Identification of the Juvenile Wood Transition Age and of Some Growth Characteristics in Plantation *vs*. Native Populations of Cuban *Pinus caribaea* M. var. *caribaea* B&G

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Identifying the transition age between juvenile and mature wood is key for designing more efficient silvicultural strategies and optimizing timber exploitation. The objective of this study was to identify the juvenile wood transition age and analyze certain growth characteristics of Cuban *Pinus caribaea* M. var. *caribaea* B&G by comparing plantation and native populations. Radial variations in growth ring width, latewood proportion, and ultrasonic longitudinal speed were examined to identify the delimitation age from juvenile to mature wood. Visual assessment and statistical analyses, including segmented regression and k-means clustering, were applied. The findings indicated that juvenile wood is formed within the first 5 to 9 years, while mature wood develops after 21 to 26 years. Plantation trees exhibited higher variability and a wider juvenile wood zone (60 mm from the pith) than native trees (43 mm). The mean growth ring in the mature wood was 3.14 mm in native and 3.67 mm in plantation. The latewood proportion stabilized above 50% beyond the transition age, confirming the shift to mature wood, trees from native population developing 22% more latewood than trees from plantation. The ultrasonic speed pattern was similar between populations, validating its use as an indirect indicator of wood maturation.

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INTRODUCTION

Species of the Pinaceae family, especially those of the genus *Pinus*, are among the most widely used conifers worldwide due to their rapid growth and wood quality (Loiola *et al*. 2021). *Pinus caribaea* Morelet has been widely established in commercial plantations and can now be found on four continents (Berlyn *et al*. 1991). In 1962, Barrett and Golfari classified this species into three varieties: *caribaea*, *bahamensis*, and *hondurensis* (IPNI 2019), differentiated by DNA content, habitat, seed size and needle morphology (Kronka *et al*. 2005; Iwakiri *et al*. 2010).

The variety *hondurensis* is the one that has spread the most to other areas outside its natural distribution, and in countries such as Queensland, Australia, Brazil, the Fiji Islands, and Venezuela; it has become a species of great commercial importance among the three (Moura and Dvorak 2001). This has also determined that it has been the subject of more research on different ecological and genetic aspects and properties of its wood (Cown 1981; Boschiero and Tomazello-Filho 2012; Coneglian *et al*. 2017; Gonçalez *et al*. 2018; Márquez-Carrero *et al*. 2022).

However, a limited number of publications can be found on var. *caribaea*, which is endemic to Cuba (Berlyn *et al*. 1991), where it was restricted to Pinar del Río and Isla de la Juventud (Farjon and Styles 1997). It is the one that contributes the greatest volume to the Cuban forest industry (Ibañez-Drake *et al*. 2005). In the 1960s, it was introduced in other regions of the country as part of a provenance and progeny testing program (Geada *et al*. 2017). Its excellent adaptation and development in certain areas of the central region have made it the species of choice for reforestation and forest harvesting plans. Nevertheless, no comprehensive research has been developed regarding the behavior of the physical-mechanical properties, anatomical structure, and chemical composition of its wood in these plantations, nor have the variations that these properties may perform concerning native populations been evaluated. Studies of this type have only been published by Plumptre (1984), in which relevant information has been presented; yet, after those studies, not all aspects related to the subject have been systematically addressed, so that at present there is still a lack of information.

Wood characteristics are the result of growth processes influenced by several factors. Variations in soil, growing seasons and environmental conditions can significantly affect their quality. In addition, intrinsic factors such as tree age, proportion of latewood and proportion of juvenile wood play a determining role in its properties (Álvarez *et al*. 2013; Ruano *et al*. 2017).

According to Tian *et al*. (2009), the evaluation of the anatomical properties and growth characteristics such as growth ring width are very important tools for understanding tree growth and its reaction to varying climatic settings. At the same time, the study of the transition between juvenile and mature wood is fundamental, since both present notable differences in their anatomical characteristics, physical and mechanical properties as well as chemical composition (Larson *et al*. 2001; Mutz *et al*. 2004; Ruano *et al*. 2017; Lu *et al*. 2021; Refort *et al*. 2024). These characteristics determine the mechanical strength of wood and, consequently, its handling, industrial applications and final product characteristics (Sadegh and Kiaei 2011).

Studies on the behavior of growth ring width have been carried out by Gonçalez *et al*. (2018) on *P. caribaea* var *hondurensis* and by Oyelere *et al*. (2019) on *P. caribaea* (var not specified). In both, the authors have verified the differences between the values reached by this variable in juvenile and mature wood, as well as its relationship with different wood properties. To delimit the transition from juvenile to mature wood, several authors have proposed to analyze the radial variation of some wood characteristics, in the pith-bark direction, followed by certain mathematical-statistical analyses, such as segmented regression (Evans *et al*. 2000; Zhu-Jian *et al*. 2000; Bhat *et al*. 2001; Clark *et al*. 2006; Gapare *et al*. 2006; Coneglian *et al*. 2017); while Mutz *et al*. (2004) proposed analyses based on a non-linear mixed effects model. Compared to mature wood, juvenile wood has a lower density, shorter tracheids, higher lignin content, lower proportion of cellulose and lower mechanical strength (Bendtsen and Senft 1986; Cown 1992; Larson *et al*. 2001; Mutz 2004).

Plumptre (1984) confirmed these differences in *P. caribaea*, noting that juvenile wood may attain only two-thirds the density and half the strength of mature wood. In addition, undesirable characteristics, such as a pronounced spiral grain and a higher proportion of compression wood, may be present. Mature wood, having more regular growth rings, is the most valuable wood in the tree; therefore, identifying the transition age is key for designing more efficient silvicultural strategies and optimizing timber harvesting (Zobel and Sprague 1998; Wang and Stewart 2012).

Since the transition from juvenile to mature wood is gradual, it is difficult to identify a specific point where it occurs. Clark *et al*. (2006) and Ruano *et al*. (2017) state that the point of transition can vary not only between the different species but also between locations, trees and even within the same tree; it can also vary depending on the method used and the variable being studied. Among the most evaluated variables for determining the age of transition from juvenile to mature wood are the direct measurements of the tracheid length and density (Mutz *et al*. 2004; Coneglian *et al*. 2017; Vinha-Zanuncio *et al*. 2022). Apart from the above, an indirect method that can be non-destructively used for monitoring the length of tracheids is by using ultrasound vibrations. As stated by Bucur (2006), the longitudinal speed of ultrasonic waves is a useful method that can indirectly provide information on the length of tracheids. However, in the majority literature, the ultrasound speed, have been evaluated mainly for the calculation of the dynamic modulus of elasticity, and the study of its behavior on samples of different species (Gonçalez *et al*. 2018 and Refort *et al*. 2024). Therefore, in the present study, it was hypothesized that the ultrasonic method could serve as a good tool for juvenile-to-mature wood demarcation and will be tested for its usefulness in monitoring the tracheids length from the pith to the bark. To a lesser extent, there are publications on the evaluation of the proportion of latewood for the same purpose (Meza-Juarez *et al*. 2005; Clark *et al*. 2006), which will also be one of the methods employed in this study.

Among the research on the age of transition from juvenile to mature wood in species of the genus *Pinus*, it can be mentioned that Meza-Juárez *et al*. (2005), studied samples from a 16-year-old plantation of *P. patula* Schl. et Cham. By contrasting the proportion of latewood, wood density, and tracheid length, they concluded that the transition in this species occurs at 10 years of age and that tracheid length is more effective than the other two characteristics for its determination. Subsequently, Clark *et al*. (2006) studied samples of 20 to 27-year-old plantations of *P. taeda* from five physiographic regions in the southern United States, based on the evaluation of the basic density, the proportion of latewood and the angle of inclination of the microfibrils, concluding that the age of transition varies between 5.5 and 20 years depending on the method used and the variable evaluated, highlighting the great influence of genetic and environmental factors. Ruano *et al*. (2019) employed near infrared-hyperspectral imaging (NIR-HI) and micro X-ray densitometry (μXRD) on *Pinus sylvestris* L. They estimated that the transition occurs between 16 and 18 years of age. However, it was found that the results vary depending on the method applied for measuring the variable, and on the method used to process the data. More recently, Refort *et al*. (2024) applied a combination of destructive and non-destructive methods, including tracheid length assessment and ultrasound testing. In the latter case, the wave speed was determined, and subsequently the dynamic modulus of elasticity (MOEd) was determined. The latter was the variable evaluated on samples from a 35-year-old plantation of *Pinus contorta* Douglas. The authors identified the transition age between 12 and 16.5 years, confirming the existence of significant differences in the anatomical, physical and elasto-resistant parameters between both types of wood.

Most research on *P. caribaea* species has focused on the study of transition age as a function of tracheid length (Coneglian *et al*. 2017; Zanuncio *et al*. 2022). The most important findings of such studies highlighted that the transition age in this species is between 8 and 9 years and there does not appear to be a production of mature wood until after 20 years of age.

Research reported in the literature, aiming to delimit the transition age between juvenile and mature wood of P. caribaea var caribaea, is not yet sufficient to quantify their proportion in the native and Cuban plantation wood. Currently, there is little or no information on transition age studies evaluating the proportion of latewood and ultrasound speed in this species, which will be the methods employed in this study.

Beyond its academic relevance, this study addresses urgent operational challenges in Cuba's forestry sector. Currently, *P. caribaea* var *caribaea* plantations prioritize yield-driven practices while overlooking wood quality. For economic reasons, no priori quality screening is performed either. This creates a critical bottleneck: juvenile wood —with its higher propensity for dimensional instability and deformation during processing— dominates the raw material supply. Compounding this issue, obsolete sawing technology in local mills fails to adapt cutting patterns to wood heterogeneity, causing two synergistic problems: unintentional waste of mature wood, which is sawn off during squaring of logs and higher juvenile wood content in final products, leading to warping, checking, and quality downgrades. By establishing a reliable transition age threshold, the present work can enable optimized sawing protocols that minimize removal of mature wood and isolate deformation-prone juvenile sections for lower-value uses and adjusted rotation cycles to increase mature wood yield. The implementation of this knowledge could reduce processing waste and significantly improve product stability in Cuba's *P. caribaea* var *caribaea* industry.

The objective of this study was to identify the juvenile wood transition age and analyze some growth characteristics in trees of *P. caribaea* var. *caribaea* from a plantation and a natural population by analyzing the radial ring width variation, the radial proportion of latewood within the growth rings, and the ultrasonic longitudinal speed in the cross-section from the pith to the bark.

EXPERIMENTAL

Sampling Areas

Wood samples were obtained from two areas located in Cuba (Fig. 1), corresponding to a plantation about 40 years old at the "La Felicidad" site, belonging to the Agroforestry Company of Sancti Spíritus province in the central region of the country; and to a natural population over 60 years old at the "Badén Las Catalinas" site, belonging of the Agroforestry Company of Pinar del Río province in the western region.

Both areas are characterized by a seasonal rainfall regime with an average rainfall of up to 2000 mm, with a rainy period extending from May to October and another less rainy period from November to April. The average annual temperature ranges between 22 and 24 °C, and the soil type is classified as Ferrallitic red yellowish lixiviated in the plantation area (Reyes *et al*. 2007) and Brown carbonate in the natural population area (Luis 2004).

Fig. 1. Location of the sampling areas in Pinar del Río province (native) and Sancti Spíritus province (plantation), Cuba

Six trees from the plantation and five from the native were randomly selected in each area. Their locations and general characteristics are shown in Table 1.

Table 1. Location and General Characteristics of the Trees Selected for the Study

	Tree	Location	Altitude (masl)*	Slope	Total Height (m)	DBH** (cm)
Plantation	1	21º57'39.99"N 79º59'21.41"W	667	45°	34	45
	2	21º57'37.99"N 79º59'19.41"W	678	45º	32	52
	3	21º57'38.31"N 79º59'19.06"W	677	45º	30	47
	4	21º57'40.41"N 79º59'21.52"W	675	45º	28	43
	5	21º57'38.83"N 79º59'18.85"W	651	45º	28	50
	6	21º57'39.13"N 79º59'18.23"W	683	45º	28	48
Native	1	22º40'39.07"N 83º24'19.07"W	122	40º	26	53
	2	22º40'40.19"N 83º24'18.90"W	117	40º	23	51
	3	22º40'40.31"N 83º24'18.74"W	108	40º	23	36
	4	22º40'42.27"N 83º24'16.11"W	117	40º	28	41
	5	22º40'42.60"N 83º24'16.37"W	114	40º	30	50

*masl: meters above sea level
**DBH: diameter at breast height with bark included

Sampling Procedure

As illustrated in Fig. 2, a 50 mm thick disc was extracted from the selected trees at the DBH, and from this, a central 60 mm width strip without bark was cut out from the largest diameter part, containing the pith, thus obtaining the initial sample for the evaluation of different properties. This strip was used for the measurement of ultrasound speed from the pith to the bark.

In the next step, a 10 mm thick strip was sawn out in order to enhance the color contrast between the wood growth areas and manage the count and measurement of the growth rings' width (mm) as well as the determination of the proportion of latewood The evaluations of all the variables were carried out radially from the pith to the bark in both rays (meaning both sides: left and right).

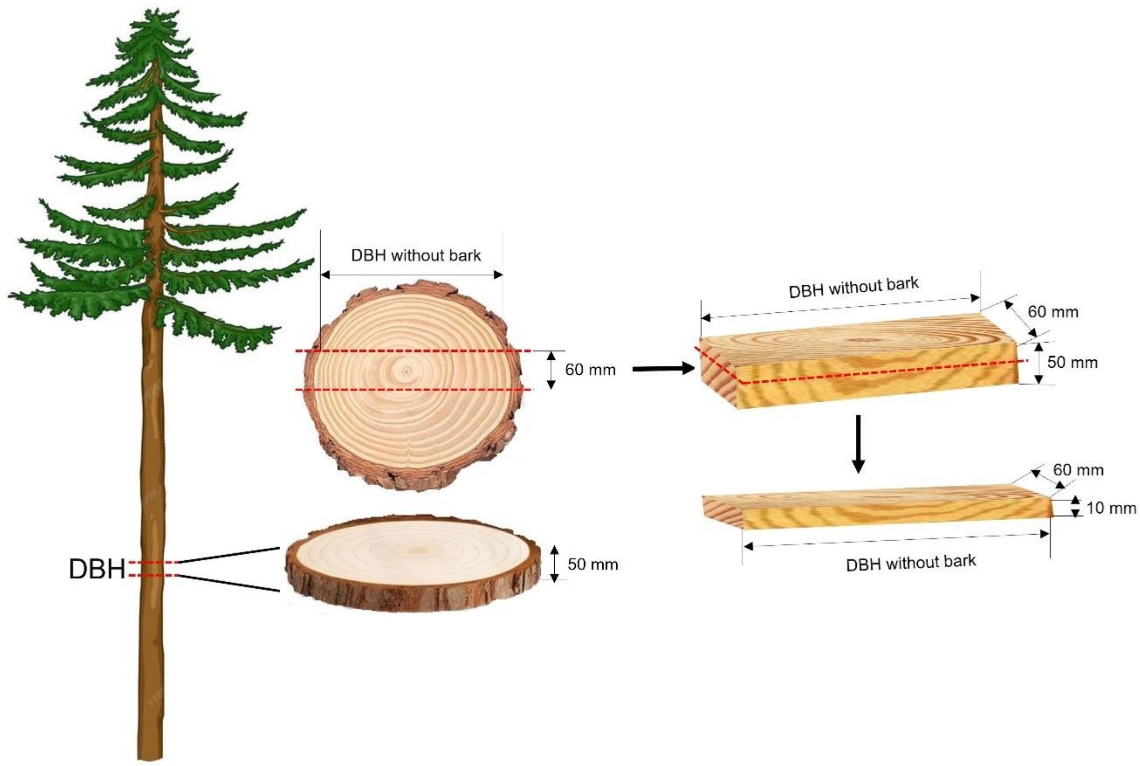

Fig. 2. Schematic representation of the sampling process

Ultrasound Speed Measurement

To evaluate the radial variation of the ultrasonic wave propagation speed (m.s^{-1}) from the pith to the bark, measurement points were marked every 5 mm on both rays and on both sides of the initial strip. The analysis was carried out on the samples of greatest length (diameter) for each of the provenances, 5 samples from plantation and 3 samples from native to which the thickness was accurately measured with a digital caliper MarCal 16 EWR (Mahr GmbH Esslingen) and at precision of 0.01 mm, as well as the Moisture Content (MC) using a wood moisture meter model HMB-WS13 (Merlin Technology). The moisture content of the samples during the ultrasound speed measurements was 12%.

To measure the ultrasound speed, a LucchiCremona measuring instrument, manufactured in Cremona, Italy, with a measurement precision of ±0.16 microseconds was used. The values of both sides at each specific measurement point were averaged. Two kinds of graphs were considered: one in which the x-axis represented the distance from the pith (mm) and another one in which it represented the age in years. For the latter, the average ultrasonic speed was calculated for each growth ring. The first category of graphs was used for visual comparison with the specimen itself, but also with the graphs of the latewood proportion (Fig. 5). The first category of graphs was considered useful, because their length was equal to the sample length and, when the sample picture, the latewood proportion and the ultrasonic graphs are placed nearby, one can have a visual idea about the length evolution of the tracheids in the juvenile wood, growing abruptly to a more steady region presumed to be the transition area, while the same pattern can be identified in the latewood proportion graphs and evolution of the ring widths in the real sample.

The graphs depicting the ultrasonic speed against the tree age are especially useful for comparisons between trees at a certain age (Fig. 8). Mean values per each ring were also calculated by considering the speed of ultrasound from both rays. In this way, one graph per each tree was computed, and further, per each category namely plantation and native, in order to observe their trend. The values per tree and per origin were further analyzed statistically to determine the border from juvenile to transition and mature area and were compared with the visual observations.

Count, Measurement of the Growth Rings' Width and Calculation of the Latewood Proportion

Digital images were captured from the freshly cut side of the 10 mm thick strip with a Smartphone (Samsung Galaxy A05s) to count and measure the growth rings using the image analysis method with ImageJ software (1.54f. Java 1.8.0_322. http://imagej.org). First, brightness and contrast adjustments were made to the images to achieve better sharpness. The scale of the images was referenced to a ruler placed on the face of the samples and a known distance of 10 mm was set for all measurements. To count the growth rings, they were delimited by marking the end of each ring with a vertical line and taking as the main criterion the presence of a clearly defined and continuous line (abrupt transition) between the latewood being darker of the ring and the light color earlywood of the following ring, while the false rings were disregarded. The false ring phenomenon occurs when the normal growing is interrupted by factors such as drought in the rainy season. According to Boschiero Ferreira and Tomazello-Filho (2009) *P. caribaea* is known as a species that frequently develops false rings, with thin tissues of latewood developing during the earlywood season and therefore are commonly observed in the wood cross-section. The parameters measured were the width of the growth rings (mm) and the width of the latewood within each ring (mm) (Fig. 3).

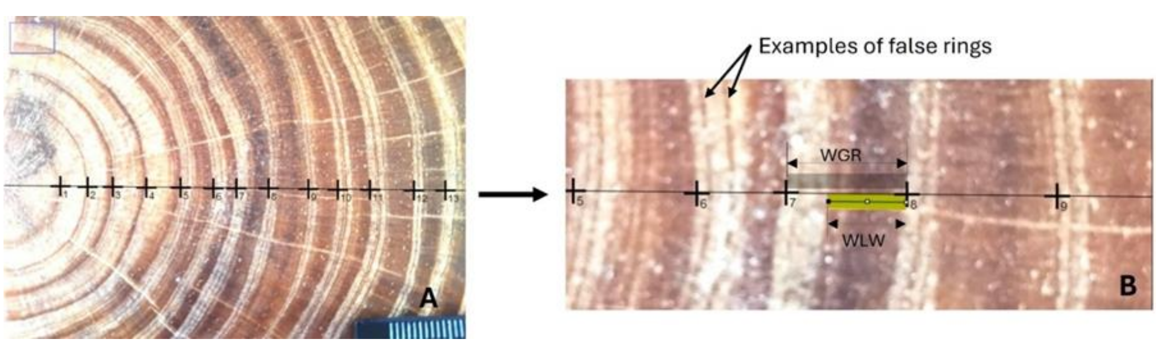

Fig. 3. Example of the delimitation, count (A) and measurement (B) of the growth rings in the samples. WGR= Width of the growth rings; WLW= Width of the latewood

The percentage of latewood within each growth ring was determined by Eq. 1,

$$PLW\ (\%) = \frac{WLW}{WGR}\ .100 \quad (1)$$

where PLW is percentage of latewood (%), WLW is width of latewood (mm), WGR is width of growth ring (mm).

Scattered graphs indicating the evolution of the latewood percentage in each growth ring from pith to bark were made for each tree. As mentioned above, they are helpful to have visual information, on both tree rays, which was compared with the real samples, as well as with the ultrasonic graphs. In order to have a perfect alignment with the sample, the x-axis was cumulating the growth widths. Also, mean latewood values were calculated per each ring by considering the LW proportion from both tree rays. In this way, graphs with the evolution of the latewood proportion were produced per each tree, but also with the mean values per origin (plantation or native). Statistical analysis was performed per each tree, but also per each origin, in a trial to find the inflexion regions that separate the juvenile from the transition area and further the border from the transition area to a more steady mature wood region.

Estimation of the Age of Transition from Juvenile to Mature Wood

According to Plumptre (1984), the juvenile core of *P. caribaea* is formed in the first 5 to 8 years of growth, while the separation of the juvenile wood from the mature wood is not straightforward. The cited author suggests that the juvenile core is followed by a gradual transition to the mature wood, which in this paper will be called the "transition area". The delimitation between the juvenile core and the transition area plus the mature wood was estimated based on the values of the proportion of latewood and the behavior of the longitudinal ultrasound speed monitored in radial direction. One type of analysis was visual, by placing together each sample image, aligned with its graph of the latewood proportion and the graph of the ultrasonic speed in both rays. The juvenile wood core was first visually determined in the latewood proportion graphs and left-right vertical lines were drawn to delimit this region (Fig. 5). Within the juvenile zone, the latewood proportion increases rapidly with increasing tree age. Beyond the juvenile zone, the latewood proportion continues to increase, but the increase is usually more gradual. The boundary between juvenile and mature wood was defined as the growth ring where the latewood proportion first reached ≥50% and remained at or above this threshold in subsequent rings toward the bark. The juvenile core was further delimited with vertical lines in the ultrasound graphs, as well as directly on the sample image and the age of delimitation for each tree was recorded. The visual estimation was further checked with statistical programs that evaluated the major inflexion points in the graphs, such as: cluster analysis and segmented regression, as detailed in the next section. The final decision about the age of transition from one stage of growth to another was based on both: visual and statistical analysis.

Data Analysis

All data were analyzed using IBM SPSS software (ver. 21.0). Normality tests (Kolmogorov-Smirnov and Shapiro-Wilk) were applied. For comparison between populations (native and plantation) T-test (for data with normal distribution) and Mann-Whitney U test (for data with non-normal distribution) were applied. Differences were considered statistically significant when $p < 0.05$.

To determine the inflexion point between the juvenile and the next region of transition and mature wood, a segmented regression analysis was used on the data of the variables proportion of latewood (%) and ultrasound speed (m/s). A simple linear regression model was initially fitted, in which the variables were modeled as a function of radial distance from the pith (age) (Eq. 2),

$$Y=\beta_0+\beta_1X+\varepsilon \qquad (2)$$

where Y is the variable in question, X is the radial distance (age), and ε is the random error term.

This model allows the estimation of the change point at which the slope of the curve depicting the relationship between the variable and the radial distance from the pith changes significantly. The estimated change point was extracted directly from the fitted model. The two segmented analysis gave the indication of the first inflexion point in the graphs. However, a three segmented regression analysis was also performed attempting to observe the location of a second inflexion point in the graphs, presumed to separate the transition area characterized by a less steep and gradual variable increase (proportion of latewood, ultrasonic speed) from the mature wood, where the variable showed a stabilization.

If one is expected to have three distinctive regions in the graphs, a confirmation was searched by performing a cluster analysis (K-means) with the variables growth ring width (mm), proportion of latewood (%), and ultrasound speed (m/s) applied for both populations, taken together. The optimal number of clusters was determined by analysis of validity index (elbow method and silhouette coefficient). Confirmation of significant statistical differences between clusters was done by ANOVA for 95% confidence.

All analyses and graphs were performed in the RStudio statistical environment (2024.09.0+375), using the segmented and base graphics packages.

RESULTS AND DISCUSSION

Results of the Cluster Analysis

The cluster analysis was applied to all trees collectively, and the optimal partitioning was determined to consist of three clusters based on validity indices. The results reveal distinct groupings that align with the expected characteristics of the juvenile wood, mature wood, and a transition zone (Fig. 4).

Cluster 1 (Juvenile Wood):

Rings with a low proportion of latewood, wider growth rings, and lower ultrasound were grouped in this cluster. These traits are consistent with juvenile wood, which is generally less dense, structurally heterogeneous, and mechanically weaker. The lower ultrasound speed in this cluster is indicative of shorter tracheid lengths.

Cluster 2 (Transition Zone):

This cluster included rings with intermediate values for the proportion of latewood, growth ring width, and ultrasound speed. These intermediate characteristics suggest a gradual transition between juvenile and mature wood, where the properties of both zones merge. The presence of this transition zone highlights the progressive nature of wood maturation.

Cluster 3 (Mature Wood):

This cluster grouped rings with a high proportion of latewood, narrower growth rings, and higher ultrasound speed. These characteristics are typical of mature wood, which is known for its higher density, greater mechanical strength, and more homogeneous structure. The high proportion of latewood and elevated ultrasound speed reflect the increased density and tracheid lengths, specific to the mature wood.

Among the three variables analyzed, ultrasound speed provided the clearest differentiation between clusters, with well-defined minimum, maximum, and mean values that did not overlap. This underlines the utility of ultrasound speed as a reliable indicator for distinguishing between juvenile and mature wood, as well as for identifying the transition zone. The mean values were 3208, 4097 and 4746 m/s for juvenile, presumed transition and mature wood respectively.

Gonçalez *et al*. (2018) measured the ultrasound speed to calculate the dynamic modulus of elasticity in *P. caribaea* var *hondurensis* from 20-year-old plantation and mean values in mature wood of 5852.85m/s, in juvenile wood of 4848.30m/s and in presumed transition wood 5262.22m/s, finding significant statistical differences among the three zones. All these values are higher than those obtained in this study, in spite of similar wood moisture content.

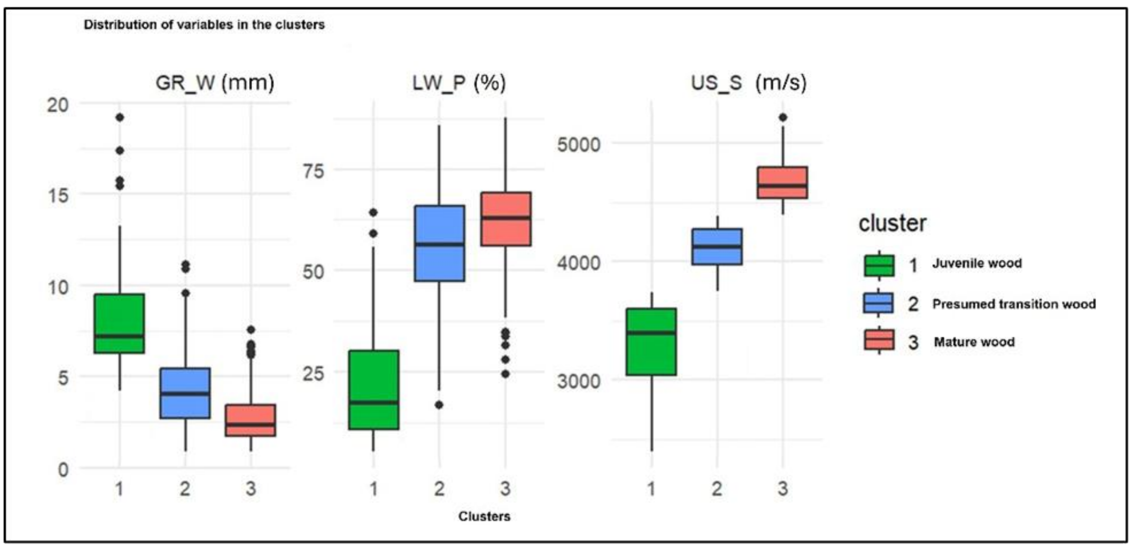

Fig. 4. Results of k-means cluster analysis for growth ring width, proportion of latewood and ultrasound speed in *P. caribaea* var *caribaea* for both populations taken together (where GR_W – growth ring width; LW_P – latewood proportion; US_S- ultrasound speed)

Lu *et al*. (2021) used the k-means clustering method by R-studio software to analyze the transition from juvenile to mature wood in another species of conifer, *Cunninghamia lanceolata*, (four 20-year-old clones), evaluating the radial variation of the length of tracheid, microfibril angle and chemical components in both earlywood and latewood within each growth ring. These authors concluded that cluster analysis is an appropriate method for the classification of wood properties, being scientific, reasonable and reliable.

Based on the findings in this study the cluster analysis has confirmed the need to look for three different zones of growth: juvenile wood, transition wood, and mature wood, zones most clearly evidenced by the ultrasound speed. In the following sections, the analysis is deepened on individual trees, but also on population groups.

Identification of the Juvenile Wood Age of Transition by Visual and by Segmented Regression Methods

Figure 5 is an example of visual analysis, where the proportion of latewood on both rays was used as the first reference for delimiting the juvenile core from the neighboring tissue. The delimitation lines were added to the ultrasonic graph and on the sample image, in order to check by comparison, if the delimitation is consistent in all three situations. It can be observed that the juvenile core corresponded to a region of the lowest ultrasonic speed, to a slightly lighter color and generally wider rings in the sample image. Visual identifications were repeated for all samples of plantation and native trees and included in a centralized table as displayed in Table 2.

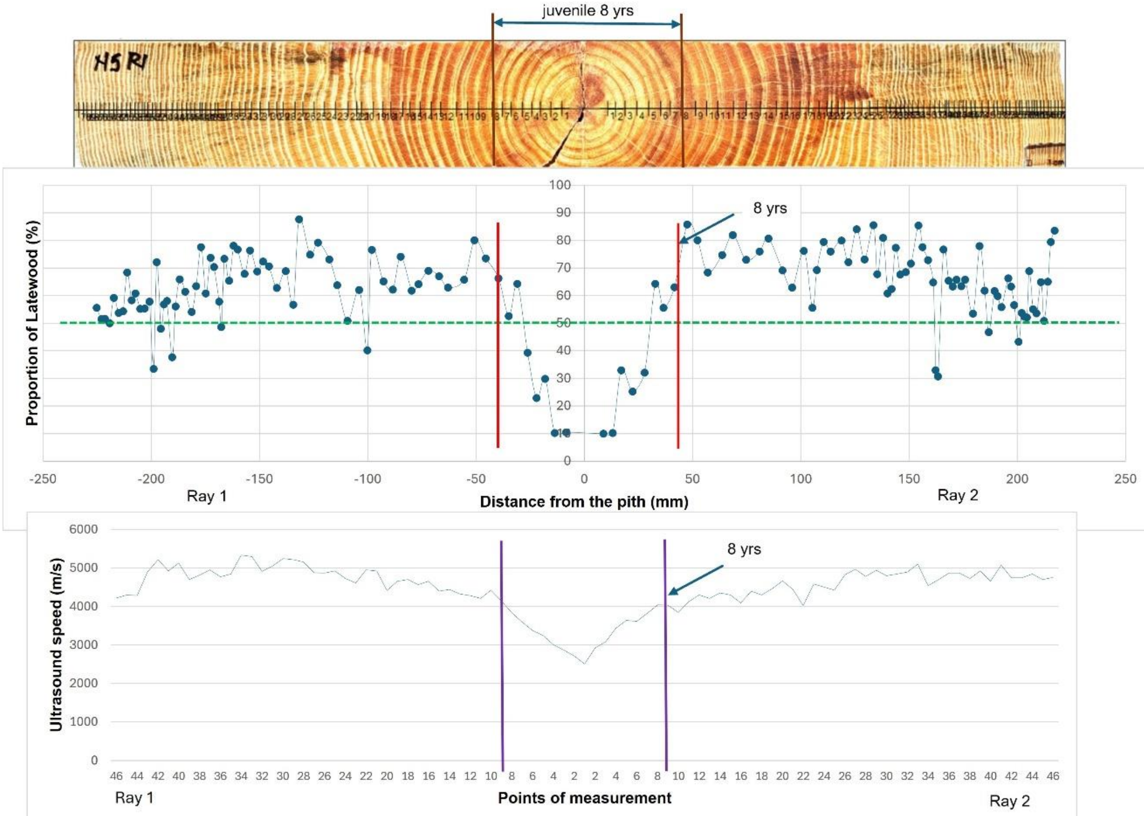

Fig. 5. Example of the delimitation of juvenile wood from the neighboring tissue by visual estimation in *P. caribaea* var *caribaea.* Note: the points of measurement of ultrasound speed are taken radially at every 5 mm from the pith, where 1 was in the pith (The sample corresponds to one of the trees of native).

Table 2 summarizes all results. The juvenile wood transition was estimated by considering the visual estimation values, which were confirmed by statistical analysis. The first transition to core juvenile wood occurred between 5 and 9 years in individual trees. When the trees were grouped on origin, the segmented regression of the latewood proportion suggested an overall transition at 8 years for native (breakpoint at 8.30 ±0.34 years) (Fig. 6), while for plantation the transition was detected at a breakpoint of 7.27 years (±0.73 years) (Fig. 7).

Table 2. Estimation of the Age of Transition from Juvenile to Mature Wood in Samples of *P. caribaea* var *caribaea*

Species (codes)	Age (years)	Tree diameter (without bark) (DBH) (mm)	Juvenile wood limit determined by visual estimation (years)	Inflexion age detected by two-segmented regression in latewood proportion curves (years)			Inflexion age detected by two segmented regression in ultrasound speed curves (years)			Inflexion age detected by three segmented regression in ultrasound speed curves (cumulated rays) (years)	**Conclusion about juvenile wood limit** (years)	Distance from the pith of juvenile wood (mm)	Juvenile Wood (%)	Presumed transition to mature wood (years)
				Ray 1	Ray 2	Cumulated rays	Ray 1	Ray 2	Cumulated rays					
P1	44	336	8	**8**	23	27	**8**	11	**8-9**	point 1: **8.8**	8-9	75	44	23-27
P2	44	304	7	**6**	20	**6-7**	9	20	10	16 and 23	6-7	45	29	20-23
P3	44	408	6	**8**	**6**	**7-8**	14	**8**	11-12	**6** and 17	6-8	52	25	14 -17
P4	44	386	7	**7**	5	**6-7**					6-7	40	21	
P5	46	461	5-7	**5**	**7**	**6-7**	**5**	30	24	**4** and 24	5-7	47	20	24
P6	36	428	9	5	**9**	6	5	**9**	**8-9**	**8.7** and 27	8-9	99	46	27
N1	64	501	6	**6**	9	8	4	**6**	4	point 1: 4	6	53	21	
N2	74	474	6	12	**8**	10	21	26	14	point 1: 12	6-8	45	19	21-26
N3	66	314	7	**7**	**6**	**6-7**					6-7	38	24	
N4	71	363	7	**8**	**8**	**8**					7-8	36	20	
N5	70	436	8	**8**	9	**9**	15	**10**	26	**8** and 31	8-9	41	19	26
All plantation	**43**					**7**			**10**	**4 and 12**	**5-9**	**60**	**31.125**	**20-26**
All native	**69**					**8**			**21-22**	**5 and 26**	**6-9**	**43**	**20.593**	**21-26**

As shown in Fig. 6, beyond the age of 8 years, the proportion of latewood stabilized above 50%, making it difficult to distinguish a defined transition period. This stabilization aligns with the expected shift from juvenile to mature wood, where cambial activity becomes more uniform, and cell differentiation stabilizes.

In plantation trees, the radial variation pattern in Fig. 7 exhibits an increasing proportion of latewood up to 7 years, followed by a relatively stable phase until approximately 17 years, where values balance around 50%. However, complete stabilization above 50% was observed from ring 21. This suggests a prolonged transition phase between 7 and 21 years, probably due to site conditions, silvicultural practices, and genetic variability.

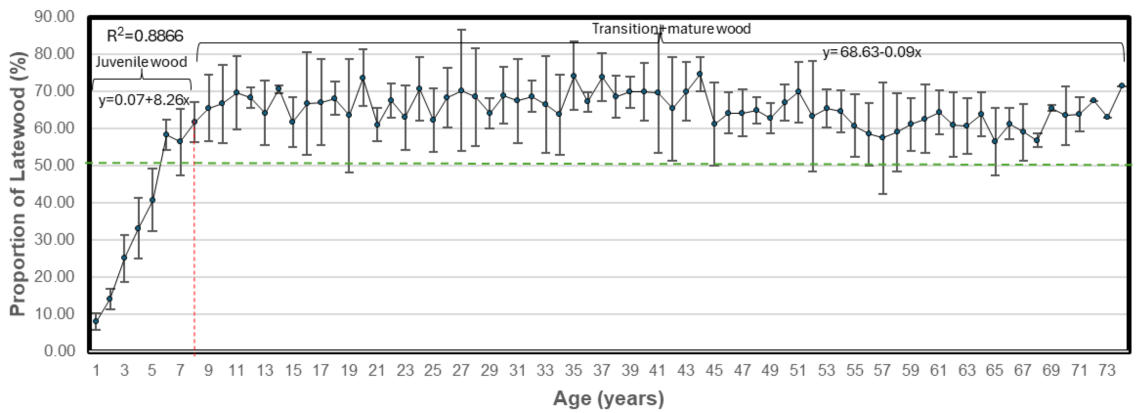

Fig. 6. Radial variation pattern of the proportion of latewood in *P. caribaea* var *caribaea* (native) with juvenile wood delimited by two segmented regression

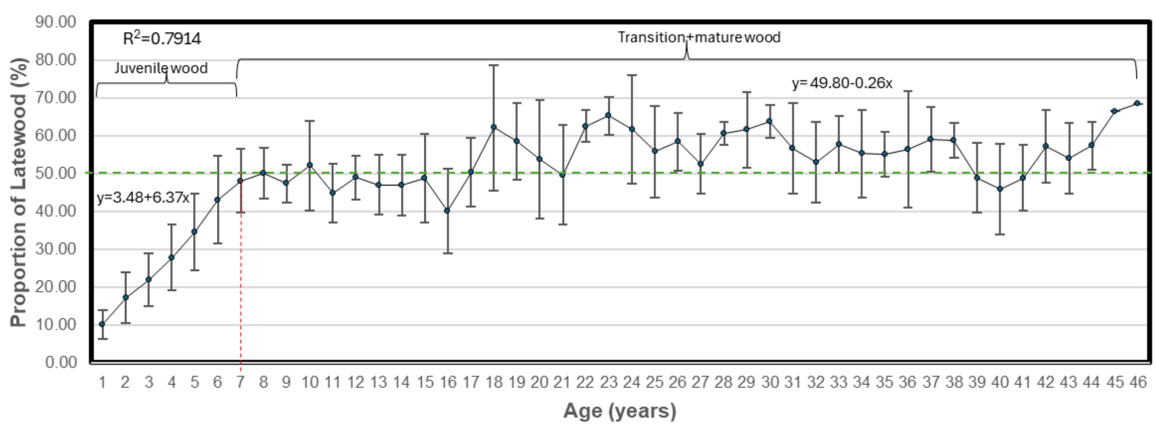

Fig. 7. Radial variation pattern of the proportion of latewood in *P. caribaea* var *caribaea* (plantation) with juvenile wood delimited by two segmented regression

When the ultrasonic data were examined, the segmented regression seemed to find inflexion points that may correspond to the second border from the transition area to the more stable mature wood. The values presumed to belong to the second inflexion point are highlighted with blue in Table 2. Although this assumption is hard to prove in the absence of effective measuring the tracheid lengths, assuming that the ultrasonic speed is an indirect measure of the cell length, it can be concluded that the second inflexion point generally occurs after the age of 20, which converges with the expected age of maturation in this species and confirms the usefulness of the ultrasonic measurements for distinguishing this transition age. The two segment regression analysis performed on the overall native species, seems to confirm a second inflexion point at the age of 21 (21.37 ±1.21 years), as shown in Fig. 8.

However, a three-segmented regression analysis for ultrasound speed in Native trees revealed two breakpoints: one at 5.09 ±0.50 years and another at 26.37 ±1.79 years. Because the statistical method employed can influence the results, a combined analysis statistical-visual can be more informative. Table 2 consolidates the transition age estimates across methods, confirming that the transition periods did not differ significantly between origins.

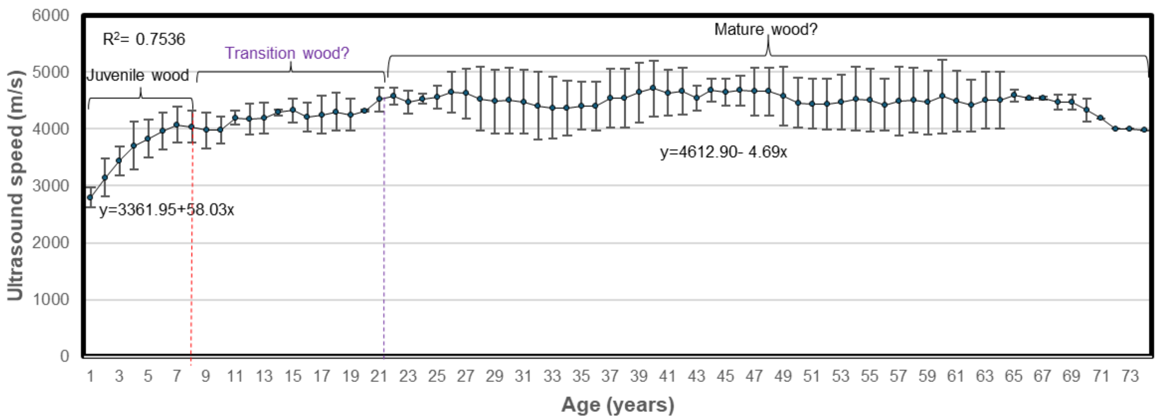

Fig. 8. Radial variation pattern of the ultrasound speed in *P. caribaea* var *caribaea* (native) with transition to the mature wood delimited by the two segmented regression

The observed transition ages in this research are consistent with prior studies on *Pinus* species, where the transition period (juvenile and intermediary transition growth) generally occurs within the first 5 to 20 years of growth, depending on species, site conditions, and silvicultural management. Research on *Pinus taeda*, *Pinus radiata*, and *Pinus contorta* var. *latifolia* has similarly reported transition period from 7 to 20 years, influenced by the characteristics of the growing sites and climatic factors (Clark *et al*. 2006; Washington *et al*. 2006; Wang and Stewart 2012).

In the following sections, the graphs of the growth ring widths, of the percentage of latewood and ultrasonic speed are grouped per origin and comparative native-plantation with focus on the statistical differences between the juvenile core wood and the next growth region considered together: transition and mature wood. The visual representation not only shows whether there is a pattern difference between native and plantation but also intends to confirm if the previous judgement of the juvenile wood delimitation is sustained by all variables: growth ring width, percentage of latewood and the ultrasonic speed.

Radial Variation of the Growth Rings Width

The radial variation of the growth ring width followed a similar pattern in both native and plantation samples, with wider rings observed in the juvenile wood region. However, Fig. 9a indicates that trees from native exhibited more uniform behavior, while trees from plantation showed greater variability (Fig. 9b). This suggests that environmental or genetic factors may have contributed to the observed differences in growth ring development.

On average, native trees exhibited narrower growth rings compared to plantation trees. Figure 10 illustrates that in both populations, growth rings were widest up to approximately 7 to 8 years of age, after which their width gradually decreased.

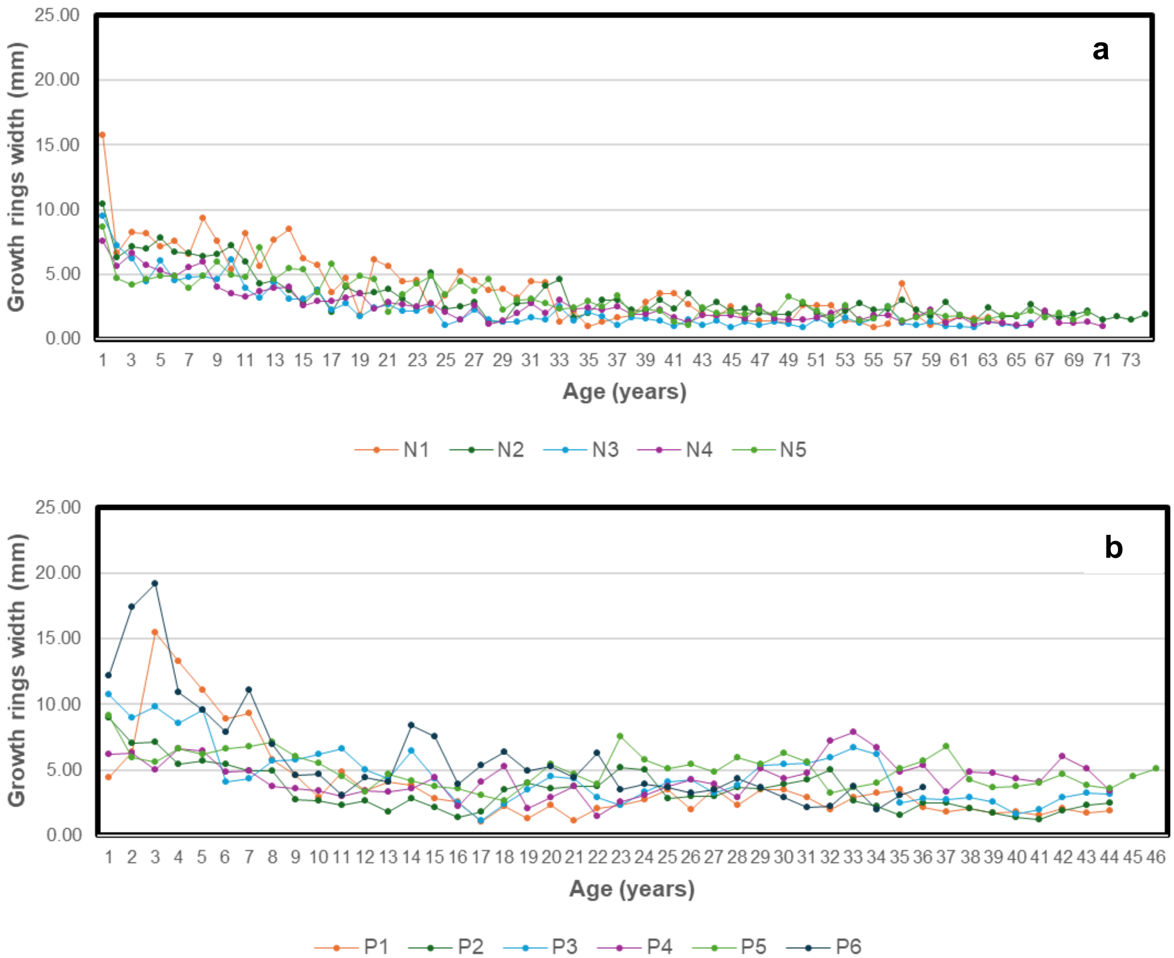

Fig. 9. Radial variation of growth ring width in sampled trees of two populations of *P. caribaea* var *caribaea*: a) native; b) plantation

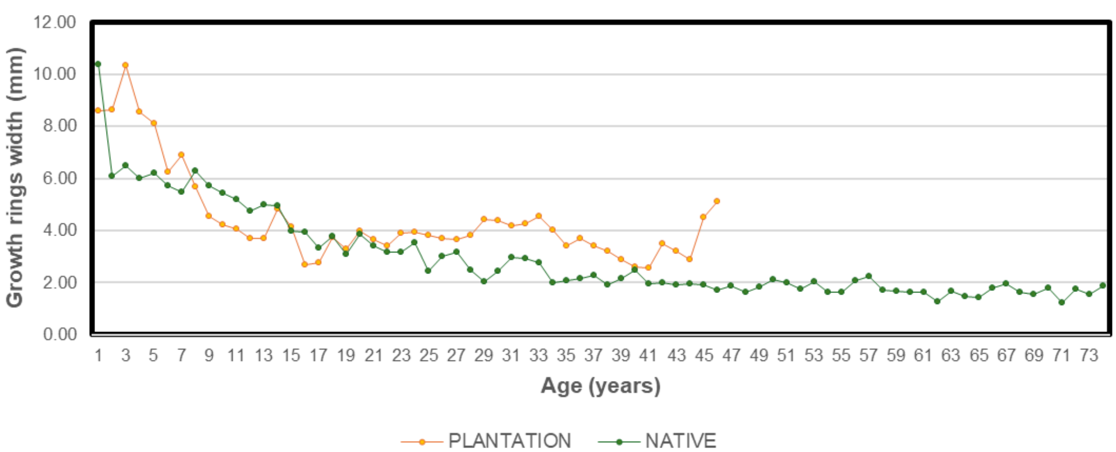

Fig. 10. Radial variation pattern of growth ring width in *P. caribaea* var *caribaea* (native *vs.* plantation)

In native trees, this stabilization occurred around 34 years of age, whereas plantation trees did not show a clearly defined stabilization phase, maybe because they were younger than the natives at the moment of measurement. This lack of stabilization in plantation trees could also be linked to factors such as continuous silvicultural interventions, genetic diversity, or climatic variations. It may also be attributed to the different exposure to sunlight due to the steep slope conditions in which these trees grow.

Table 3 provides descriptive statistics for the growth ring width in juvenile and mature wood for both populations. The trees of plantation exhibited growth rings in juvenile wood that were 22% wider than in native trees. Additionally, the coefficient of variation (CV) indicates that native trees had greater variability in mature wood (CV = 57.23%), while plantation trees exhibited more variability in juvenile wood (CV = 41.93%).

Table 3. Descriptive Statistics and t-Test Results of the Growth Rings' width (mm), for Native and Plantation

Statistics	Native			Plantation		
	Juvenile wood	Transition plus mature wood	Mature wood (t-Test) N=63	Juvenile wood	Transition plus mature wood	Mature wood (t-Test) N=84
Minimum	3.90	0.88	1.00	4.05	1.05	1.12
Maximum	15.74	9.34	6.13	19.191	8.38	7.56
Mean ± SE	6.66± 0.41	2.67 ± 0.08	3.14±0.15	8.12± 0.51	3.67± 0.10	3.67±0.16
SD	2.32	1.53	1.17	3.41	1.47	1.46
CV (%)	34.77	57.23	37.26	41.93	39.24	40.05
N= No. of occurrences						

Gonçalez *et al*. (2018) classified the growth rings in *P. caribaea* var *hondurensis* (20-year-old plantation) according to their width, establishing an interval between 0 and 7 mm for mature wood and an interval between 12 and 20 mm for juvenile wood. These authors confirmed the proportional relationship between the narrower rings, corresponding to those of mature wood, and properties such as density and stiffness. Oyelere *et al*. (2019), obtained mean growth ring width values of 8.46 ± 0.25 mm in those closest to the pith (juvenile wood) and 1.06 ± 0.10 mm in those closest to the bark, which is mature wood when analyzing samples of *P. caribaea* (var not specified) taken at DBH in a 26-year-old plantation.

A t-test for independent samples was conducted for growth ring width between 20 and 40 years of age in both populations, domain presumed to belong to the tree maturation as displayed in Table 3. The results indicated a statistically significant difference ($p = 0.018$) between native and plantation trees, with the latter showing a significantly higher mean growth ring width (3.67 mm) than the former (3.14 mm), which indicates that plantation trees had, in general, growth rings app. 17% wider than native trees in the mature zone. These values were slightly lower than those obtained by Oyelere *et al*. (2019) in *P. caribaea* var *hondurensis* (3.72 ± 0.10 mm) for the younger, 26-year-old, plantation, which is expected. These findings suggest that plantation trees maintain relatively higher growth rates even in later stages of development, which is likely due to improved site conditions, controlled spacing, and other factors favoring faster growth.

Even though the juvenile stage occurred in both populations approximately at the same age interval 5 to 9 years, the juvenile wood in plantation was wider, as quantified by the mean distance from the pith, reaching 60 mm (31%), compared to 43 mm (21%) in native species as displayed in Table 2. Such results are due to the wider growth ring widths in the juvenile wood of the plantation population, similar to other findings from literature (Plumptre, 1984). This difference in ring width can be attributed to the controlled management used in plantations, where trees have a larger access to sunlight than the native ones.

Radial Variation of the Proportion of Latewood Within the Growth Rings

The radial variation in the proportion of latewood followed a similar pattern in both populations during the first 7 to 8 years, showing a sustained increase. However, stabilization tended to occur from 17 to 21 years onwards, more prominently in native trees than in plantation trees, as illustrated in Figs. 11 (a-b) and 12. The results are in agreement with the previous visual assessment and mathematical delimitation.

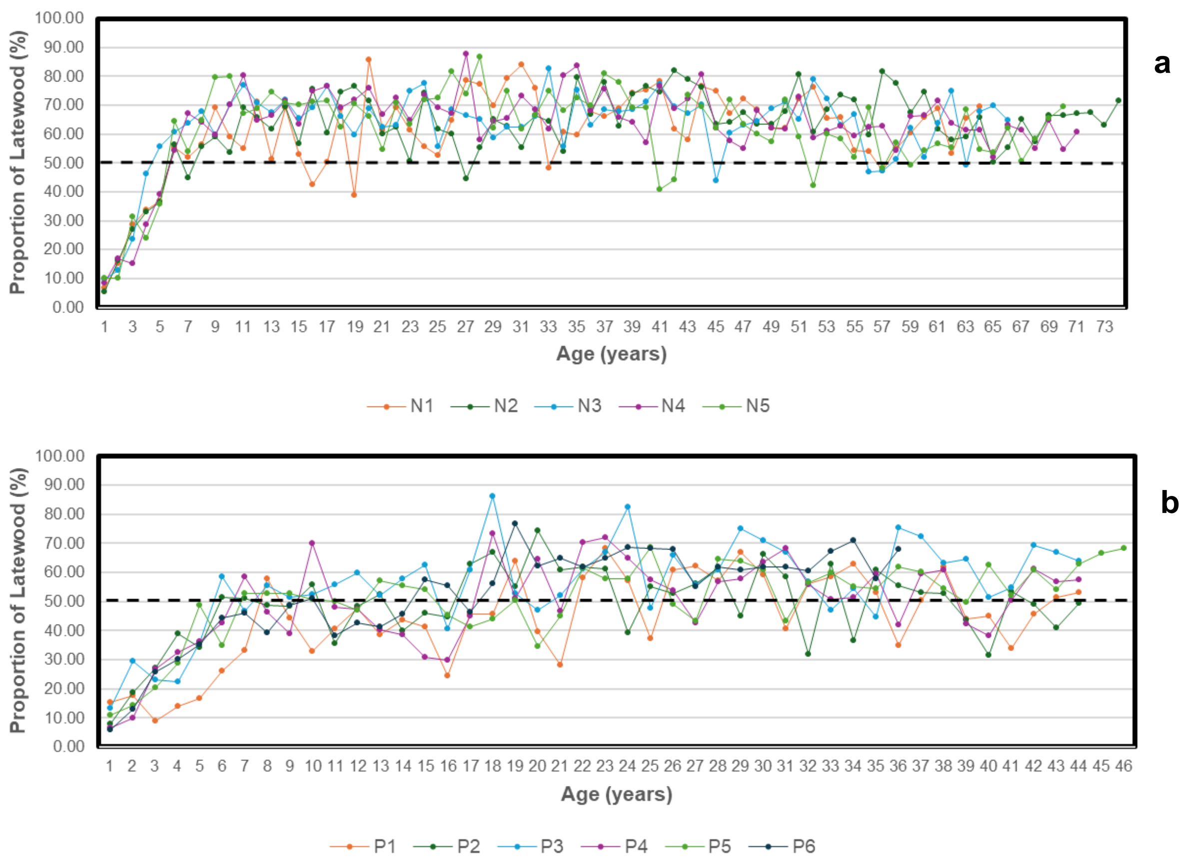

Fig. 11. Radial variation of the proportion of latewood within the growth rings in the sampled trees of each population: a) native; b) plantation

Table 4 presents the descriptive statistics for the proportion of latewood, as well as the results of the t-test for the 20 to 40 years period in each population. Juvenile wood exhibited greater variability, with native trees showing a 6.28% higher latewood proportion than plantation trees. In transition and mature wood, native trees maintained a significantly higher latewood proportion (20.30% more than plantation trees), indicating a more defined stabilization in the former. The coefficient of variation (CV) was also higher in juvenile wood (59.01% in native, 51.75% in plantation) than in transition plus mature wood.

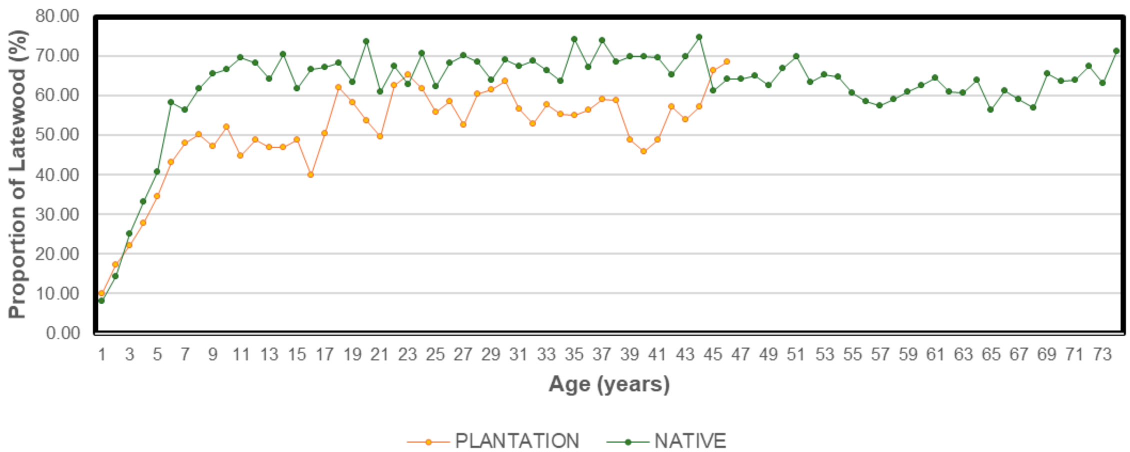

Fig. 12. Patterns of radial variation of latewood proportion in *P. caribaea* var *caribaea* (native *vs*. plantation)

Table 4. Descriptive Statistics and t-Test Results of the Proportion of Latewood (%), for Native and Plantation

Statistics	Native			Plantation		
	Juvenile wood	Transition plus mature wood	Mature wood (t-Test) N=63	Juvenile wood	Transition plus mature wood	Mature wood (t-Test) N=84
Minimum	5.27	38.72	44.53	6.06	24.37	28.07
Maximum	64.65	87.68	86.63	58.66	86.28	82.34
Mean ± SE	31.78± 3.31	65.47± 0.50	67.82±1.17	29.90± 2.33	54.41± 0.74	55.65±1.19
SD	18.75	8.90	9.30	15.48	10.81	10.91
CV (%)	59.01	13.60	13.71	51.75	19.87	19.60
N= No. of occurrences						

A t-test for independent samples confirmed statistically significant differences ($p = 0.000$) in latewood proportion between populations for the 20 to 40-year period (presumed to belong to mature wood only), with native trees displaying 22% higher mean proportion than plantation trees (Table 4). This result suggests that native trees develop a denser wood structure with a higher proportion of latewood over time, potentially due to slower growth rates, environmental conditions, and intrinsic genetic factors.

These differences in latewood proportion align with findings in other *Pinus* species, where growth conditions and genetic selection significantly influence wood characteristics. In plantation settings, faster growth rates typically result in a lower proportion of latewood, which can impact wood density and mechanical properties (Gryc *et al*. 2011). The observed patterns reinforce the importance of considering stand origin and growth conditions when assessing wood quality in *P. caribaea* var. *caribaea*.

Radial Variation of the Ultrasound Speed

Among the three variables evaluated, ultrasound speed exhibited the highest data stability, with close mean values and lower coefficients of variation across the studied populations. Figure 13 illustrates the radial variation patterns of ultrasound speed in the sampled trees from each population namely samples from native and plantation.

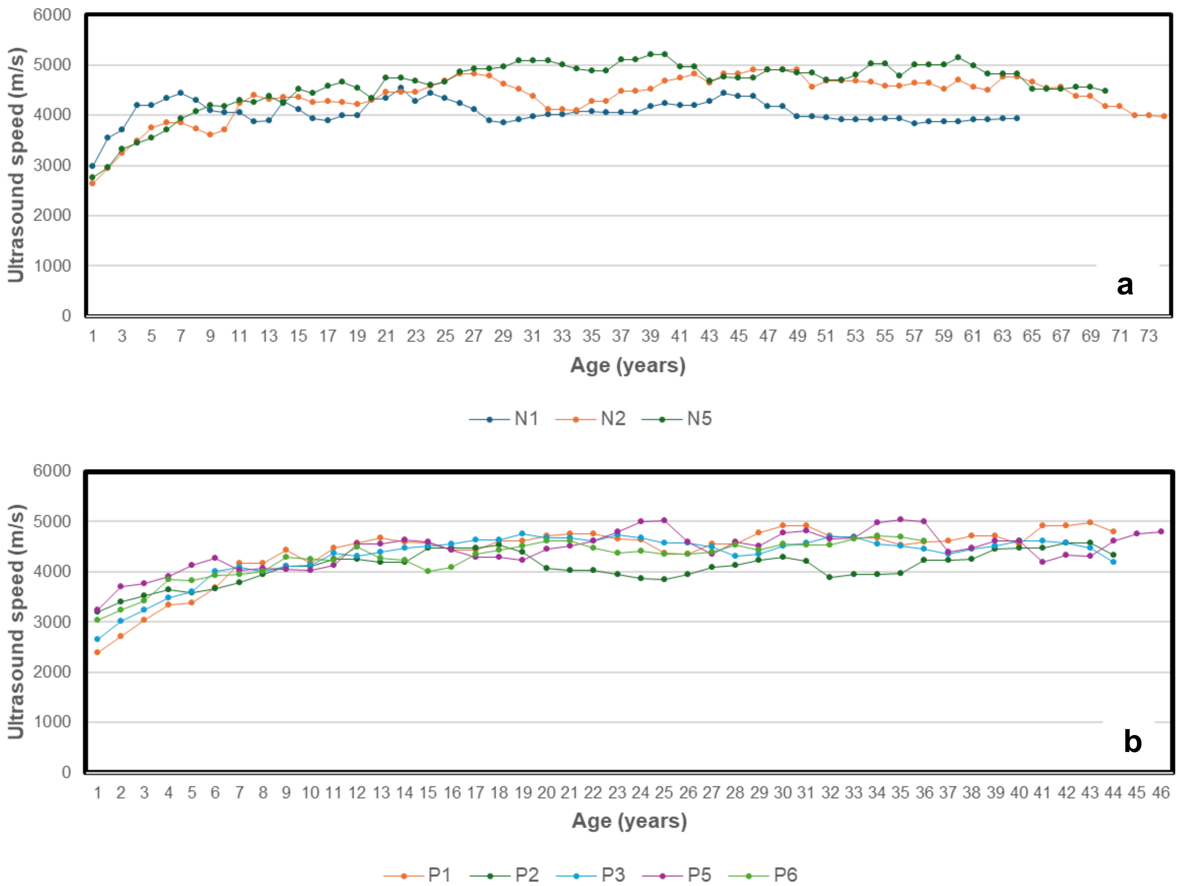

Fig. 13. Radial variation of ultrasound speed in the sampled trees of each population: a) native; b) plantation

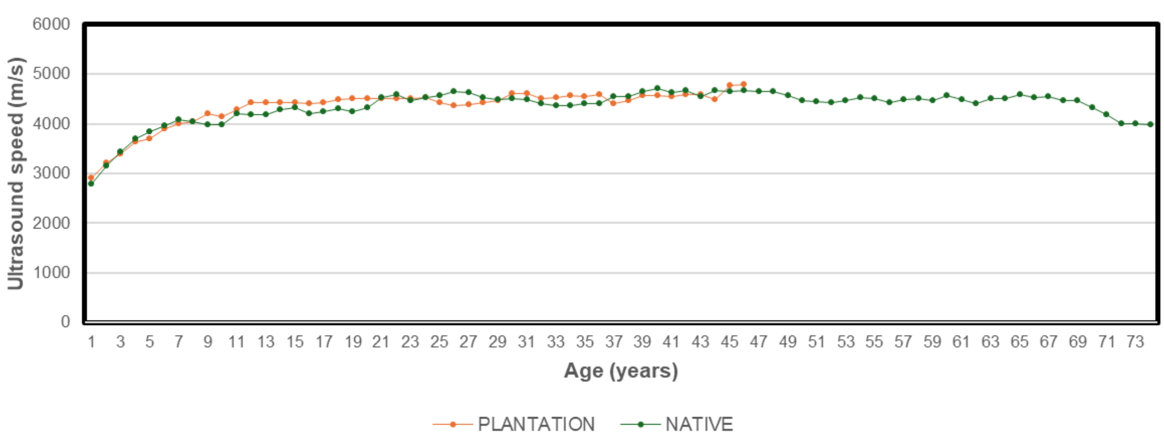

Fig. 14. Radial variation pattern of the ultrasound speed in *P. caribaea* var *caribaea* (native *vs.* plantation)

The comparative analysis between the two populations revealed a similar radial pattern in both cases. Ultrasound speed increased from the pith outward, reaching a plateau after the age of 21 years (Fig. 14) which may be indirect information about the growth pattern of the tracheids. Beyond this point, the values tended to stabilize. However, sporadic decreases in ultrasound speed were observed, which could be attributed to the presence of compression wood in samples from both origins, since as Bucur (2006) has stated in compression wood the tracheids are shorter than in normal wood, with a higher lignin content and with a steeper microfibril angle.

Descriptive statistics for ultrasound speed, as well as the results of the Mann-Whitney U test for the 20 to 40 years period in each population, are presented in Table 5. The coefficients of variation were lower in mature wood compared to juvenile wood.

Table 5. Descriptive Statistics and Mann-Whitney U Results of the Ultrasound Speed (m/s), for Native and Plantation

Statistics	Native			Plantation		
	Juvenile wood	Transition plus mature wood	Mature wood (Mann Whitney U) N=63	Juvenile wood	Transition plus mature wood	Mature wood (Mann Whitney U) N=84
Minimum	2629	3619	3863	2394	3850	3850
Maximum	4336	5217	5217	4285	5035	5035
Mean ± SE	3533 ± 111.52	4446 ± 27.35	4508±47.36	3574 ± 75.75	4463 ± 19.49	4500±31.77
SD	498.75	375.04	375.91	460.80	259.30	291.21
CV (%)	14.12	8.43	8.34	12.89	5.81	6.47
N= No. of occurrences						

The Mann-Whitney U test for independent samples indicated no statistically significant differences in ultrasound speed between the two populations ($p = 0.917$). This suggests that, despite differences in growth conditions (native *vs*. plantation), the radial variation patterns and overall ultrasound speed values were consistent across both origins.

The variations in latewood proportion and ultrasound speed suggest a complex transition process from juvenile to mature wood rather than an abrupt change. Similar trends have been reported in *P. patula* and *P. taeda*, where juvenile wood properties stabilize progressively over a range of growth rings rather than at a single definitive age (Ringo and Klem 1980; Bendtsen and Senft 1986). Palermo *et al*. (2013) found that in *P. elliottii* var *elliottii* (35-year-old plantation), juvenile wood is limited to the first seven years of tree growth and the formation of mature wood occurs after twenty years.

Specifically in *P. caribaea* var *hondurensis*, Coneglian *et al*. (2021) identified in a 40-year-old plantation a transition region from 9 to 17 years, and from this age onward, mature wood production. Zanuncio *et al*. (2022) detected juvenile wood production during the first 8 years in a 20-year-old *P. caribaea* (var not specified) plantation, and a transition zone from 8 to 20 years of age, without confirming the presence of mature wood in the samples analyzed. In both studies, the variable evaluated was the length of tracheids. Boschiero Ferreira and Tomazello-Filho (2009) also stated that *Pinus caribaea* var. *hondurensis* form juvenile wood in the initial 5 to 8 years. Oluwadare (2007) evaluated the basic density and tracheid length in wood samples of *P. caribaea* (var not specified) with five different ages, and according to his results concluded that it can be classified as juvenile wood up to 5 and 7 years old, transition wood at 15 years old, and mature wood from 20 or 25 years old onwards, which converge with the results in this research.

The findings in the present study contribute to the knowledge about transition ages in P. *caribaea* var *caribaea*, plantation versus native wood, and are particularly important to optimize the management schemes of plantations of this species in Cuba, since, in general, a minimum cutting cycle of 25 years has been established and these results show that at this age the trees may still have a very low proportion of mature wood, which together with the limitations of the sawing systems could negatively influence the quality of the final products due to a greater presence of juvenile wood. Gonzalez *et al*. (2008) have shown that in this species defects such as warpage, face curvature and edge curvature are strongly influenced by the distance from the pith. They found that these deformations are significantly higher in the area close to the pith coinciding with the presence of juvenile wood.

The results can be very useful for modifying the current schemes in the plantation establishment-management-harvesting chain. The data obtained suggest that a longer rotation shift and adjustments in silvicultural management, taking into account the conditions in which these trees grow, can translate into an improvement in the quality of the final products made from the wood of this species, which will lead to greater reliability and satisfaction on the consumers of these products and at the same time will increase the diversity of assortments.

Further work will add new information meant to clarify and sustain the transition ages found in this study by bringing supplementary data about the chemical composition from the pith to the bark, by monitoring the tracheid lengths, the cell wall thickness and local density in the trees' radial direction.

CONCLUSIONS

1. Based on empirical evidence from this study, it can be concluded that natural stands of *Pinus caribaea* M. var *caribaea* B&G serve as irreplaceable genetic reserves and ecological benchmarks, but they cannot supply Cuba's timber demand due to limited area, making plantations essential to industry supply chains; however, current rotation cycles trap the sector in low quality because the juvenile wood content causes warping and cracking in the final products, which can lead to the rejection of this raw material in sensitive industries such as furniture manufacturing and construction; therefore, a shift towards quality-oriented forestry, based on knowledge of the age of transition from juvenile to mature wood, is economically advisable.
2. Juvenile wood is a tissue with inferior properties compared to those of the mature wood and is undesirable for wood utilization; therefore, its delimitation needs to be determined. This study was conducted to identify the transition age and to clarify if there are any differences between the native and plantation populations of Cuban *Pinus caribaea* M. var. *caribaea* B&G to have a better understanding about the behavior of juvenile wood of such species. The analysis was done by monitoring the growth ring width, the percentage of latewood in the radial direction as well as the value of the longitudinal ultrasonic speed from the pith to the bark. A cluster analysis of the above variables on the combined populations has revealed that there are three groups of values, namely one attributed to the juvenile wood, one to the intermediary transition growth, and one to the mature wood. The two transition ages were identified by combining the visual assessment of the curves and of the specimens, with a two and three-segmented regression applied to the data. The result showed that the core juvenile

wood forms between the first 5 to 9 years in both populations, while the mature wood forms beyond the age of 21 to 26 years, with a gradual transition from the juvenile to the wood complete maturation.

3. The rings width was higher in the plantation wood compared to native by 22% in the juvenile wood having mean values of 8.12 mm in plantation and 6.66 mm in native samples. Corresponding values in the mature wood samples were 3.67 mm and 3.14 mm respectively, 17% higher in plantation than in native population and with higher variability. As a consequence, the juvenile wood extended wider in the plantation population, app. 60 mm from the pith (31%), compared to the native population, app. 43 mm (21%).
4. The proportion of latewood was higher in the native wood compared to that of plantation by 6.28% in the juvenile wood (mean of 31.78% in native; 29.9% in plantation) and by 22% in mature wood (mean of 67.82% in native; 55.65% in plantation), with generally less variability in native wood compared to plantation.
5. The ultrasonic speed test of the samples indicated a similar pattern in the two populations with no significant differences and was the variable with the best definition of the groups in the cluster analysis, which validates its usefulness for the delimitation of juvenile, mature and transition wood.
6. Based on the findings of this work, the combined analysis of segmented regression, clustering and visual assessment proved to be effective in identifying inflexion points in the pattern of growth. The combination of latewood proportion and ultrasonic speed as key variables allowed a more accurate delimitation of juvenile wood from transition and mature wood and facilitated the identification of a presumed transitional zone.

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