters; DBH = Diameter at 1.3 m above the ground, in centimeters. Syx% = Standard error of the estimate, in percentage; Adjusted R² = Adjusted coefficient of determination; ln = Neperian logarithm.

Table 2: Parameters and statistics of volumetric models or tapering equations at the ages worked.

Age	β_0	β_1	β_2	β_3	β_4	β_5	Syx%	R² Adjusted
6	-0.02	0.005	-0.0002	-1E-04	0.0001	-	10.67	0.983
14 and 23	0.95	-1.35	0.38	-	-	-	11.5	0.911
36	1.13	-3.11	12.87	-25.27	21.16	-6.58	6.7	0.950
50 and 58	0.94	-0.68	-0.28	-	-	-	11.4	0.892

In which: Syx%= standard error of the estimate, in percentage; R² = coefficient of determination.

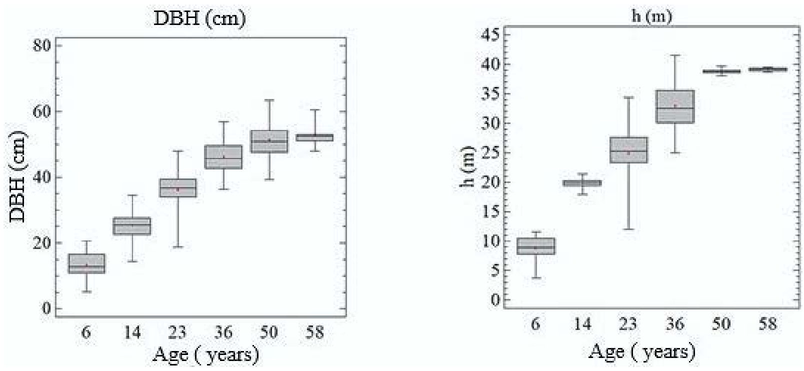


Figure 2: Evolution of average diameters (cm) and heights (m) for the ages studied.

The average found by Nicoletti et al. (2022) was 26.2 cm in a *Pinus elliottii* stand at 14 years of age in Correia Pinto, SC, Brazil, which was subjected to thinning in the 11th year. This average value is very close to that estimated in the present study, which was 26.6 cm. Fockink et al. (2023) obtained DBH values ranging from 36.9 cm to 43.1 cm, with an average of 38.6 cm in their study with *Pinus* sp. unmanaged at 45 years of age in the municipality of Santa Maria, RS, Brazil. This constitutes an average of more than 10 cm lower that found in the present study, which can be easily justified by the absence of thinning compared to the 4 interventions carried out up to the 40th year.

Other information was the number of trees per hectare of the forest at the ages at which the stand underwent intervention before and after thinning, and the basal area of the stand before and after thinning (Figure 3)

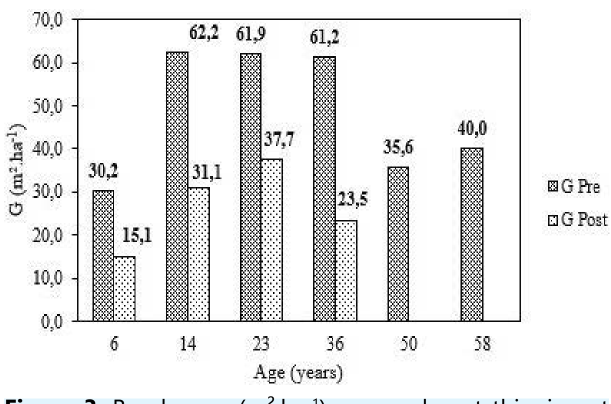


Figure 3: Basal areas (m^2.ha^{-1}) pre- and post-thinning at each thinning age and in the censuses at 50 and 58 years.

Figure 4 describes the main information obtained in 2013 and 2021 when the forest was 50 and 58 years old, respectively. The p-values of the Bartlett test for the variables N, G, V, and dg were 0.9393, 0.8832, 0.3787, and 0.5704, respectively, while the p-values of the ANOVA were 0.8320, 0.3047, 0.0547, and 0.0549, respectively, indicating homogeneity of variances and statistically equal averages at a 95% confidence level.

Volume and assortments

Figure 5 describes the mean individual volume values at each age studied, in addition to an extrapolation of this volume considering the number of trees per hectare in each year.

Figure 6a shows the wood volume per hectare divided into assortment classes for the ages studied. Figure 6b shows the standing stock of wood after thinning for each age evaluated, the accumulated harvested wood volume at each age and the total production (accumulated harvested volume + standing stock). The values highlighted in the labels of Figure 6 represent the absolute quantities expressed in the measurement unit of the explored variable.

DISCUSSION

The intensity of the first two thinnings in the stand under study was 50%; then, 39% of the volume was removed during the third thinning, and finally, 55% was removed in the last intervention. According to Mainardi et al. (1996), the ideal basal area value for intervention in a *Pinus* forest is around 40 m^2 ha^{-1} in order to obtain a value without competition of 25 m^2 ha^{-1}. Thus, it can be assessed that the thinning which occurred at 6 years of age of the forest was early and of high intensity. On the other hand, the following thinnings occurred at appropriate times or even later than the recommended time, and may even have been performed with greater intensity.

It is observed also that even though there was an increase in the basal area in the periods from 2013 to 2021 (50 to 58 years of age), the growth rate was much lower than that obtained at the date of the last thinning (at 36 years of age). This information can be an important guide for assessing the economic viability of future projects aiming at a long rotation period, as the vigor of the trees and the forest does not respond in the same way after 36 years.

No outliers were observed in the diagrams of the variables under study, and an average increase of 0.6 m^2.ha.year^{-1} and 14.4 m^3.ha.year^{-1} was observed due to the differences between the G and V variables between the two measurements, respectively, highlighting that this increase occurs between the ages of 50 and 58 years of the forest. According to Ibá (2024), the average productivity of *Pinus* spp. in Brazil is 30.9 m^3 ha year^{-1} considering average rotations of 16.3 years, and that the values observed in this study with old trees are compatible with averages of countries such as the United States (14 m^3 ha year^{-1}) and Chile (18 m^3 ha year^{-1}).

The decrease in the number of trees per hectare from one census to another is due to the mortality of individuals in the population, which can be caused by competition, age, genetic factors, or senescence (Dobbertin and Biging, 1998). It is worth noting that this loss of trees in both periods represents 4.9% of the remaining trees in the stand. According to Zhao et al. (2007), the probability of survival decreases with increasing forest age (Ryu et al., 2024) due to reduced physiological vigor, lower capacity to respond to environmental stresses, and the accumulation of damage over time. In other words, as the forest grows over the years, the space available for development decreases, leading to greater competition among individuals until a stage is reached where natural mortality begins, characterizing natural thinning (self-thinning) (Schneider et al., 2008). This pattern is consistent with that observed by Ryan and Yoder (1997), who highlight that, in more advanced stages of development, larger individuals face water and energy constraints, becoming more susceptible to mortality caused by drought, competition, or biotic agents, especially considering that the Pinus elliottii trees evaluated were between 50 and 58 years old — an advanced age range for commercial plantations of the species in Brazil.

Despite the decrease in the number of individuals per hectare, the basal area, which is one of the most useful parameters for controlling thinning and describing a stand, increased during the period. When associated with stand age, the basal area variable provides data such as the forest stagnation point, the maximum growth point of the species as a function of the site and/or spacing (Finger, 1992).

The mean quadratic diameter (dg), as well as the volume per hectare, also increased considerably during the period between the two censuses, presenting values compatible with those observed by Vivian et al. (2022) in *Pinus taeda* stands which were also old (43 years old) and thinned throughout the rotation.

In evaluating *Pinus taeda* stands in the south-central region of the Paraná state and in the mountainous region of the Santa Catarina state, Kohler et al. (2015) found an average volume per tree of 1.157 m^3 for the stand in Paraná and 0.959 m^3 for the stand in Santa Catarina at 18 years of age, constituting higher values than those found in the present study at both 15 and 23 years of age. Oliveira and Mayrinck (2021) found an individual volume between 0.1223 m^3 and 1.1508 m^3 in their comparison of plantings with different spacings in an experimental *P. taeda* stand at 17 years of age in Irati, Paraná; the values found in the present study are within this range from 6 to 23 years.

Cruz et al. (2023) observed a volume per hectare of 622.2 m^3 ha^{-1} in a treatment with higher-intensity thinning and 1,160.2 m^3 ha^{-1} in a treatment without thinning in their study evaluating different thinning intensities in a 37-year-old *P. taeda* plantation in the municipality of Campo Belo do Sul, SC, Brazil. The volume in the higher-intensity thinning case is between that found in the present study for ages between 36 and 45 years. It is worth noting that although denser stands represent a higher basal area value and consequently volume, stands with thinning have larger trees at older ages, which represents greater added value in the timber.

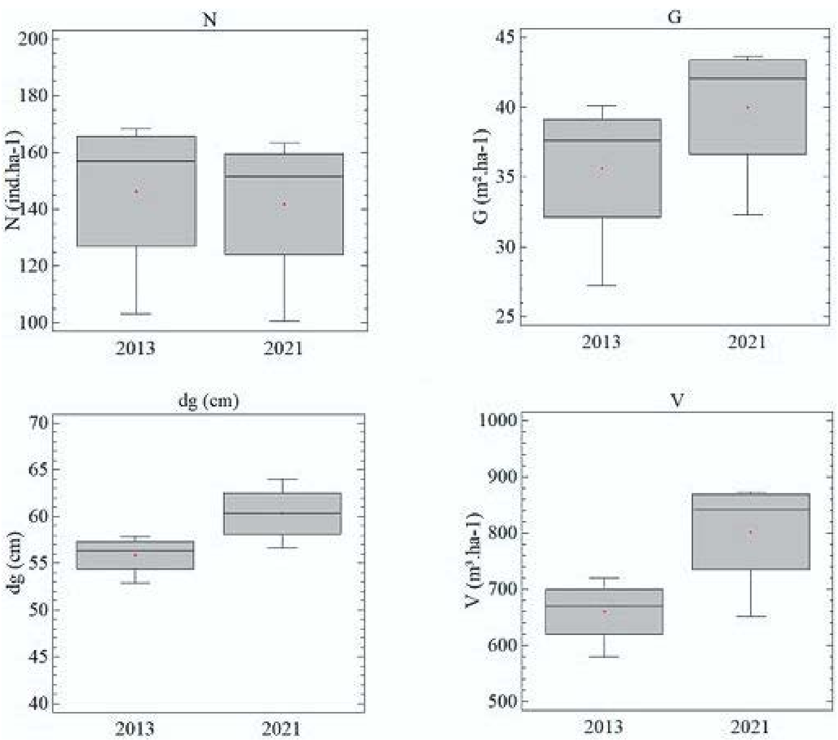


Figure 4: Boxplots of number of trees per hectare (N), basal area per hectare (G), quadratic diameter (dg) and volume per hectare (V) from the censuses of the years 2013 and 2021, when the forest was, respectively, 50 and 58 years old.

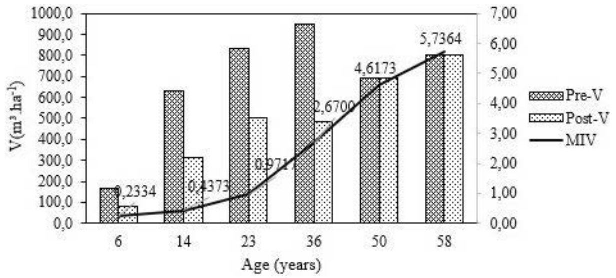
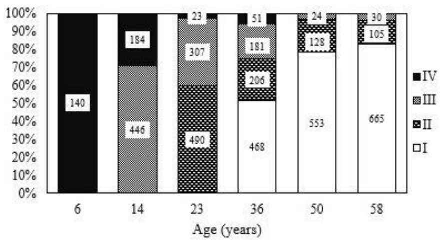
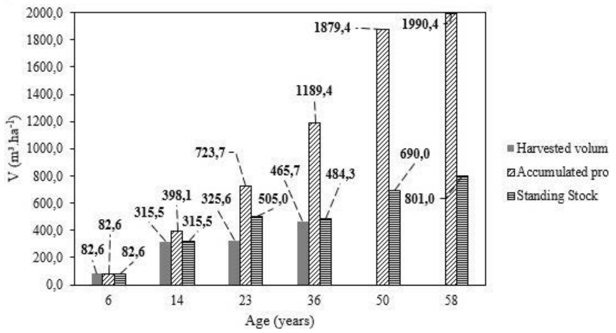


Figure 5: Mean individual volumes (MIV) in m^3 and per hectare pre- and post-thinning at each of the thinning ages and in the censuses at 50 and 58 years.



(a)



(b)

Figure 6: Standing timber stock in the forest: (a) in volume per hectare before thinning and (b) evolution of standing volume, harvested volume and accumulated production (harvested volume + standing stock) at the ages of interventions and in the censuses at 50 and 58 years. Where: Assortment classes were defined based on the small-end diameter of 2.6-meter-long logs, as follows: Class I – small-end diameter greater than 35 cm; Class II – small-end diameter between 25.0 and 34.9 cm; Class III – small-end diameter between 18.0 and 24.9 cm; Class IV – small-end diameter from 8.0 to 17.9 cm.

Vivian et al. (2022) obtained an average individual volume of 6 m^3 studying a *P. taeda* stand at 43 years of age with five thinnings in Correia Pinto, SC, Brazil, which is a higher value than that found in the present study at 48 and 50 years of age; however, the density obtained by this author is very similar to our study, with 165 individuals per hectare.

The forest structure and the relationship of the timber volume in each assortment class are modified as the number of trees per hectare is reduced due to thinnings. The volume increases in classes I and II from 36 years of age, which is the last age at which the forest underwent intervention. These classes are nobler, and therefore have greater added value. According to Schneider and Finger (1999), thinning has the purpose of increasing the commercial productivity of the assortments by increasing the log size, targeting more noble markets.

It is possible to observe that the assortments which become more representative throughout the forest development and with the establishment of thinning are those with greater added value. Logs appear in assortment I at 36 years old, since according to Dobner Júnior and Quadros (2019), trees aged 30 years represent 30% of the total volumes up to a height of 6 m (17% of the total height), which represents 50% of the total stand revenue. Assortment IV is highly representative at 14 years old and decreases until 36 years old, when the majority of the trunks of individuals are in class I.

In a study conducted by Dobner Junior (2014) in a 30-year-old *Pinus taeda* stand, it was also found that the interventions positively influenced diametric growth, a variable which that has a very high correlation with volume. In a study with *P. elliottii* at nine years of age in Capão Bonito, SP, Brazil, evaluating treatments with different thinned volume percentages (25%, 50%, 75%, and the control without thinning), Pereira and Tomaselli (2004) consider that the increase in thinning intensity has little effect on the wood properties. Therefore, the parameters to be considered when deciding on the thinning intensity should be of an economic and productive nature.

Studies that can evaluate the economic potential of these long-term forests are desirable and encouraged, because even though more than 80% of the volume is in the highest value-added assortment class at 58 years of age, it is necessary to verify whether this production is economically viable, in addition to identifying sensitivity factors (Dzotsi et al., 2013), considering the long-term investment and the possibility of changes in production costs over the planning horizon (Neto et al., 2020).

It can be seen that the accumulated production in the forest (volume harvested during thinning + standing stock) after 58 years generated an equivalent of 1,990.36 m^3 ha^{-1}. With this amount, an average annual increase of 34.3 m^3 ha year^{-1} can be determined, which is compatible with the information available in the statistical yearbooks of the Ibá (2024).

It is important to highlight that the hypsometric, volumetric, and assortment estimates for the ages of 6, 14, 23, and 36 years were derived from equations available in the literature. The transfer of hypsometric and taper functions developed for other species, geographic regions, or age classes is a common approach, particularly in the absence of local data to develop new models (Zianis et al., 2005). However, environmental, morphological, and ontogenetic differences may impair the accuracy and applicability of these models when extrapolated to different contexts (Bontemps and Bouriaud, 2014; Parresol, 1999). While this methodology enables the conservation of time and resources by capitalizing on the statistical robustness of previously calibrated models (Pretzsch, 2009), it is critical to acknowledge that mature trees exhibit growth dynamics distinct from juvenile phases, potentially introducing bias into the estimates. Consequently, efforts were made to ensure regional and age-class similarity among the sampled trees for the estimation process, accompanied by a rigorous critical evaluation of the estimates against findings reported in the extant literature.

CONCLUSION

A reduction in diameter growth and height stabilization was observed after 36 years, coinciding with the last thinning. The production of the highest-value assortment (diameter > 35 cm) began after this age, representing 40% of the total volume per hectare. At 50 and 58 years, this assortment accounted for 78% and 83% of the volume, respectively, despite no statistically significant differences being observed in the main dendrometric variables between these two ages.

If the management objective is the production of higher value-added timber, it is recommended to adopt long rotations, exceeding 36 years, combined with specific guidelines regarding the intensity and schedule of thinnings — or alternatively, the use of optimal basal area ranges — to promote individual growth and wood quality throughout the production cycle.

An economic, sensitivity and risk assessment is recommended to assess and identify the viability of long-term planting, especially to determine the optimal age that balances production and the proportion of wood from the most valuable assortments in the shortest time, including uncertainties related to prices, costs, inflation, and discount rates.

AUTHORSHIP CONTRIBUTION

Project Idea: GLO; TFS; MFN; MHP; GG; PRCS

Funding: GLO; TFS; MFN; MHP; GG; PRCS

Database: GLO; TFS; MFN; MHP; GG; PRCS

Processing: GLO; TFS; MFN; MHP; GG; PRCS

Analysis: GLO; TFS; MFN; MHP; GG; PRCS

Writing: GLO; TFS; MFN; MHP; GG; PRCS

Review: GLO; TFS; MFN; MHP; GG; PRCS

DATA AVAILABILITY

The datasets supporting the conclusions are included in the article.

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