TreeDimensional Journal, Vol. 15, e0250047, 2025
Original Article | DOI: doi.org/10.55746/treed.2025.04.0047

Diameter Growth in Mixed-Age Plantation of *Araucaria angustifolia*

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Abstract
This study aims to evaluate the diameter growth of a mixed-aged plantation of *Araucaria angustifolia* (Bertol.) Kuntze (Brazilian pine), located in the municipality of Ivaí, Paraná, through partial stem analysis using increment cores. The study stand covers approximately 41.5 hectares and is managed under a multi-strata system, where the canopy is composed of *Araucaria angustifolia* intercropped with a commercial plantation of *Ilex paraguariensis* St. Hil. (yerba mate). For the analyses, 30 trees were selected, from which two increment cores were collected using a Pressler borer. These cores were later processed and digitized to allow for measurement of the growth rings. Based on the compiled data, growth and yield functions by Chapman-Richards (C-R) and Schumacher (SCH) were fitted to assess growth trends over time, using the Current Annual Increment (CAI) as a reference. The average CAI was then correlated with meteorological variables, including temperature, precipitation, and hours of sunlight. The *Araucaria angustifolia* stand showed ages ranging from 25 to 50 years, with an average diameter of 38.5 cm. The Chapman-Richards model provided the best fit to the dataset, allowing for the technical cutting age to be estimated at 14 years, when average diameters of 24.4 cm could be obtained. It was found that diameter growth over time was not correlated with local climate data.

Keywords
Diameter Growth — Brazilian Pine — Forest Management — Southern Brazil.

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1. Introduction

The Mixed Ombrophilous Forest (MOF) is a phytophysiognomy belonging to the Atlantic Forest Biome, one of Brazil's main biomes, which originally covered an area of 200,000 km². This forest formation, also known as Araucaria Forest, is distinguished from others by the prominent presence of the Brazilian pine – *Araucaria angustifolia* (Bertol.) Kuntze (IBGE, 1990).

Although these forests have been altered, they hold high ecological importance due to their rapid growth and accumulation of atmospheric carbon, erosion control, nutrient conservation, hydrological benefits, and the maintenance of residual and migratory biodiversity, according to Pereira and Vieira (2001). In addition, they function as stepping-stones or forest corridors, connecting fragmented areas (Silva et al., 2012).

According to Dalla Côrte et al. (2007), the Mixed Ombrophilous Forest (MOF) is a very important forest formation from a biodiversity perspective. This formation is distributed, according to Roderjan et al. (2002), in the state of Paraná, at altitudes ranging from 500 to 1500 m, with formations at the upper limit of its occurrence being rare.

In addition to the presence of *Araucaria angustifolia*, the forest also includes individuals from the genera *Drymis* and *Podocarpus*, occurring in diverse associations with species from the families Lauraceae, Myrtaceae, Aquifoliaceae, Anacardiaceae, Flacourtiaceae, Euphorbiaceae, and Sapindaceae, among others (Seger et al. 2005). The Atlantic Forest biome, where the MOF is located, has been considered one of the most notable in terms of ecological value, as it shelters typical species and unique biological attributes found nowhere else on the planet (Ziliotto et al. 2004). Similarly, due to its wealth of both timber and non-timber resources, it greatly influenced the development of Southern Brazil from the early 20th century, generating progress and wealth for many

Received: 2024/03/18 | **Accepted:** 2025/04/25 | **Online published:2025/04/31**

cities in the region (Correia et al. 2011).

Another important characteristic of the MOF is the presence of yerba mate (*Ilex paraguariensis* St. Hil.), which is a key species for human populations in its natural occurrence area (Daniel, 2009). It represents a source of work and income for farmers, as well as the generation of jobs throughout its production chain. Yerba mate is a small tree with a short trunk and.

The large area of occurrence of the Araucaria Forest, and consequently the native *I. paraguariensis* stands within it, along with the ease of *I. paraguariensis* exploitation, culminated in the period from 1830 to 1930 in the Yerba Mate Cycle, during which it was one of Brazil's main export products (Gerhardt, 2003). Understanding the *I. paraguariensis* exploitation systems can be an important incentive for the conservation of the Araucaria Forest, as it is a highly profitable activity closely linked to the native forest. According to Souza (1998): “Possibly, native *I. paraguariensis* is one of the most significant types of sustainable exploitation in native forests in Brazil, and undoubtedly the most significant in Ssouthern Brazil.”

The cultivation, harvesting, and consumption of *I. paraguariensis* are practices with cultural and identity significance in the countries of Southern Latin America, from Chile to Brazil. The history of *I. paraguariensis* production and consumption dates back thousands of years. *I. paraguariensis*, a shade-tolerant species, naturally occurs in the understory of the Araucaria Forest (Mixed Ombrophilous Forest - MOF, part of the Atlantic Forest biome), and its cultivation is integrated with natural resource management practices based on traditional ecological knowledge (Nimno et al., 2022). It is precisely the way *I. paraguariensis* is produced in native forests, with associated traditional practices and knowledge, that makes this system unique and of great global relevance, as it is the most important agroforestry system in the Southern Plateau, in the southern region of Brazil (Nogueira; Pereira, 2021).

For the implementation of reliable management plans, it is necessary to understand the growth rate of the species, whether in planted forests or fragments of native forests. Many studies have been conducted with data derived from trunk analysis, whether complete or partial (Finger, 1992). Trunk analysis (ANATRO) is a technique that allows for the recording of a tree's past growth by measuring its growth rings (Husch et al., 1982). In the case of complete ANATRO, the tree is felled, and a specific number of slices are taken along the trunk. When the tree is not felled, and only an increment core is extracted, it is referred to as partial trunk analysis.

According to Wolff II et al. (2019), trunk analysis has been used to obtain data in growth and production modeling studies, as can be observed in several works (Elesbão, 2008; Novaes, 2009; Hess; Schneider, 2010; Sanquetta et al., 2010; Munhoz, 2011; Hess et al., 2015; Lima et al., 2021). Based on the data measured in trunk analysis, it is possible to develop mathematical model adjustments that allow for estimates of forest growth and production (Clutter et al., 1983).

The objective of this study is to evaluate the diameter growth of a multi-aged plantation of *Araucaria angustifolia*, intercropped with *Ilex paraguariensis*, located in the municipality of Ivaí - Paraná, through partial trunk analysis developed in increment cores.

2. Material and Methods

The study area is located in the municipality of Ivaí, Paraná, at 25° 00' 59.54” (South latitude) and 50° 47' 29.87” (West longitude), within a private property (Figure 1). The city of Ivaí – PR is located in a region with a humid subtropical mesothermal climate, classified as Cfb according to Köppen's climate classification, where the average annual temperature ranges from 6.4℃ to 19.2℃ (Alvares et al., 2013), and total annual precipitation can range from 810.9 to 2557.7 mm. It is important to note that the property in question is situated at an average altitude of 850 meters above sea level.

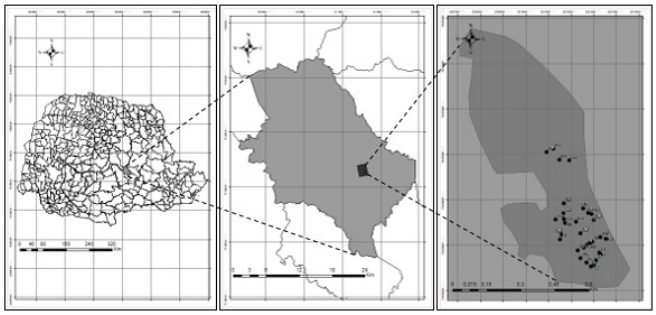


Figure 1. Location of the sampled trees in the private property located in the municipality of Ivaí-PR.

The plantation, the subject of this study, covers a total area of 41.5 hectares (ha), with a multi-strata management regime. The canopy is occupied by *Araucaria angustifolia* and the understory with commercial planting of *Ilex paraguariensis*. The *Araucaria angustifolia* plantation was established after the planting of *Ilex paraguariensis* in two probable planting dates, the first in 1983 and the second in 1993, with the intention of providing shading to improve the development of the *Ilex paraguariensis* crop.

The database for this study comes from a forest inventory of *Araucaria angustifolia* trees conducted in 2022, where dendrometric variables such as diameter at breast height (DBH), height (h), commercial height (hc), and crown diameter (CD) were measured.

Besides these variables, 30 trees were randomly selected in proportion to the diameter distribution of the forest, which were georeferenced, and two increment cores were collected in a non-destructive manner, in orthogonal directions (one in the North-South direction and the other in the East-West direction) using a Pressler borer. The samples were placed on wooden supports, dried in the shade, and later sanded with 125-grit ... sandpaper (grains·cm^{-2}).

Subsequently, the increment cores were digitized using a scanner with a resolution of 1200 dpi and later processed in the Image Pro Plus software to estimate the approximate age of the plantation and measure the growth rings. The software itself is a tool that allows extracting quantitative data from images using a variety of measurement options. In this case, the metrology tool enables measuring lines, arcs, and circles for best fit. After measuring the growth rings, the data were processed by calculating the annual current annual increment (CAI) for each tree and subsequently obtaining the diameter at breast height (DBH), which corresponds to the accumulated increment, and the Mean Annual Increment (MAI).

After the approximate determination of the age of each tree, the data were processed in Excel, where the values of the annual current increment (corresponding to the width of the growth ring) measured for each tree in the study were organized in descending order. With the accumulated annual current increment, it was possible to determine the DBH value for each tree, with the aim of generating a growth curve for the trees, allowing the estimation of the growth of the plantation in question. For this, the Chapman-Richards and Schumacher models were tested (Table 1).

For the selection of the best regression model, the adjustment of each equation was considered through comparison, observing the statistical criteria defined by: coefficient of determination (R^2) and standard error of the estimate (Syx (%)).

Table 1. Tested growth models.

Model	Equation
Chapman-Richards	$DBH = \beta_0(1 - e^{-\beta_1 t})^{\beta_2}$
Schumacher	$DBH = \left(e^{\beta_0 + \frac{\beta_1}{t}}\right)$

In which: $\beta_0, \beta_1, \beta_2$ = coefficients; DBH = diameter at breast height (cm); t = age (years).

Growth estimation graphs for DBH (cm) of the trees as a function of age (years) were also created, which is a simpler analytical tool.

A data crossover of the growth ring width measurements with the historical climate data from the Ivaí – PR region, between 1983 and 2021, provided by the National Institute of Meteorology (INMET, 2023), was carried out with the aim of identifying potential correlations between variables using the Pearson linear correlation coefficient method (p-value ≤ 0.05). The meteorological attributes considered in this study were: sunshine hours, minimum, mean, and maximum temperatures, and accumulated precipitation.

3. Results and Discussion

The *Araucaria angustifolia* stand presents, in 2022, an average DBH of 34.4 cm. The stand has ages ranging from 25 to 50 years, where the dispersion can be identified in the box-plot graph in Figure 2. The graph shows that 50% of the sampled trees are between 28 and 37 years old, with the average age of the stand being approximately 33 years.

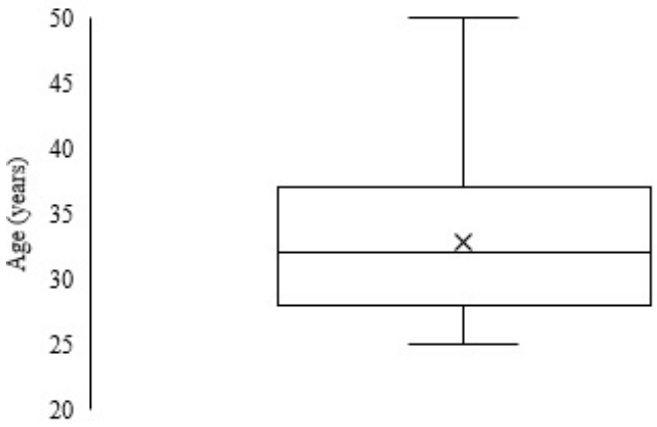
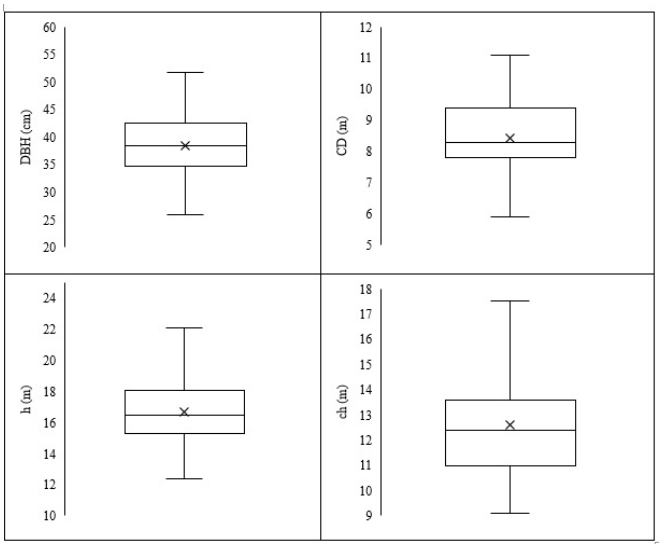


Figure 2. Box-plot of the dispersion of the ages of the evaluated trees, where the 'X' represents the mean.

Figure 3 demonstrates, through box-plot graphs, the dispersion of dendrometric variables such as DBH (cm), Crown Diameter – CD (m), total height – ht (m), and commercial height – ch (m) of the sampled stand.

In relation to the DBH variable, it can be observed that 50% of the diameters collected are between 34.7 and 42.5 cm, with an average of 38.5 cm. For the Crown Diameter (CD) variable, the highest concentration of values was between 7.8 and 9.4 meters, with an average of 8.4 meters. For the total height variable, the highest accumulation of collected data is between the values of 15.3 and 18.1 meters, with an average height of approximately 16.7 meters. In contrast, the commercial height (from the ground to the first live branch, excluding the crown) has a higher grouping of values between 11 and 13.6 meters, with an average of 12.6 meters, and this commercial



In which: DBH = diameter at breast height; CD = crown diameter; h = height; ch = commercial height.

Figure 3. Box-plot of the dispersions of the evaluated dendrometric variables, where the 'X' represents the mean of each variable.

Table 2. Results of the adjustment of the Schumacher and Chapman-Richards models for the variable diameter at breast height — DBH (cm).

Model	Coefficient	Value
Schumacher	R^2	0.8456
	R^2_{adj}	0.8454
	Syx (%)	13.1
	β_0	3.8788
	β_1	-12.1829
	β_2	–
Chapman-Richards	R^2	0.8501
	R^2_{adj}	0.8497
	Syx (%)	12.7
	β_0	37.3780
	β_1	0.0864
	β_2	1.7950

In which: Syx% = standard error of the estimate as a percentage; R^2_{adj} = adjusted coefficient of determination; β_n = model coefficients.

height is the part designated for use, representing the greatest commercial value.

According to the adjustment values obtained (Table 2), the model that performed best for estimating diameter growth was the Chapman-Richards model. According to Silva (1986), the Chapman-Richards model is a nonlinear model widely used to describe phenomena in forest sciences.

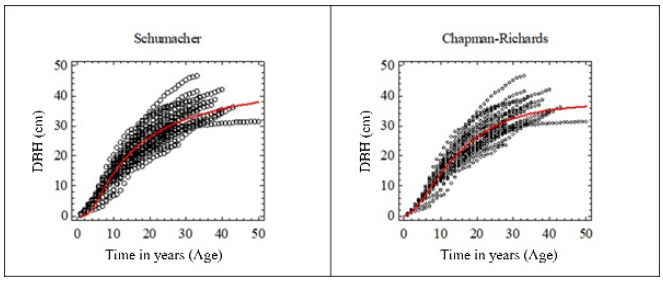


Figure 4. Growth curves obtained for the DBH variable by the Schumacher and Chapman-Richards models.

For the variable in question, DBH, the Chapman-Richards model obtained a standard error of estimate of 12.7%; a coefficient of determination of 0.8501; and an adjusted coefficient of determination of 0.8497. Didoné (2016), in a study conducted using different progenies of *Araucaria angustifolia*, achieved similar values in the adjustment of the Chapman-Richards model for the DBH variable, with values such as 0.78 for the coefficient of determination and 14% for the standard error of estimate.

Graphs were processed representing the average growth curves for the diameter at breast height variable as a function of age (Figure 4).

Through the Schumacher model, it is possible to observe that there is a higher growth vigor until the age of 20, with a slight decrease in the growth rate until the age of 30. It is noted that from 30 to 40 years old, the growth tends to approach an asymptote, which implies the onset of maturity, indicating a lack of significant growth in the following years.

In contrast, in the estimate with the Chapman-Richards model, it can be observed that there is greater and gradual growth vigor until around 22 years of age, followed by slower growth until approximately 32 years of age. Thus, from 32 years onward, growth decreases, with the curve of the graph tending to an asymptote, again indicating a stagnation of growth.

In Figure 5, the curves for Current Annual Increment (CAI), Mean Annual Increment (MAI), and DBH growth as a function of age are shown through the Schumacher model. It can be inferred that the Technical Cutting Age (TCA), or age of stagnation of the growth technique, should occur around 12 years of age of the stand (the intersection of the CAI and MAI curves), resulting in a DBH of approximately 20.3 cm. In contrast, in Figure 6, which shows the CAI, MAI, and DBH growth curves as a function of age for the Chapman-Richards model adjustment, the TCA would be slightly later (14 years of planting), with a diameter of approximately 24.4 cm.

Table 3. Correlation of diameter growth × meteorological data, considering the period from 1983 to 2021.

	Daily Sunshine	Total Precip.	Max Temp.	Mean Temp.	Min Temp.	CAI
Daily Sunshine	1					
Total Precip.	0.13^{ns}	1				
Max Temp.	0.64^{*}	0.40^{ns}	1			
Mean Temp.	0.61^{*}	0.39^{ns}	0.98^{*}	1		
Min Temp.	0.62^{*}	0.54^{*}	0.87^{*}	0.90^{*}	1	
CAI	0.14^{ns}	0.21^{ns}	0.07^{ns}	-0.20^{ns}	-0.07^{ns}	1

In which: ns = not significant; * = significant.

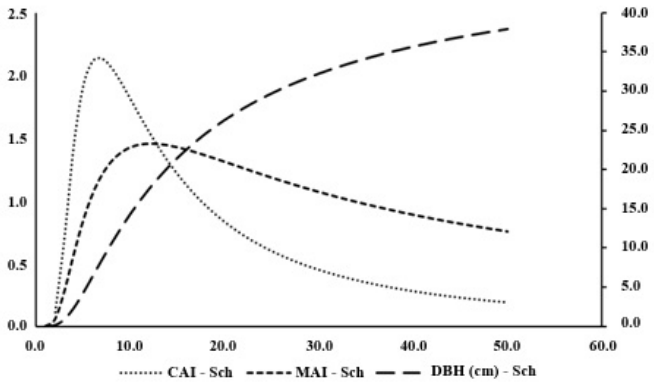


Figure 5. Evolution of the CAI, MAI, and DBH curves as a function of age for the Schumacher model.

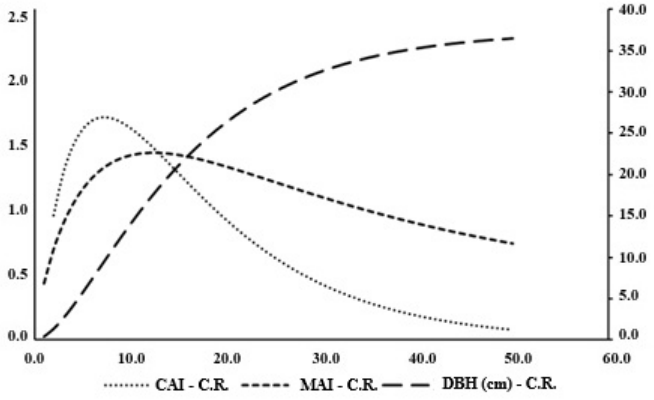


Figure 6. Evolution of the CAI, MAI, and DBH curves as a function of age for the Chapman-Richards model.

According to Campos and Leite (2013), the coefficient B1 of the Schumacher model indicates the age of technical stagnation ($-\beta_1$), which

would be around 12 years, as actually occurred. Another point that can be assessed in agreement with these authors is that the coefficient β_0 of the Chapman-Richards function indicates the maximum value that the variable Y, in this case the DBH, can reach. Therefore, based on the adjusted data, if no intervention is made in the forest, it may reach, at most, 37.4 cm of DBH.

It can be observed, however, in Figure 3, that the average DBH of the forest is 38.5 cm, which is very close to the maximum diameter obtained by fitting the Chapman-Richards model. This shows that the forest is very close to a stagnation in the growth of the DBH variable (Figures 4, 5, and 6), due to the existing competition and primarily the lack of management at the indicated age (approximately 12 years).

In order to obtain the relationship between diameter growth and meteorological data from the city of Ivaí - PR, provided by INMET, with a historical record from 1983 to 2021, it was possible to observe the correlation between the climatic variables and the CAI. The result can be seen in Table 3.

It was observed that the highest correlation found (0.21) was between the CAI and the total annual precipitation. However, as with the other variables analyzed, no significant correlations were found, indicating that the meteorological variables, when considered in isolation, did not influence the growth rate of the stand's trees.

In a similar study, also conducted with *Araucaria angustifolia* plantations in the São Francisco de Paula National Forest, Zanon and Finger (2010) reported that the highest growth increments were associated with higher average monthly temperatures and also with periods of greater precipitation.

4. Conclusion

The stand includes trees ranging from 25 to 50 years old, with an average DBH of 38.5 cm and an average height of approximately 17 m. At least one of the sampled *Araucaria angustifolia* trees was already present before the earliest probable planting date (1983), suggesting it may be a product of natural regeneration from an adjacent forest.

The average measured diameters are close to the asymptotic value indicated by the Chapman-Richards model (38.5 cm), suggesting that the forest is developing with reduced vigor, as the diameter at the age of technical stagnation was 20.3 cm.

In seeking to understand the correlation between diameter growth and meteorological data, it can be inferred that the relationship between the studied variables was weak.

Acknowledgments

No acknowledgments were declared for this work.

Author Statements

- ✓ No conflicts of interest were declared.
- ✓ All existing funding sources were acknowledged.
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