

Radial Variation in Oven-Dry Density and Shrinkage of *Pinus caribaea* M. var. *caribaea* B&G Wood: Native vs. Plantation-Grown Trees

Ana G. Trocones-Boggiano ^{a,b}, Lidia Gurau ^b and Mihaela Porojan ^{b,*}

Radial variations in oven-dry density and shrinkage were compared between older native forest (exceeding 60 years of age) and fast-growing plantation (approximately 40 years of age) wood of Cuban *Pinus caribaea* M. var. *caribaea* B&G. Native timber exhibited a 30.2% higher mean oven-dry density (0.935 g/cm³ vs. 0.718 g/cm³) due to greater age, slower growth, and a higher mature wood fraction. Intense resinification and localized compression wood (CW) near the pith uncharacteristically inflated juvenile wood density over mature zones in both populations. Volumetric, radial, and tangential shrinkages rose progressively from juvenile to mature wood zones, peaking in the high-density native timber due to a higher cell-wall fraction. Conversely, longitudinal shrinkage was 3.49% higher in the plantation category. Severe stem eccentricity in plantation trees induced massive CW formation. X-ray densitometry and scanning electron microscopy (SEM) confirmed that CW heavily altered earlywood tracheid anatomy, producing hyper-thickened cell walls, reduced lumens, and helical micro-cracks. These structural modifications compressed the latewood-to-earlywood density ratio and triggered chaotic, elevated transverse anisotropy values, which increased warping risks. While native forests yielded dense, dimensionally stable timber, fast-grown plantation wood exhibited reduced dimensional stability and lower density. This may limit its performance in high-value structural applications.

DOI: 10.15376/biores.21.4.11719-11746

Keywords: Oven-dry density; Wood shrinkage; Anisotropy; Compression wood; Microscopy; X-Ray densitometry; Plantation; Native; *Pinus caribaea*

Contact information: a: Department of Agronomy and Forestry, Faculty of Agricultural Sciences, University of Sancti Spiritus “José Martí Pérez” (UNISS). Str. Cdte Manuel Fajardo s/n. CP. 60100. Sancti Spiritus, Cuba; b: Department of Wood Processing and Wood Products Design, Faculty of Furniture Design and Wood Engineering, Transilvania University of Braşov. B-dul Eroilor nr.29, 500036, Romania; *Corresponding author: mporojan@unitbv.ro

INTRODUCTION

Pinus caribaea Morelet var. *caribaea* Barret and Golfari is a fast-growing conifer species native to Cuba that plays a vital role in industrial forestry, wood processing, and regional re-afforestation initiatives. A study by García-Quintana *et al.* (2007) concluded that this species thrives in poor soil conditions with low nutrient content, under intense competition from other trees and understory vegetation. In contrast, plantations are established in sites selected for their productive potential, generally with better soil conditions and management practices that promote faster and more homogeneous growth compared to native forests.

To satisfy commercial timber demands, evaluating wood quality metrics has become paramount to ensuring optimal structural and end-use performance. Wood quality is governed primarily by key physical traits, chief among which are oven-dry density and dimensional stability under varying moisture regimes (Panshin and de Zeeuw 1980). Denser wood generally displays superior mechanical properties but exhibits greater susceptibility to complex volumetric shrinkage behaviors during drying (Schulgasser and Witztum 2015). The variations in these interrelated physical vectors are further compounded by environmental and edaphic differences across growing regions (Muller *et al.* 2017; Borges de Moura *et al.* 2021).

In conifers, physical properties naturally show considerable variation along the radial gradient from the pith to the bark (Zobel and van Buijtenen 1989; Leng *et al.* 2024; Schimleck *et al.* 2025). The wood core surrounding the pith is classified as juvenile wood (JW), which structurally transitions over time into mature wood (MW) *via* a progressive transition zone which has been reported in *P. caribaea* var. *caribaea* (Trocones-Boggiano *et al.* 2025). Standard anatomical patterns establish that conifer wood density steadily increases outward from the pith toward the bark as cells transition from fast-growing, thin-walled structures to slow-growing, thick-walled tracheids (Wang *et al.* 2008; Kiaei 2011; Hara *et al.* 2023). Concurrently, transverse shrinkage (radial and tangential) is expected to rise in the dense mature wood, whereas longitudinal shrinkage typically peaks in the juvenile wood zone owing to a steeper microfibril angle and the presence of compression wood (CW) as well (Udoakpan 2013; Loiola *et al.* 2021; Ruano *et al.* 2022).

However, this conventional radial pattern is frequently modulated or entirely disrupted by distinct chemical and biological variables. A dominant confounding factor in *P. caribaea* var. *caribaea* is the high deposition of extractives and oleoresins near the pith core. Plumptre (1984) highlighted that resin accumulation within the juvenile wood can represent up to 40% of the dry weight of a wood piece. This heavy chemical infiltration uncharacteristically inflates local wood density values near the pith without generating the expected volumetric shrinkages or drying strains typically associated with hyper-dense cell wall fractions (Schulgasser and Witztum 2015). While some softwoods demonstrate a predictable correlation in which volumetric shrinkage can be estimated directly from oven-dry density (Riesco and Barrio 2010), this relationship becomes weak or distorted when chemical extractives artificially alter density profiles.

Furthermore, silvicultural conditions and high growth rates introduce structural instabilities. Fast-grown plantation trees harvested at younger cambial ages commonly exhibit severe stem eccentricity and a larger proportion of juvenile wood compared to slow-growing natural populations (Vidaurre *et al.* 2011). Trees adapt to these geometric asymmetries and severe mechanical stresses by massively producing reaction wood, specifically compression wood (CW), on the eccentric growth axis (Tomazello Filho and Silva 1987; Donaldson *et al.* 2004); especially in *P. caribaea*, a high incidence of CW has been reported in even relatively straight trees (Boone and Chudnoff 1972). At the cellular level, severe compression wood (as classified by Donaldson *et al.* 2004), significantly alters the anatomical architecture, introducing hyper-thickened cell walls, reduced lumen diameters, intercellular spaces, and helical structural micro-cracks (Leonardon *et al.* 2010). These physical and chemical interactions yield chaotic, erratic volumetric shrinkage patterns and spike the shrinkage anisotropy coefficient, causing severe timber distortions.

An integrated approach that allows relating cell anatomy to the physical behavior of wood, would also be valuable for evaluating the quality of wood from fast-growing plantations, where CW is frequent and its effects on dimensional stability are critical for

its use (Ruwanpathirana *et al.* 1998; Leonardon *et al.* 2010).

While multiple studies have quantified general pine wood properties, comprehensive investigations on *P. caribaea* var. *caribaea* bridging wood density with multi-directional shrinkage parameters in response to eccentricity remain scarce.

This study investigated the radial variations in oven-dry wood density and shrinkage properties across Cuban *P. caribaea* var. *caribaea* by comparing a fast-growing plantation with a native population, aiming to determine how tree eccentricity and juvenile-to-mature wood transitions dictate final timber quality. Localized X-ray densitometry and microstructural scanning electron microscopy (SEM) analysis were used to exemplify the presence of severe compression wood (as classified by Donaldson *et al.* 2004).

EXPERIMENTAL

Sampling Areas

Wood samples were obtained in two areas located in Cuba (Fig. 1), corresponding to a plantation about 40 years old at the “La Felicidad” site (21°57'39.99"N 79°59'21.41"W), belonging to the Agroforestry Company of Sancti Spiritus province in the central region of the country; and to a natural population over 60 years old at the “Badén Las Catalinas” site (22°40'39.07"N 83°24'19.07"W), belonging to the Agroforestry Company of Pinar del Río province in the western region.



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

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). The study of the main soil properties carried out on samples from both areas showed differences in terms of pH (5.41 for native and 4.53 for plantation), texture (Sandy loam for native and clay Sandy loam for plantation), cation exchange capacity (very small for native and small for plantation), as well as in terms of the base saturation degree (oligobasic for native and mesobasic for plantation). The observed differences in soil properties between the two areas (pH, texture, cation exchange capacity, and base

saturation degree) may influence wood formation and, consequently, the physical properties of the timber. Several studies have shown that soil characteristics such as pH, nutrient availability, and texture can affect tracheid dimensions and wood density in *Pinus* species (Gundogan *et al.* 2005; González *et al.* 2009; Corrêa and Bellote 2011; Vázquez-Cuecuecha *et al.* 2015). It is critical to recognize that the variations identified between the native and plantation populations in this study cannot be solely attributed to their raw forest origin. Trees harvested from natural stands and managed plantations differ fundamentally in terms of cambial age, geographic exposure, microclimates, and localized edaphic properties. For instance, the plantation soil's superior cation exchange capacity and mesobasic base saturation likely acted as chemical drivers for accelerated tree growth. Therefore, the physical and anatomical differences reported herein represent a coupled reaction to both silvicultural management and site-specific environmental baselines.

Six plantation trees and five native trees were randomly selected and felled for the study; however, every effort was made to ensure that the selected trees were as similar as possible in terms of DHB. Therefore, the significant age differences between the native and plantation trees (which typically contribute to variations in wood properties) could not be identified before the study, but only after the growth rings were delineated and counted in the samples (Trocones-Boggiano *et al.* 2025).

Sample Collection and Preparation

From the selected trees, a 50 mm thick disc was extracted at the DBH, and from this, a central 60 mm width strip without bark was cut out from the largest diameter part, thus obtaining the initial sample for the evaluation of different properties that cover all the radial variability from the pith to the bark. After that, the strip with 60 mm thickness was processed by ripping into a thinner strip 20 mm thick and variable length according to the DBH of the trees. Other ripping operations were used to cut a central 20 mm wide strip which included the pith. Out of this, successive cuts were made from pith to bark to obtain cubic specimens of 20 x 20 x 20 mm (R x T x L) for each radial sampling direction (referred to as 'rays' to denote directionality): Ray 1 (the extended radial path or sampling direction along the longest growth axis of the eccentric stem cross-section) and Ray 2 (opposite to the eccentric side) (Fig. 2). "Ray" signifies a directional radial path rather than an anatomical wood ray. The cubic specimens numbered from 1 onward appear arranged in Fig. 2 according to their location in the initial strip. The number of specimens obtained per tree varied, depending on the radial length available on each strip. The procedure was carried out in accordance with ISO 3129 (2012). The specimens were sealed in plastic bags immediately after machining to minimize moisture loss.

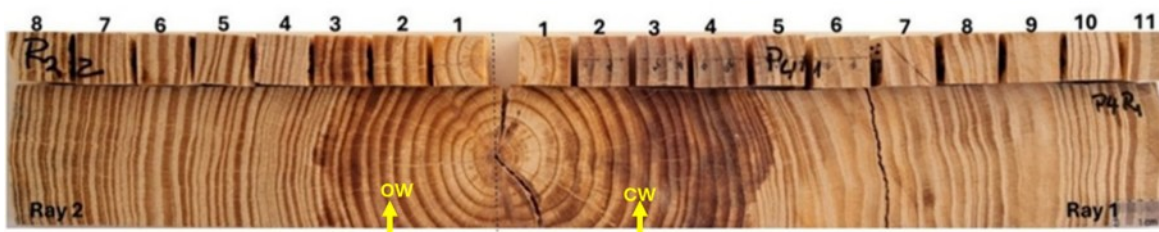


Fig. 2. Numbered specimens for density and shrinkage tests. The yellow arrow in the image indicates the location of growth ring 8_Ray 1 axis used in the compression wood (CW) and the opposite wood (OW) studies (plantation, tree P4)

Determination of the Dimensions and Mass of the Test Specimens

The mass of each specimen was recorded using a precision Kern EW digital scale (Kern & Sohn GmbH, Balingen-Frommern, Baden-Württemberg, Germany), (± 0.001 g); and its dimensions (radial, tangential, longitudinal) were measured with a MarCal 16 EWR digital caliper (Mahr GmbH, Esslingen, Baden-Württemberg, Germany) (± 0.01 mm) to subsequently calculate the volume. First, the specimens were soaked in distilled water at a temperature of 20 ± 2 °C until no further change in dimensions occurred. The changes in dimensions were checked every 3 days through repeated measurements at the same points until the difference between two successive measurements did not exceed 0.02 mm. Subsequently, the specimens were oven dried at 103 ± 2 °C until a constant mass was obtained. The same specimens were used for calculating both: the oven-dry density, as well as the various shrinkages.

Calculation of the Density

The calculation of the density was carried out in accordance with the ISO 13061-2 (2014) standard. Density in the absolutely dry condition (oven-dry density) was calculated as the ratio between the anhydrous mass and volume. Once the specimens were dried, they were placed in a vapor-tight container (desiccator) with absorbent material (silica gel) to maintain air dryness.

The oven-dry density is the most important, followed by the basic density, when wishing to compare trees of the same type as well as of different origins; for this reason, it was the type of density chosen for the analyses performed in this study.

X-Ray Densitometry

From the remaining cross-section wood slice obtained at the DBH 60 mm width (now with a thickness of app. 25 mm), a thin 10 mm thick strip was cut out by ripping, to be used in further tests. For X-ray densitometry, one plantation tree was selected, namely P4 in this paper, which was considered representative for fast-grown trees affected by eccentricity. To adapt them to the requirements of the densitometry equipment, sections of approximately 50 mm in length were cut, resulting in final specimens with approximate dimensions of 60 mm width x 10 mm thickness x 50 mm length (Fig. 3). The moisture content at the moment of testing was app. 9%.



Fig. 3. Plantation specimens used for X-ray densitometry testing

The analysis was carried out on a DPX 300 IMAL X-Ray Wood Densitometer (DPX300-LTE; IMAL s.r.l., San Damaso, Modena, Italy), with a precision of 0.01 mm. The specimen was mounted in the instrument's sample holder with its radial axis (ring growth direction) aligned perpendicular to the X-ray beam. Densitometric data was recorded from the pith to the bark, which allowed the identification of individual growth rings, identification of false rings, as well as the local density values of earlywood (EW) and latewood (LW).

Calculation of Shrinkages and Anisotropy Coefficient

The calculation of radial and tangential shrinkages was carried out in accordance with ISO 13061-13 (2016), while the calculation of volumetric shrinkage in accordance with ISO 13061-14 (2016). Longitudinal shrinkage was also calculated, taking into account that it is a good indicator of the presence of compression wood, especially in JW. Since there is no specific ISO standard for longitudinal shrinkage, it was measured using the same methodological principle as in the previous standards, but measuring the length of each specimen, in the direction parallel to the grain.

Identification of Compression Wood and Morphometric Analysis Using SEM

For the identification and anatomical characterization of compression wood, images were obtained at a low vacuum with an electronic microscope type Phenom XL G2 Desktop SEM, produced by Thermo Fisher Scientific, Eindhoven, The Netherlands, with an electron optical magnification range between 160 and 200000x. This equipment is suitable for various materials, including electrically non-conductive samples with a certain moisture content such as wood. The wood samples, corresponding to the tree 4 from plantation (coded P4), growth ring 8 from both growth axes (one with compression wood from the eccentric side and the corresponding one from the opposite side, called here opposite wood), were initially processed for histological observation. Prior to sectioning, the wood blocks were boiled for 5 h in a 1:1 mixture of alcohol and benzene to extract resinous compounds and other extractives. To soften the tissue and facilitate microtome sectioning, the blocks were then boiled for approximately 6 h in a 1:1 (v/v) solution of distilled water and glycerin. Following extraction and softening, the remaining material was stored in an alcohol-glycerin mixture (4:1) until further use. For scanning electron microscopy (SEM) observation, the stored blocks were removed from the solution, boiled in distilled water for 3 h in a conventional pot to achieve additional tissue softening, and then cut into small 5 mm blocks encompassing the transverse, radial, and tangential planes. Sectioning was performed using fresh razor blades to ensure clean surfaces with minimal structural damage. The samples were dehydrated through a graded alcohol series (50%, 70%, and absolute), followed by a final acetone bath to remove residual water and preserve cellular structure. After drying, the specimens were mounted directly onto stubs using conductive carbon tape and placed in the SEM chamber. Digital micrographs of the wood were captured at 2000× magnification to visualize cell morphology and tracheid walls.

It should be emphasized that the sub-microscopic scanning electron microscopy (SEM) datasets were derived exclusively from tree P4 to serve as a visual, qualitative benchmark of localized compression wood (CW) cell morphology in a tree with eccentricity, and should not be broadly generalized across all plantation zones.

The identification of compression wood was carried out following the criteria established by the IAWA for conifers (IAWA Committee 2004), considering as diagnostic characteristics the circular shape of the tracheids in cross section, the presence of intercellular spaces and the observation of helical micro-cracks in the cell wall. For morphometric analysis using ImageJ 1.54g Java 1.8.0_345 (64-bit), (National Institutes of Health, USA), 35 cells per sample were measured. Cells were selected randomly within each micrograph, with the only inclusion criterion being that they were intact, with clearly defined and visible contours, and free from cutting artifacts. Radial and tangential diameters (total cell and lumen) were recorded, averaged to obtain mean diameters in each case, and wall thickness was calculated by difference. Circularity was also calculated from area and perimeter values.

Statistical Analysis

All data were recorded, and preliminary calculations were performed in Microsoft Excel sheets. IBM SPSS Statistics v.21 software (IBM Corp., Armonk, NY, USA) was used for inferential statistical analysis. Comparisons were made considering two types of wood: Juvenile Wood (JW), Transition + Mature Wood (TW+MW), whose delimitation was previously established based on the reference Trocones-Boggiano *et al.* (2025). For each variable, compliance with the assumptions of normality (Shapiro-Wilk test) and homoscedasticity (Levene test) of the residuals were assessed.

To assess differences between JW and TW + MW, paired t-tests (if parametric assumptions were met) or the non-parametric Wilcoxon test for related samples were applied independently for each tree category (plantation and native). To assess differences between categories or origins (plantation or native), independent samples t-tests (with Welch adjustment in case of violation of homoscedasticity) or the Mann-Whitney U test (non-parametric) were used.

To determine the differences between the variables related to cell morphometry in CW vs. OW, an independent samples t-test was applied.

Regardless of the test used and given the importance of assessing the practical significance of differences found beyond statistical significance, effect sizes were systematically calculated and interpreted. For t-tests, Cohen's d (for independent samples) or Cohen's d (for paired samples) were reported. For nonparametric tests, the effect size r was calculated from the value of the test statistics. Values were interpreted according to conventional criteria (Cohen 1988; Sawilowsky 2009).

RESULTS AND DISCUSSION

Radial Variation of the Oven-dry Density

The graphs for the oven-dry density for all plantation and native trees are presented in Figs. 4 and 5, respectively.

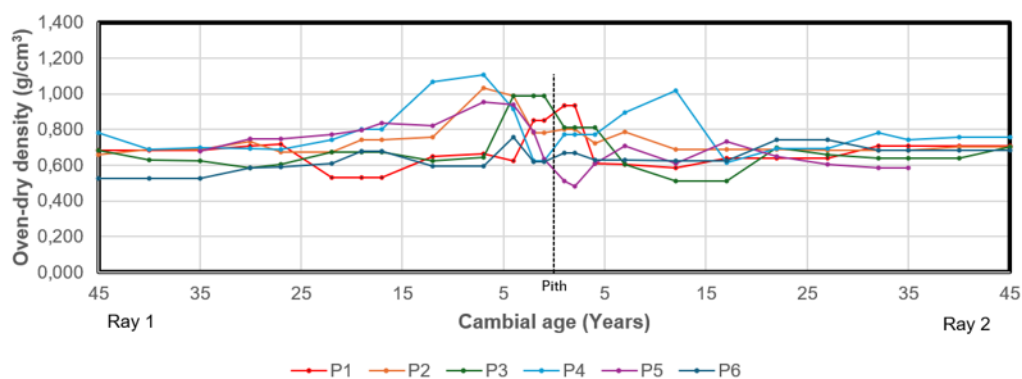


Fig. 4. Radial distribution of the oven-dry density in plantation (all trees)

The standard pattern of wood density should increase from the pith (low density) to the bark (high density) as result of the gradual transition from fast-growing and thin-walled cells in juvenile wood to slower-growing and thicker-walled cells in mature wood. The literature on *P. caribaea* consistently documents this radially increasing pattern. Márquez-Carrero *et al.* (2022), in 25-year-old plantations of *P. caribaea* var. *hondurensis*

in Venezuela, reported dry air densities of 0.595 g/cm³ near the pith, 0.681 g/cm³ in the middle zone, and 0.820 g/cm³ near the cambium. Riki *et al.* (2022) found that rings 11 to 15 from the pith had the highest density values (0.649 g/cm³) in *P. caribaea* from Nigeria. In their study of *P. caribaea* in Sri Lanka, Ruwanpathirana *et al.* (1998) documented the following density pattern: high in the first 2 to 3 cm near the pith, rapidly decreasing to a minimum, and then increasing toward the bark.

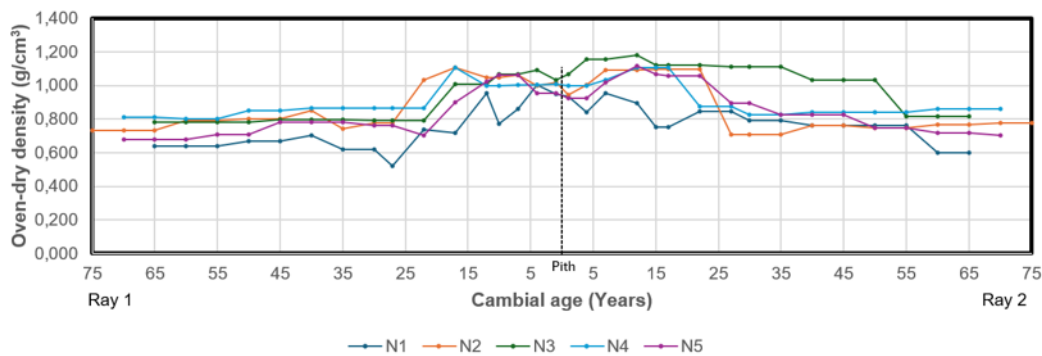


Fig. 5. Radial distribution of the oven-dry density in native (all trees)

However, this was not the pattern observed in this study (Figs. 4 and 5, Table 1). The difference may have been due to high resin content in areas close to the pith, development of heartwood (HW), and the presence of compression wood (CW). These factors may explain a high variability between trees in the JW and TW regions, especially in the plantation category. Cown (1981) reported the effect of resin impregnation on the increase in density in areas near the pith in *P. caribaea* var. *hondurensis*.

A compelling example of this phenomenon was observed in tree N3 from the native population (Fig. 5). Despite maintaining a very small global eccentricity (4.54% - Table 3) at its advanced cambial age of over 60 years, its radial density and shrinkage profiles exhibited a highly distinct, localized asymmetry. Tree N3 reached its maximum oven-dry density on Ray 2 axis (the opposite, narrower side), whereas its highest volumetric shrinkage was recorded on Ray 1 axis (the eccentric, wider side), culminating in the highest overall shrinkage among all examined native trees (Table 3).

Macroscale re-examination of the physical cross-section of tree N3 revealed that the heartwood zone had developed significantly more extensively on the Ray 2 side than on Ray 1. This anatomical configuration confirms that the prolonged high-density zone extending outwards on Ray 2 axis was heavily driven by asymmetric duraminification, characterized by intense resinification and heartwood extractive deposition over several decades. These hydrophobic chemical compounds artificially inflated the oven-dry mass, and consequently the calculated density, without inducing a corresponding increase in transverse shrinkage, as extractives do not participate in the hygroscopic expansion or contraction of the cell wall matrix. Conversely, the lower extractive content but higher cell-wall substance fraction on Ray 1 axis dictated its elevated volumetric shrinkage. The structural layout of tree N3 suggests that while it likely experienced directional mechanical stress during its earlier developmental decades (triggering localized defense mechanisms and asymmetric heartwood formation on Ray 2 axis), it successfully re-stabilized its growth symmetry in later years.

Table 1. Oven-dry Density Values for Plantation and Native Trees and Per Different Tree Regions; Density Values in g/cm³.

Tree Code	Age (Yrs)	Eccent. (%)	Oven-dry mean dens. in HW	Oven-dry mean dens. in SW	Proportional diff. of HW related to SW (%)	Oven-dry mean dens. in JW	Oven-dry mean dens. in TW+MW	Oven-dry mean dens. per sample	Proportional diff. of JW related to TW + MW (%)
P1	44	12.63	0.705	0.653	7.96	0.714	0.653	0.684	9.34
P2	44	10.39	0.865	0.700	23.57	0.823	0.723	0.773	13.83
P3	44	3.14	0.898	0.634	41.64	0.761	0.636	0.699	19.65
P4	46	15.29	0.914	0.724	26.24	0.802	0.792	0.797	1.26
P5	36	5.84	0.703	0.711	-1.14	0.703	0.712	0.708	-1.28
P6	44	18.99	0.666	0.625	6.56	0.666	0.625	0.646	6.56
All plantation trees (mean)	43	11.05	0.792 (0.17)	0.675 (0.07)	17.33	0.745 (0.17)	0.690 (0.09)	0.718 (0.08)	7.97
N1	64	13.28	0.907	0.697	30.13	0.932	0.752	0.842	23.94
N2	74	19.63	1.040	0.768	35.42	0.991	0.875	0.933	13.26
N3	66	4.54	1.092	0.843	29.54	1.086	0.970	1.028	11.96
N4	71	8.81	1.036	0.843	22.89	1.011	0.900	0.956	12.33
N5	70	2.95	1.013	0.752	34.71	0.989	0.845	0.917	17.04
All native trees (mean)	69	9.84	1.018 (0.09)	0.781 (0.09)	30.35	1.002 (0.08)	0.868 (0.15)	0.935 (0.17)	15.44
Proportional diff. of native related to plantation (%)			28.54	15.70		34.50	25.80	30.22	

Note: The numbers in parentheses next to each mean value are the standard deviations (SD).

Shifting environmental and silvicultural dynamics typical of older native forests, such as the fall of neighboring canopy trees or changes in localized wind exposure, frequently alter the mechanical demands on the stem over a 60-year lifespan. Ultimately, these findings demonstrate that density anomalies near the pith and along eccentric axes are functional biological adaptations. They further demonstrate that wood quality variations in old-growth native populations do not respond exclusively to absolute density profiles, but are instead governed by a complex, localized interaction of cell-wall microfibril angles, extractive topography, and historical reaction wood development across the stem profile.

The oven-dry density per plantation and native trees and per different tree regions is contained in Table 1. The mean oven-dry density in plantation category was 0.718 g/cm^3 and 0.935 g/cm^3 in native. The oven-dry density was higher in the heartwood area in comparison with the sapwood region by 17.3% in plantation and by 30.4% in native, due to the high content in extractives and resin deposited in the heartwood during the duramification process, which also increased the density of JW in comparison with the neighboring wood. In plantation, the density of JW ranged from 0.666 to 0.823 g/cm^3 , with a mean of 0.745 g/cm^3 , while in the TW+MW it ranged from 0.625 to 0.792 g/cm^3 with a mean of 0.690 g/cm^3 . The JW oven-dry density was higher than that in TW+MW by 7.97%. The density of JW of native ranged from 0.932 to 1.086 g/cm^3 , with a mean of 1.002 g/cm^3 , while in the TW+MW ranged from 0.752 to 0.970 g/cm^3 , with mean of 0.868 g/cm^3 . The JW oven-dry density was higher than that in TW+MW by 15.44%. Plumptre (1984) pointed out that in *P. caribaea* the resin is the most important substance different from the wood itself in its composition, since it can represent up to 40% of the weight of a piece of wood. Except for P5, all trees in both categories showed higher density in HW related to SW and in JW related to TW+MW. Tree P5 can be considered an outlier, because in both cases, it exhibited negative values, suggesting that in this tree the sapwood was slightly denser than the heartwood, and the transition + mature wood is slightly denser than the juvenile wood.

This behavior (different from the rest of the evaluated trees) could be due to low extractive content in the heartwood (younger tree); a high proportion of juvenile wood (46%) and/or particular genetic or microenvironmental characteristics.

The Wilcoxon test indicated that the oven-dry density of the heartwood in plantation was significantly higher than that of the sapwood, with statistically significant differences between the trees in the plantation category: $Z = -1.992$, $p = 0.046^*$, with a large effect size ($r = 0.81$). The juvenile wood had significantly higher oven-dry density than that of transition + mature wood, with statistically significant differences between trees in the plantation category $Z = -1.992$, $p = 0.046^*$, with a large effect size ($r = 0.81$).

The Wilcoxon statistical test confirmed that there were significant differences between the native trees for the oven-dry density variable comparing heartwood vs. sapwood ($Z = -2.023$, $p = 0.043^*$, $r = 0.90$), as well as comparing juvenile wood vs. transition + mature wood ($Z = -2.032$, $p = 0.042^*$, $r = 0.91$). Overall, the trees from native were app. 20 to 30 years older than those from plantation, and the latter showed generally more eccentricity. The radial distribution of the mean oven-dry density from the pith to the bark, calculated from all plantation and, respectively, all native trees, in Fig. 6, shows high values in JW and TW followed by a steady evolution in the mature zone.

The radial distribution of the oven-dry density evaluated in both plantation and native categories reveals that the highest differences were mainly found in the juvenile wood and transition zones. This may be attributed to the higher extractives and resin

content in the heartwood of native trees, which are older than the plantation ones and comprising a larger proportion of heartwood.

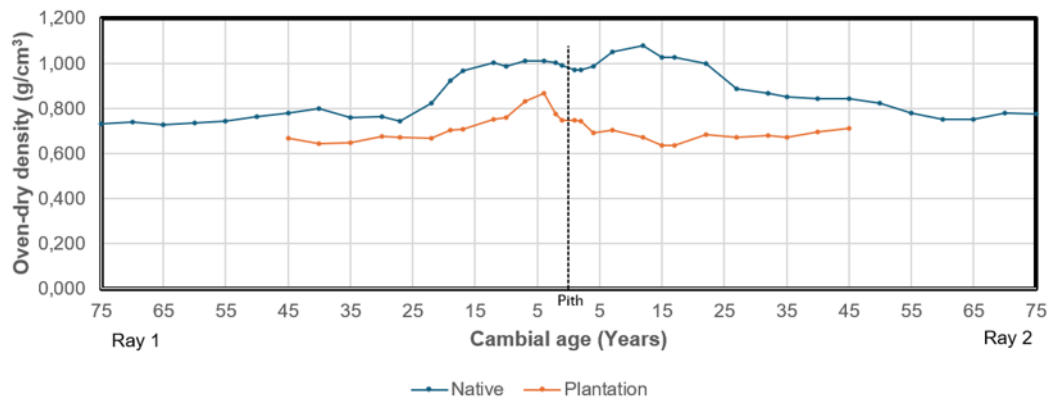


Fig. 6. Radial variation of the oven-dry density in *P. caribaea* var. *caribaea* (native vs. plantation)

The oven-dry density was consistently higher in native than in plantation, especially in the area close to the pith. Considering the mean density per origin, the native had 30.2% higher overall oven-dry density compared to plantation (0.935 g/cm^3 for native; 0.718 g/cm^3 for plantation) and 25.8% in the TW+MW (0.868 g/cm^3 for native vs. 0.690 g/cm^3 for plantation). Overall, oven-dry density was significantly higher in the native category compared to the plantation category, both in heartwood vs. sapwood and in juvenile wood vs. transition + mature wood, because the density of wood is influenced by age, growth rate and edaphic conditions. This was shown by Corrêa and Bellote (2011), in their study on the influence of soil properties on the wood quality of *P. caribaea* var. *hondurensis*. Fast-grown trees in plantations, harvested at younger ages, have a larger proportion of less dense, juvenile wood and sapwood and a smaller amount of denser, mature wood and heartwood than older, slower-grown trees in natural populations. Specifically in this study, although the plantation soil exhibits a lower pH (4.53) than the native soil (5.41), which can limit the availability of certain nutrients such as phosphorus and calcium, it also presents a higher cation exchange capacity (small vs. very small) and a mesobasic base saturation degree (compared to oligobasic in the native site). These latter characteristics indicate a greater capacity to retain and exchange bases (Ca, Mg, K), which may promote faster growth rates, combined with silvicultural practices, generally associated with lower wood density and a higher proportion of juvenile wood. The proportion of heartwood and juvenile wood was determined in both cases, the native category presenting a higher proportion of heartwood (49.2%) compared to plantation (35.3%) and the plantation trees had a higher proportion of juvenile wood (30.8%) compared to the native ones (20.6%) (Trocones-Boggiano *et al.* 2025).

The non-parametric Mann Whitney U test indicated statistically significant differences between the two categories for oven-dry density in HW ($U = 180$, $Z = -5.62$, $p = 0.000^{**}$, $r = 0.64$) and in SW ($U = 594$, $Z = -5.64$, $p = 0.000^{**}$, $r = 0.53$). The oven-dry density of native was 28.5% higher in the HW and 15.70% higher in the SW compared to plantation.

Welch's t-test indicated significant differences between the categories regarding the oven-dry density for both juvenile wood and transition + mature wood. The oven-dry density of native was 34.50% higher in JW and 25.80% higher in the TW+MW compared to plantation.

Densitometry Determined by X-ray and Detection of Severe Compression Wood: An Example in Plantation

The following study has extended the research on wood density for specific growth areas of earlywood (EW) and latewood (LW), in order to understand the radial distribution of local density on the eccentric as well as on the opposite side of a plantation tree (coded P4 in this paper), which is characterized by a high eccentricity (15.3%). In Fig. 7, densitometric graphs appear overlapped on the respective samples.

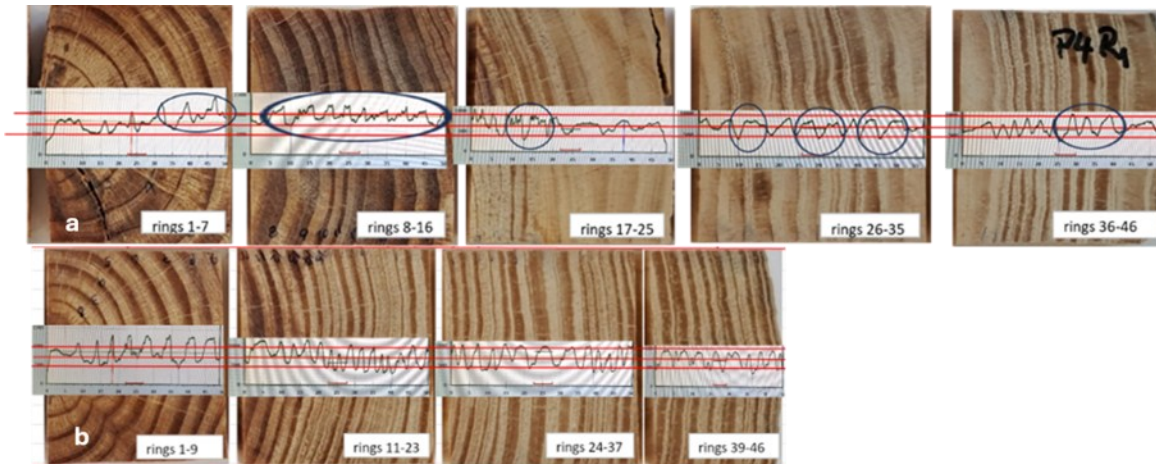


Fig. 7. X-Ray densitometry from the pith to the bark for a plantation tree (P4) of *P. caribaea* var. *caribaea*: a- taken from the widest side of the eccentric cross-section (Ray 1 axis); b- taken from the opposite side of the eccentric cross-section (Ray 2 axis). The ellipses visually presume the presence of compression wood (CW).

Densitometric data facilitated the identification of the growth rings and the exclusion of the false rings, which often occur in this species (Trocones-Boggiano *et al.* 2025). Densitometry confirmed the initial tree age measured on sample photograph (Fig. 2) with help of ImageJ 1.54g Java 1.8.0_345 (64-bit), (National Institutes of Health, USA) software (Trocones-Boggiano *et al.* 2025), namely 46 years (Table 1 and Fig. 7).

Figure 8 presents the local density values in earlywood (blue line) and latewood (orange line), as well as the mean ring density (gray line), for the radially distributed growth rings as a function of cambial age.

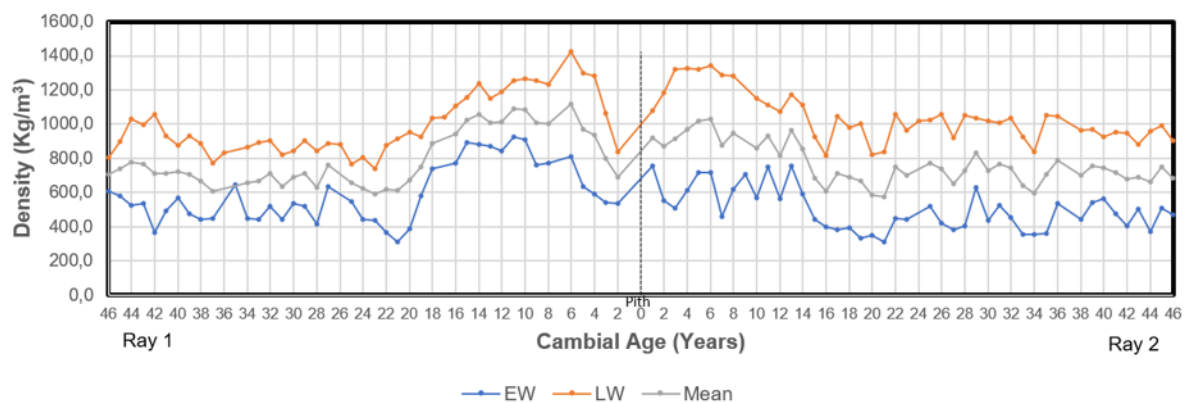


Fig. 8. Radial distribution of the density in EW, LW and the mean per growth ring in plantation, tree P4.

The pattern of density in LW and EW reveals an increased overall density in the region of heartwood, with a depression near the pith, followed by a steady variation towards the bark. The highest value of LW density was reached on Ray 1 axis, ring 6, 1420 kg/m³, while the highest density in EW reached 927 kg/m³ in ring 11 also of Ray 1 axis. It was interesting to see that the densities of EW and LW were very close on the eccentric side starting from ring 8 up to app. ring 19. The occurrence of compression wood was considered very likely on this side. Compression wood (CW) is a reaction wood that conifers develop on the eccentric side to counteract mechanical stress (wind, lean). This assumption was suggested by the fact that the massive eccentricity of the plantation led to very wide rings (Fig. 7), severe asymmetry in the volumetric shrinkage and anisotropy (Figs. 11 and 13, P4 with blue line), with pronounced variations in the eccentric side.

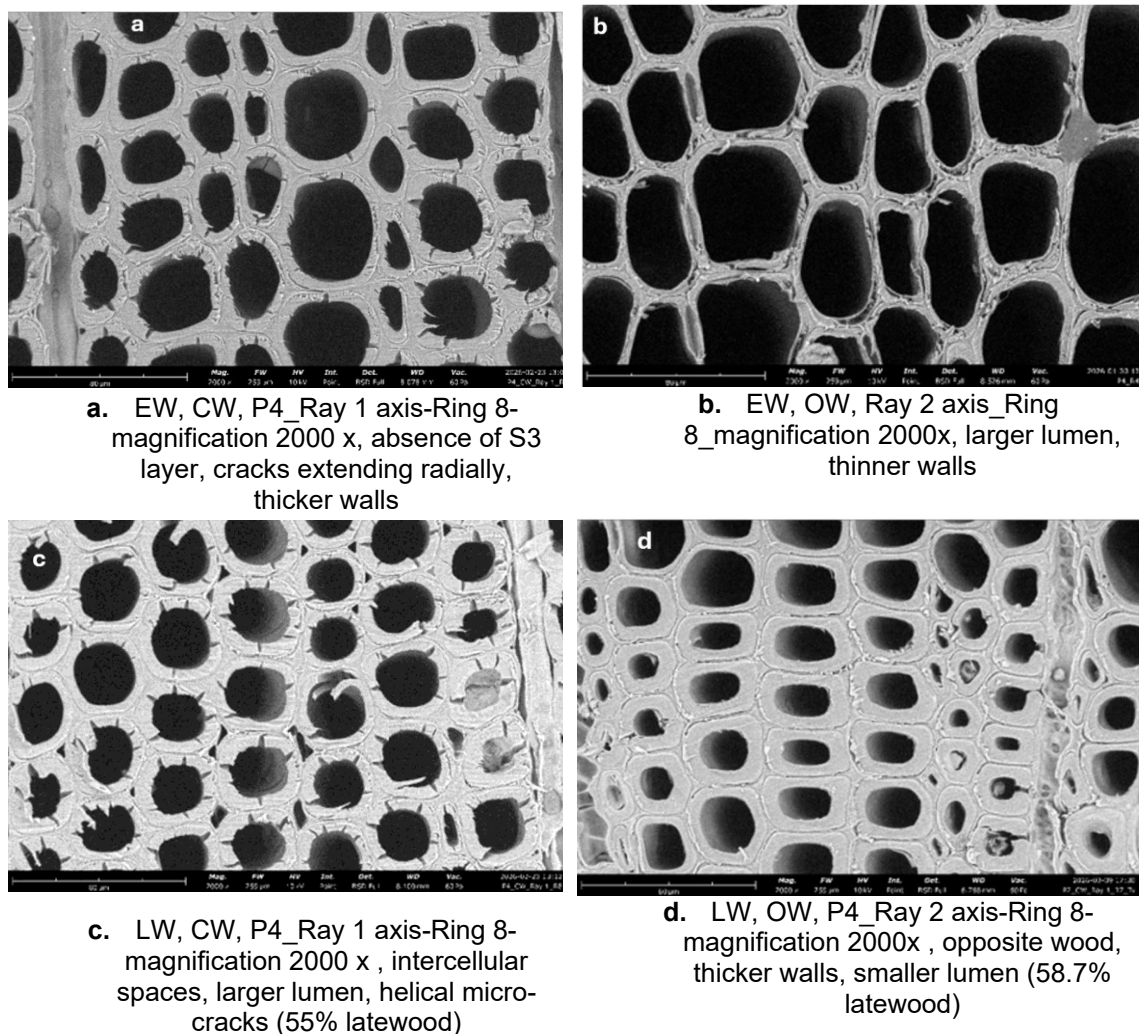


Fig. 9. Evidence of the formation of CW on the eccentric side of plantation P4 tree, growth ring 8 (a and c), compared with opposite wood (b and d) in *P. caribaea* var. *caribaea*

Comparative microscopic images taken with the SEM on a wide ring (ring 8) randomly selected from this suspected zone of the eccentric side, revealed the presence of severe compression wood on the eccentric side (as classified by Donaldson *et al.* 2004). In the fast-growing plantation wood (P4), CW production directly correlated with wider growth rings (Ray 1 side = 8.93 mm vs. Ray 2 side = 6.09 mm) due to severe tree

eccentricity (15.29%). In Fig. 9, the images compare the EW and LW cells from both sides: eccentric (CW) and opposite (OW) for this particular growth ring. Figure 10 shows the typical helical micro-cracks in the cell walls of the tangential and radial sections, confirming the presence of CW on the eccentric side.

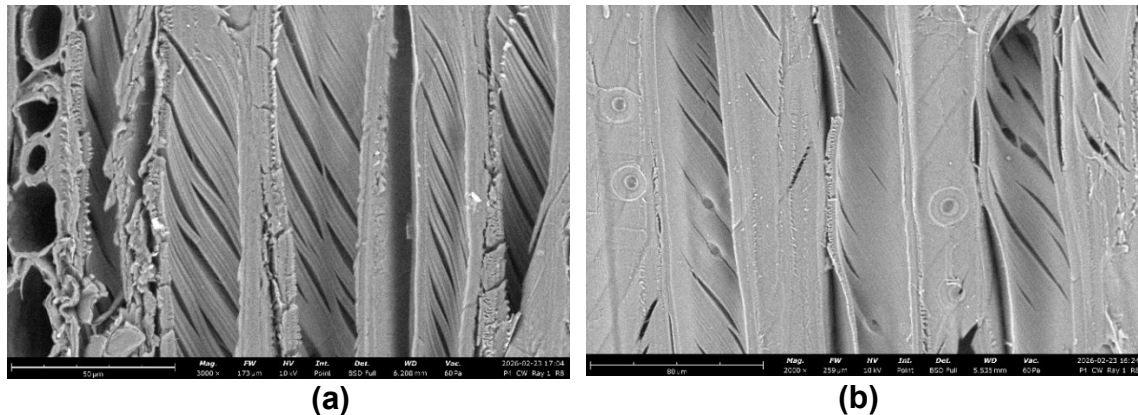


Fig. 10. Helical micro-cracks in plantation P4 tree, growth ring 8, confirming the presence of CW on the eccentric side in *P. caribaea* var. *caribaea*. in the (a) tangential and (b) radial section

The structural features observed in the CW micrographs, such as the distinctly circular tracheid profiles, systematic intercellular corner gaps, and internal helical wall cracks (Fig. 9, Fig.10), represent diagnostic anatomical responses verified by IAWA standards. These are not artifacts of microtome cutting or mechanical tissue preparation, which would otherwise present as non-geometric, random surface tears shearing linearly across contiguous cell networks. The SEM analysis of P4 served strictly as a representative visual case study demonstrating how severe stem eccentricity triggers compression wood (CW) formation at the cellular level. A T-test was performed on the cell dimensions in CW vs. OW for both EW and LW, and the results are shown in Table 2.

Table 2. Cell Dimensions for CW and OW in P4, Growth Ring 8 (EW and LW)

Code	Total Diameter		Lumen Diameter		Wall Thickness		Circularity	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
P4 R8 CW EW	40.635	3.96	30.886	4.19	4.874	1.04	0.908	0.02
P4 R8 OW EW	47.381	4.83	40.932	4.59	3.224	0.55	0.889	0.02
p-value/effect size	0.000*/1.53		0.000*/2.29		0.000*/1.99		0.001*/0.95	
P4 R8 CW LW	35.449	3.16	22.400	3.22	6.524	0.52	0.912	0.02
P4 R8 OW LW	33.940	3.22	17.898	3.20	8.021	1.16	0.913	0.02
p-value/effect size	0.052 ^{ns} /0.47		0.000*/1.40		0.000*/1.66		0.891 ^{ns} /0.05	

ns= no significant; *= significant (p<0.05)

Diameters and wall thickness are in μm .

The presence of severe compression wood is characterized by the absence of the S3 layer in EW and a very large cellulose microfibril angle in the S2 layer, as suggested by the helical cavities in Figs. 9 and 10. EW-CW cells had significantly thicker walls (4.87 μm vs. 3.22 μm) and smaller lumens (30.9 μm vs. 40.9 μm) than OW. Cells were also more circular (0.908 in CW vs. 0.889 in OW). The effect size shows very strong differences between compression wood (CW) and opposite wood (OW), particularly in earlywood (EW). The intercellular spaces and the circularity of the tracheids (which no longer fit

compactly together like hexagons, but leave gaps) weaken the transverse cohesion of the wood. The radial and helical cracks observed via SEM are zones of structural failure. These internal micro-ruptures explain why, on the eccentric side, the tree exhibits unpredictable behavior (instability) on the volumetric shrinkage graph and chaotic anisotropy values (P4 with blue line in Fig. 11 and Fig. 13). The radial and helical cracks in the tracheid walls act as “stress-relief valves”. During drying, the cell wall can crack along these lines of microscopic weakness. The cells of EW were structurally modified into hyper-dense compression wood to compensate for the weakness of the trunk. Plantation trees, being subjected to rapid growth stress and instability (high eccentricity), were forced to massively produce reaction wood (compression wood) in the early rings to prevent collapse. CW raised the earlywood density significantly (771 vs. 617 kg/m³ in the opposite), compressing the LW/EW density ratio down to 1.60 (compared to 2.07 in OW). The earlywood (EW) is almost equal to the average density value in this tree. This confirms the SEM observation (circular tracheids with thick walls). The compression wood has biologically transformed the earlywood structure of a very large ring width (8.93 mm) into an extremely dense and massive zone (ring average density 1001.8 kg/m³). The generally lower LW/EW ratio on the eccentric side confirms this observation.

In the latewood zone, CW actually has a larger lumen (22.4 vs. 17.9 µm) and a thinner cell wall (6.52 vs. 8.02 µm) than its OW counterpart. However, the LW density was very high: 1230 kg/m³ in Ray 1 axis (55% latewood proportion) and 1280 kg/m³ in Ray 2 axis (58.7% latewood proportion). Although this result seems to partially contradict the classical dogma that compression wood always has thicker walls in the latewood, Harris (1977) and Timell (1986), reported that in latewood with severe compression wood or in certain species the expected trend can be reversed due to different factors or changes in cellulose deposition as reported by Cresswell *et al.* (2025).

For *Pinus spp.* the frequent presence of compression wood and its effect on density due to the greater thickness of the cell walls and reduction of the lumen has been mentioned by Tomazello Filho and Silva (1987); Donaldson *et al.* (2004) and Leonardon *et al.* (2010).

Taken together, these findings show that densities do not only reflect anatomical differences between sapwood, heartwood, or juvenile/mature wood zones, but are also modulated by the accumulation of extractives and the presence of compression wood.

Radial Variation of Shrinkage

Figures 11 and 12 illustrate the radial variation of the volumetric shrinkage for all plantation, respectively all native trees.

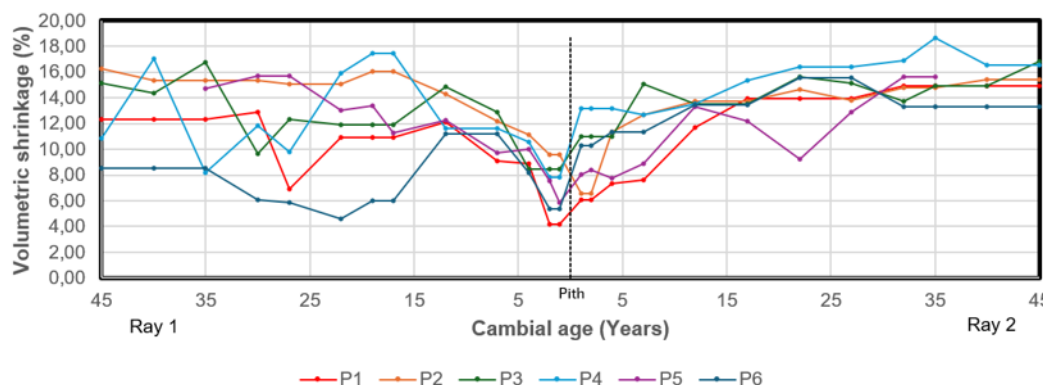


Fig. 11. Radial distribution of the volumetric shrinkage in plantation (all trees)

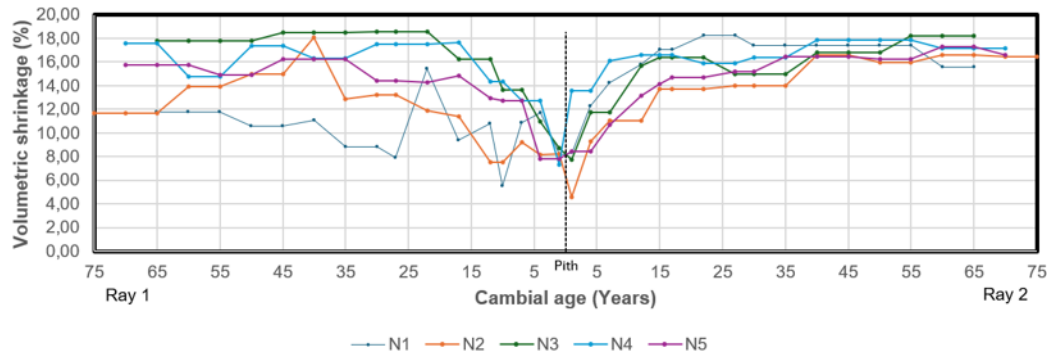


Fig. 12. Radial distribution of the volumetric shrinkage in native (all trees)

Table 3 presents the values of the volumetric shrinkage, analyzed for all plantation and all native trees, in the juvenile and transition + mature wood zones. The volumetric shrinkage was consistently lower in juvenile wood than in the TW+MW, for each individual tree. This may be due not only to the anatomical characteristics of the juvenile wood (steeper fibril angle, lower proportion of latewood), but also to the presence of compression wood and the high resin content, factors that modify the expected volumetric behavior. These factors greatly influence the behavior of shrinkage values in the trunk cross-section of conifers (Gapare *et al.* 2008; Hara *et al.* 2023). Especially in *P. caribaea*, Plumptre (1984) has highlighted that this species is very prone to present high resin content in the juvenile wood zone.

Table 3. Volumetric Shrinkage Values for Plantation and Native Trees and per Different Type of Wood. Shrinkage Values in %

Tree Code	Eccentric. (%)	Volumetric shrinkage in JW	Volumetric shrinkage in TW + MW	Volumetric shrinkage mean per sample	Oven-dry mean density per sample (g/cm ³)	Proportional difference of TW+MW related to JW
P1	12.63	6.52	11.96	9.24	0.684	83.44
P2	10.39	9.65	14.54	12.10	0.773	50.67
P3	3.14	11.85	14.21	13.03	0.699	19.92
P4	15.29	11.06	14.11	12.59	0.797	27.58
P5	5.84	8.27	13.05	10.66	0.708	57.80
P6	18.99	8.80	9.39	9.10	0.646	6.71
All plantation trees (mean)		9.36 (2.53)	12.88 (2.98)	11.12 (3.41)	0.718 (0.08)	37.61
N1	13.28	10.12	12.82	11.47	0.842	26.68
N2	19.63	7.55	13.47	10.51	0.933	78.41
N3	4.54	9.80	16.68	13.24	1.028	70.20
N4	8.81	12.43	16.62	14.53	0.956	33.71
N5	2.95	9.92	15.14	12.53	0.917	52.62
All native trees (mean)		9.96 (2.73)	14.95 (2.94)	12.46 (3.47)	0.935 (0.17)	50.10
Proportional difference of native related to plantation		6.41	16.07	12.03	30.22	

Note: The numbers in parentheses next to each mean value are the standard deviations (SD).

Furthermore, the data in the JW and on Ray 2 axis was more tight together (Figs. 11 and 12), whereas was dispersed on the eccentric side and with a tendency to stabilize on the opposite side. This shows a similar behavior in the JW wood category and a more heterogeneous wood structure on the eccentric side, due to the high variability in growth rates, frequent and variable occurrence of compression wood, which is a very common characteristic in this species (Plumptre 1984).

In plantation, the volumetric shrinkage in JW ranged from 6.52% to 11.8%, with a mean value of 9.36 %, while in TW + MW ranged from 9.39% to 14.5% with a mean value of 12.9 % (Table 3). The mean volumetric shrinkage per sample ranged from a minimum of 9.1% in P6 to a maximum of 13.0% in P3, the mean volumetric shrinkage per category plantation being 11.1%.

A general directional trend of the trees' density with the volumetric shrinkage was observed, with the lowest values in the less dense trees, however, the correlation was not always consistent for denser trees, which supports the idea that in the analyzed samples of *P. caribaea* var. *caribaea* the variation in shrinkages may not be determined only by the absolute density, but also by the interaction of anatomical and chemical factors (resin content, proportion of juvenile wood, presence of compression wood).

In native, the volumetric shrinkage in JW ranged from 7.55% to 12.4%, with a mean value of 9.96%, while in TW + MW ranged from 12.8% to 16.7% with a mean value of 15.0 % (Table 3). The mean volumetric shrinkage per sample ranged from a minimum of 10.51 % in N2 to a maximum of 14.5% in N4, the mean volumetric shrinkage per category native being 12.5%. In this case, a similar behavior to the plantation category is observed in terms of the relationship between density and volumetric shrinkage.

Some authors observed in another coniferous species, *Pinus pinaster*, that the volumetric shrinkage can be predicted by the oven-dry density given the significant correlation between the two physical properties (Riesco and Barrio 2010). In the present study, while a general directional trend existed between higher density and greater shrinkage in mature wood, this relationship became statistically decoupled in juvenile zones due to resin inflation.

Statistical modeling revealed a weak direct correlation between absolute oven-dry density and volumetric shrinkage when looking across all growth zones. First, the trees had eccentricity from mild to severe. In the juvenile wood, in addition to having wider rings and a low proportion of latewood, the resin content was high, which caused an increase in the local density not associated with greater volumetric shrinkage. The presence of hydrophobic substances in this zone reduces the cell wall's affinity for water, and therefore, when the wood dries, the shrinkage is attenuated.

The native trees, being older and having a higher proportion of heartwood, likely contain a greater amount of these hydrophobic extractives, which could explain why their density is significantly higher overall, while their volumetric shrinkage is not proportionally greater. This resin-induced hydrophobicity is a key factor that decouples density from shrinkage in this species and should be considered when evaluating its wood quality. Trianoski *et al.* (2013) report similar observations in their study on dimensional stability of tropical pine species.

In the transition and mature wood, and especially on the eccentric side, in addition to the fact that some resin content can still be found (although lower), the presence of compression wood causes an increase in local density and longitudinal shrinkage, but not in radial and tangential shrinkages. These observations suggest that the variation in shrinkage does not respond exclusively to the hygroscopic cell wall fraction, but also to

the extractive components and the incidence of compression wood, factors that modify the expected volumetric behavior.

Figures 13 and 14 contain the radial distribution of the anisotropy in all plantation trees, respectively all native trees. As in case of the volumetric shrinkage the anisotropy coefficient was more grouped in Ray 2 side and more dispersed in the eccentric side.

Table 4 presents the values of the anisotropy coefficient, analyzed for all plantation and all native trees, in the juvenile and transition + mature wood zones.

Table 4. Anisotropy Coefficient Values for Plantation and Native Trees and per Different Type of Wood

Tree Code	Eccentric. (%)	Anisotropy in JW	Anisotropy in TW + MW	Anisotropy mean per sample	Oven-dry mean density per sample (g/cm ³)	Proportional difference of JW related to TW+MW
P1	12.63	2.19	1.56	1.83	0.684	40.39
P2	10.39	1.44	1.45	1.45	0.773	- 0.69
P3	3.14	1.44	1.50	1.48	0.699	- 4.00
P4	15.29	1.54	1.49	1.50	0.797	3.36
P5	5.84	1.38	1.22	1.29	0.708	13.12
P6	18.99	1.76	1.76	1.76	0.646	0.00
All plantation trees (mean)		1.63 (0.46)	1.50 (0.28)	1.56 (0.35)	0.718 (0.08)	8.67
N1	13.28	1.57	1.44	1.51	0.842	9.03
N2	19.63	1.43	1.35	1.39	0.933	5.93
N3	4.54	1.41	1.17	1.29	1.028	20.51
N4	8.81	1.33	1.22	1.28	0.956	9.02
N5	2.95	1.28	1.22	1.25	0.917	4.92
All native trees (mean)		1.40 (0.11)	1.28 (0.11)	1.34 (0.11)	0.935 (0.17)	9.38
Proportional difference of plantation related to native		16.43	17.19	16.42		

Note: The numbers in parentheses next to each mean value are the standard deviations (SD).

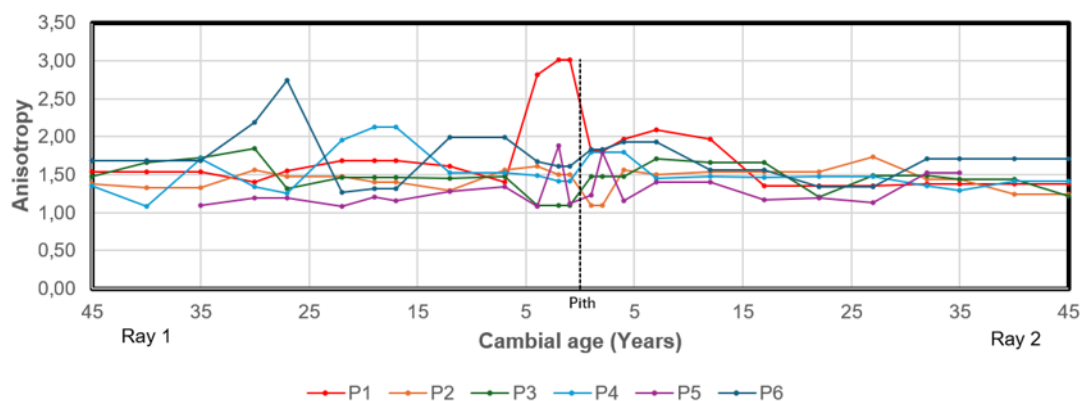


Fig. 13. Radial distribution of the anisotropy in plantation (all trees)

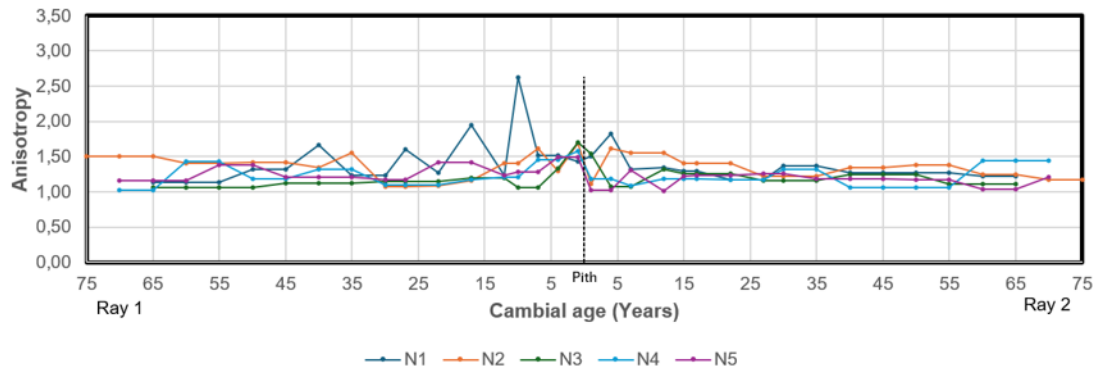


Fig. 14. Radial distribution of the anisotropy in native (all trees)

In plantation, the anisotropy coefficient in JW ranged from 1.38 to 2.19, with a mean value of 1.63, while in TW + MW ranged from 1.22 to 1.76 with a mean value of 1.50. The mean anisotropy per sample ranged from a minimum of 1.29 in P5 to a maximum of 1.83 in P1, the mean anisotropy per category plantation being 1.56. A distinct trend was observed between stem eccentricity and the shrinkage anisotropy coefficient; trees with high eccentricity exhibited elevated transverse anisotropy. This pattern is consistent with asymmetrical wood development on the eccentric side, characterized by pronounced variations in growth ring width, localized density shifts, and the frequent formation of compression wood.

In native, the anisotropy in JW ranged from 1.28 to 1.57, with a mean value of 1.40, while in TW + MW ranged from 1.17 to 1.44 with a mean value of 1.28. The mean anisotropy per sample ranged from a minimum of 1.25 in N5 to a maximum of 1.51 in N1, the mean anisotropy per category native being 1.34. There seemed to be a direct correlation between the severity of the trees eccentricity and their shrinkage anisotropy, enhanced by the particular characteristics of the eccentric side.

Table 5 gives an overview of all shrinkage types and anisotropy mean values per plantation and native categories in the juvenile region in comparison with the transition + mature wood.

Table 5. Centralized Shrinkage Values According to the Juvenile Wood (JW) vs. Transition + Mature wood (TW+MW) of all Plantation and Native Trees; Shrinkage Values in %

Shrinkage type (plantation P; native N)	JW	TW+MW	Mean (SD)	Proportional difference of TW+MW compared to JW (%)
P-Radial	3.78	5.45	4.62 (1.63)	44.18
P-Tangential	5.93	7.89	6.91 (2.12)	33.05
P-Longitudinal	1.13	1.24	1.19 (0.65)	9.73
P-Volumetric	9.36	12.88	11.12 (3.41)	37.61
P-Anisotropy	1.63	1.50	1.56 (0.35)	-7.98
N-Radial	4.32	6.94	5.63 (1.89)	60.65
N-Tangential	5.92	8.63	7.28 (1.90)	45.78
N-Longitudinal	1.13	1.16	1.15 (0.50)	2.65
N-Volumetric	9.96	14.95	12.46 (3.47)	50.10
N-Anisotropy	1.40	1.28	1.34 (0.11)	-8.57

Table 5 outlines the variations in wood shrinkage across different growth zones. Transverse and volumetric shrinkage values were substantially higher in the transition and mature wood zones (TW+MW) than in the juvenile wood (JW). For plantation-grown trees, TW+MW exhibited higher radial (44.2%), tangential (33.0%), and volumetric (37.6%) shrinkage. A similar trend occurred in native trees, with increases of 60.65% for radial, 45.78% for tangential, and 50.10% for volumetric shrinkage. Conversely, longitudinal shrinkage showed minimal variance between the zones, increasing by only 9.73% in plantation and 2.65% in native trees within the TW+MW region.

The values of anisotropy coefficient were lower in TW + MW in comparison with JW by 7.98% in plantation and by 8.57% in native.

Differences in shrinkage behavior in juvenile wood compared to transition and mature wood have been widely reported in the literature (Panshin and de Zeeuw 1980; Kollmann and Côté 1984; González-Cruz *et al.* 2007; Vidaurre *et al.* 2012; Udoakpan 2013; Loiola *et al.* 2021). The transverse and volumetric results observed in the present work are expected, since the higher shrinkage values in the mature wood, compared to the juvenile zone, are directly related to their anatomical differences. Mature wood is characterized by significantly narrower annual growth rings, a structural feature that inherently induces a higher relative proportion of latewood. This latewood zone consists of slow-growing, thicker-walled cells with reduced lumens, which substantially increases the total cell-wall substance fraction per unit volume available to hold bound water. Consequently, during the drying process, this concentration of hygroscopic material generates greater dimensional changes, thereby directly driving up the overall magnitude of volumetric, radial, and tangential shrinkage. In contrast, juvenile wood contains predominantly thinner-walled cells with larger lumens, which reduce overall volumetric variations during drying. While longitudinal shrinkage typically decreases with wood maturity due to variations in the microfibril angle, the minimal differences observed between zones in this study suggest a highly stabilized transition.

Furthermore, the anisotropy coefficient was lower in mature wood, which may be attributed to the fact that the relationship between radial and tangential shrinkage in juvenile wood is more variable due to its lower degree of structural organization and differences in the relative proportion of cellular elements (Zobel and van Buijtenen 1989).

The superior dimensional stability observed in the mature zones of the native timber, manifested as a lower anisotropy coefficient (T/R ratio = 1.28) approaching the reference standard, is structurally bound to ring geometry. Mature native wood is characterized by significantly narrower, tightly packed annual growth rings containing a high percentage of latewood tracheids. Because latewood features hyper-thick cell walls and highly aligned microfibrils with low microfibril angles, the dominance of these narrow, uniform rings enforces exceptional transverse cross-sectional balance. This structural equilibrium minimizes the differential shrinkage gradient between the tangential and radial planes, acting as a defense mechanism against internal drying stresses that typically induce structural checking, cupping, or warping.

Figures 15 and 16 visually compare the radial variation of plantation and native trees *P. caribaea* var. *caribaea*, in terms of volumetric shrinkage and anisotropy respectively.

Radial, tangential, and volumetric shrinkage values were consistently higher in native trees than in plantation-grown trees (Table 5, Fig. 15), with the most pronounced differences occurring in the transition + mature wood zone. Conversely, the smallest discrepancy between the two origins was observed in tangential shrinkage. Within the

eccentric side of the stem, longitudinal shrinkage was higher in the plantation trees. This elevated longitudinal variation may be attributed to a higher incidence or greater severity of compression wood formation in the plantation-grown trees compared to their native counterparts (Table 5). Furthermore, the transverse anisotropy coefficient was lower in native wood, suggesting a more balanced shrinkage ratio and, consequently, greater dimensional stability during the drying process.

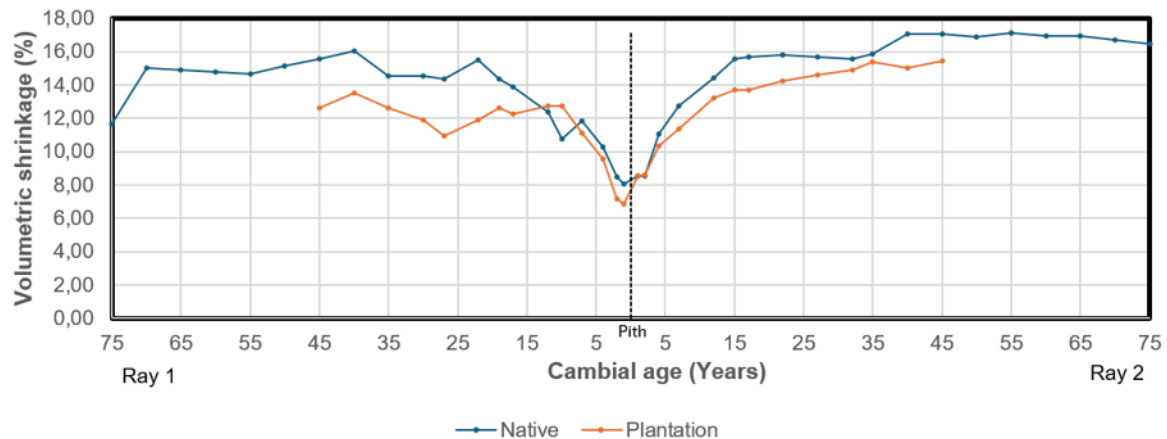


Fig. 15. Radial variation of the volumetric shrinkage in *P. caribaea* var. *caribaea* (plantation vs. native)

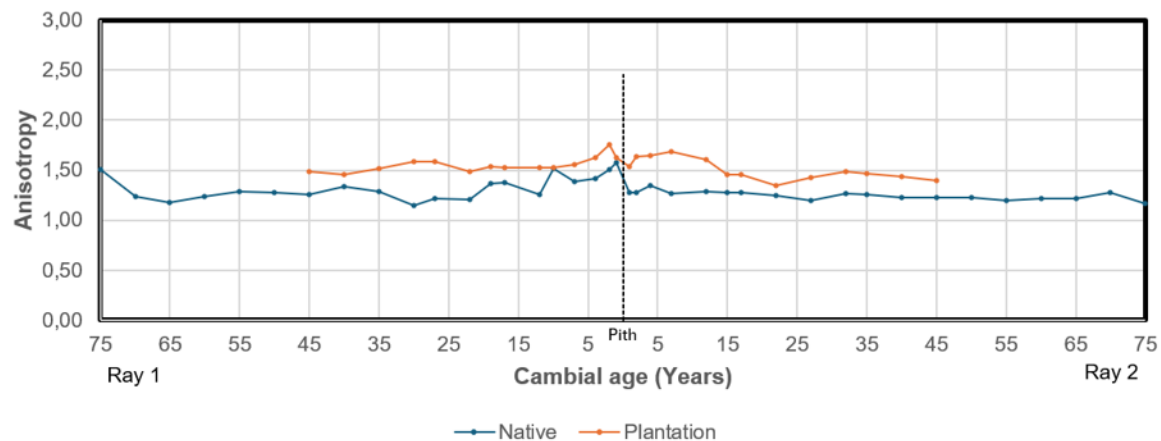


Fig. 16. Radial variation of the anisotropy in *P. caribaea* var. *caribaea* (plantation vs. native)

Similar values of volumetric shrinkage were observed in the juvenile wood zone for both categories, despite their markedly different oven-dry densities in this region (0.745 g/cm^3 for plantation and 1.002 g/cm^3 for native wood). This convergence strongly suggests that the microfibril angle plays a more dominant role in governing shrinkage within the juvenile zone than wood density alone, as a high microfibril angle is known to restrict transverse and volumetric dimensional changes. Conversely, within the transition and mature wood zones, the higher-density native wood exhibited substantially higher radial, tangential, and volumetric shrinkage compared to the plantation wood. Consequently, the relative percentage difference in shrinkage between the juvenile wood (JW) and the transition/mature wood (TW+MW) was more pronounced in the native trees than in the plantation-grown counterparts (Fig. 15).

Considering the mean values per sample category, native wood exhibited 12.0% higher volumetric shrinkage compared to plantation wood (12.5% vs. 11.1%). Similarly, native wood showed 22.0% higher radial shrinkage (5.63% vs. 4.62%) and 5.28% higher tangential shrinkage (7.28% vs. 6.91%). Conversely, plantation wood displayed 3.49% higher longitudinal shrinkage and 16.4% higher anisotropy than native wood. This behavior is primarily explained by the fact that fast-grown plantation trees retain a larger proportion of juvenile wood than older, slower-grown trees from natural populations. Specifically, the proportion of juvenile wood determined in a previous study (Trocones-Boggiano *et al.* 2025) was significantly higher in the plantation category, 30.8%, than in the native category, 20.6%. This elevated juvenile wood content, combined with accelerated growth rates that lower oven-dry density and a higher incidence of compression wood, collectively can be expected to suppress radial, tangential, and volumetric shrinkage while increasing longitudinal shrinkage and overall anisotropy.

The t-test indicated that there were no significant statistical differences between the categories for the shrinkages and anisotropy coefficient in the juvenile wood, confirming the previous observations. On the contrary, the non-parametric Mann Whitney U test indicated that there were significant statistical differences between the categories for radial and volumetric shrinkages, as well as for coefficient of anisotropy in TW+MW.

The results of this investigation are consistent with that of González-Cruz *et al.* (2007), who observed a similar pattern for shrinkage in samples from *P. caribaea* var. *caribaea* plantations. These authors obtained values for radial shrinkage that ranged from 3.1% close to the pith to 5.3% close to the bark; for tangential shrinkage the values ranged from 3.8% to 6.5%.

The shrinkage values obtained in this study fall within the range reported for *P. caribaea* in the literature. Radial shrinkage (4.62% in plantations, 5.63% in native stands) and tangential shrinkage (6.91% in plantations, 7.28% in native stands) are consistent with the values reported by Ofori (1999) for plantations in Ghana (radial: 4.5%, tangential: 6.6%) and with the reference values for *P. caribaea* native species (radial: 6.3%, tangential: 7.8%) in the Wood Database (Meier n.d). However, the observed longitudinal shrinkage (1.16 to 1.24%) in mature wood is considerably higher than the 0.43% reported by Ofori (1999) and the 0.15 to 0.88% documented by Boone and Chudnoff (1972) for wood without and with compression wood, respectively. This high longitudinal shrinkage suggests a greater incidence of compression wood in the trees evaluated in this study, which is consistent with the steep slope growing conditions of the plantation category. The greater mean anisotropy ($T/R = 1.34$ to 1.56) compared to the reference value ($T/R = 1.2$ in the Wood Database (Meier n.d), indicates a greater difference between tangential and radial shrinkage, which could translate into a higher risk of warping during drying as have been reported for this species by González-Cruz *et al.* (2019). However, in the transition and mature wood, the anisotropy of the native trees was 1.28, approaching the reference value in the Wood Database.

The results of this study have significant implications for the silvicultural management and wood utilization of *P. caribaea* var. *caribaea*. The higher density and shrinkage observed in native trees compared to plantation stock, alongside variations between juvenile wood (JW) and transition + mature wood (TW+MW), confirm that wood quality is heavily influenced by provenance, age, and growing conditions. Because juvenile wood forms within the first 5 to 9 years, whereas mature wood develops only after 21 to 26 years, plantation trees naturally exhibit a larger juvenile zone. Therefore, it is recommended to extend plantation rotation ages to increase the proportion of high-density,

dimensionally stable transition and mature wood. While this species adapts well to diverse uses, from pulp and paper to structural sawn timber, logs must be segregated by density and origin. High-density wood (native or older plantations) should be reserved for structural applications and high-value products, whereas lower-density wood (younger plantations) is best utilized for panels, pulp, or non-structural applications.

CONCLUSIONS

1. The wood density of *P. caribaea* var. *caribaea* exhibited a highly heterogeneous radial behavior conditioned by anatomical differences among wood zones, resin content, and compression wood near the pith. Native forest trees produced significantly denser timber than fast-grown plantation wood, showing an average oven-dry density of 0.935 g/cm³ compared to 0.718 g/cm³. This represents a 30.2% difference driven by older age, slower growth, and a higher proportion of mature wood. Across both categories, heartwood consistently displayed statistically higher densities than sapwood due to duraminification and extractive deposition. Specifically, plantation heartwood reached an oven-dry density of 0.792 g/cm³ (+17.3% over sapwood), while native heartwood reached 1.02 g/cm³ (+30.4% over sapwood). Atypical density patterns occurred near the pith, where juvenile wood exhibited higher-than-expected oven-dry densities (0.745 g/cm³ in plantation and 1.00 g/cm³ in native trees) compared to the transition and mature wood zones (+8.0% and +15.4%, respectively). These anomalies stem from intense resinification within the heartwood zone and localized compression wood.
2. Wood shrinkage profiles showed a consistent structural trend across both tree categories, with values rising progressively from the juvenile wood into the transition and mature wood zones. This behavior may be strongly governed by the steeper microfibril angles, high resin content, and low latewood proportion in the juvenile wood. In plantation wood, radial shrinkage increased from 3.8% to 5.4%, tangential shrinkage from 5.9% to 7.9%, and volumetric shrinkage from 9.4% to 12.9% between the juvenile and mature zones. Native wood displayed even more pronounced spatial increases, with radial shrinkage rising from 4.3% to 6.9%, tangential shrinkage from 5.92% to 8.63%, and volumetric shrinkage from 10.0% to 15.0%. Cumulatively, native trees exhibited higher mean radial (5.63%), tangential (7.28%), and volumetric (12.5%) shrinkages than plantation trees (4.62%, 6.91%, and 11.12%, respectively), directly correlating with their higher overall density.
3. Longitudinal shrinkage demonstrated extensive variability across both growth categories, peaking on the eccentric side due to the formation of compression wood. The longitudinal shrinkage was 3.49% higher in plantation wood than in native wood (1.19 vs. 1.15). Oven-dry density and volumetric shrinkage shared a general upward trend, but not a direct relationship. This pattern was disrupted near the pith, where high resin buildup increased juvenile wood density without raising volumetric shrinkage.
4. Growth asymmetry and tree eccentricity exerted a powerful influence on the shrinkage anisotropy coefficient. Severe structural asymmetry induced hyper-dense compression wood on eccentric side of the plantation tree studied, altering cellular organization through thicker earlywood walls, smaller lumens, and radial micro-cracks. This structural modification minimized the typical density gap between earlywood and latewood, leading to unpredictable, chaotic anisotropy values that were higher in

juvenile wood. The average anisotropy coefficient decreased in the mature zones, with the radial mean being 1.56 in plantation wood and 1.34 in native wood, which highlights the lower risk of deformation and cracking during drying, hence the superior dimensional stability of mature native timber. Ultimately, while native forests yield structurally stable and dense material, the suitability of plantation wood for timber structural utilization is limited by the compounding effects of elevated eccentricity, compression wood, higher longitudinal shrinkage, and an increased proportion of juvenile wood.

5. While this study highlights the lower density and dimensional stability of fast-grown *P. caribaea* var. *caribaea* wood compared to native material, a strategic approach for its establishment is recommended. New plantations should utilize genetically improved material selected for high density and low stem eccentricity. Management should aim to extend rotation ages to increase the mature wood fraction. The decision to plant *P. caribaea* var. *caribaea* should therefore be based on a cost-benefit analysis that considers the intended final product and the specific site conditions.

ACKNOWLEDGMENTS

The authors acknowledge the structural funds project PRO-DD (POS-CCE, O.2.2.1., ID 123, SMIS 2637, ctr. No. 11/2009) for providing the infrastructure used in this work. The authors acknowledge the management and technical staff of the Agroforestry Companies in the provinces of Pinar del Río and Sancti Spíritus in Cuba for their support during the sampling process. The professors at the University of Pinar del Río "Hermanos Saiz Montes de Oca" for sharing their expertise in managing the species *P. caribaea* var. *caribaea*, especially Dr. Daniel Alberto Álvarez Lazo, and the professors at the University of Sancti Spíritus "José Martí Pérez," especially MSc. Luis Alberto Delgado Fernández. Special thanks to the team at the Faculty of Silviculture in the Transylvania University of Brasov, Romania, led by Dr. Raluca Enescu, for carrying out the soil analyses.

Conflict of Interest

The authors declare no conflict of interest.

Use of Generative AI

The authors declare no use of generative AI.

REFERENCES CITED

- Boone, R. S., and Chudnoff, M. (1972). "Compression wood formation and other characteristics of plantation-grown *Pinus caribaea*," *Forest Service Research Paper* ITF-13, Institute of Tropical Forestry, Rio Piedras, Puerto Rico.
<https://nfs1.contentdm.oclc.org/digital/collection/p17053coll2/id/54900>
- Borges de Moura, V., Hallak, T., Molina, J. C., Christoforo, A. L., and Rocco, F. A. (2021). "Influence of harvest region on properties of Cambará wood," *Maderas. Ciencia y Tecnología* 23(40), 1-12. <http://dx.doi.org/10.4067/s0718-221x2021000100440>

- Burdon, R. D., Kibblewhite, R. P., Walker, J. F., Megraw, R. A., Evans, R., and Cown, D. J. (2004). "Juvenile versus mature wood: A new concept, orthogonal to corewood versus outerwood, with special reference to *Pinus radiata* and *P. taeda*," *Forest Science* 50(4), 399-415. <https://doi.org/10.1093/forestscience/50.4.399>
- Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences*, 2nd Ed., Erlbaum, Hillsdale, NY, USA.
- Corrêa, R. S., and Bellote, A. J. (2011). "Soil properties and variability of tracheid dimensions and wood density in *Pinus caribaea* var. *hondurensis*," *Pesquisa Florestal Brasileira* 31(66), 93-102. <https://doi.org/10.4336/2011.pfb.31.66.93>
- Cown, D. J. (1981). "Wood density of *Pinus caribaea* var. *hondurensis* grown in Fiji," *New Zealand Journal of Forestry Science* 11(3), 244-253. <https://natlib.govt.nz/records/31163951>
- Cresswell, R., Dickson, A., Robertson, M., Gallagher, S., Risani, R., Le Guen, M. J., Temple, H., Liskza, A., Donaldson, L., Kirby, N., Ralph, J., Hill, S., Dupree, P., Dupree, R., and Sorieul, M. (2025). "The molecular architecture distinctions between compression, opposite and normal wood of *Pinus radiata*," *Frontiers in Plant Science* 16, 1-20. <https://doi.org/10.3389/fpls.2025.1576928>
- Donaldson, L. A., Grace, J., and Downes, G. M. (2004). "Within-tree variation in anatomical properties of compression wood in *Pinus radiata*," *IAWA Journal* 25(3), 253-271. <https://doi.org/10.1163/22941932-90000364>
- García-Quintana, Y., Geada-Lopez, G., Medina Malagón, L. M., Escarré-Estevez, A., Castillo Martínez, I., and Chile-Bocourt, A. (2007). "Caracterización de atributos ecofisiológicos de *Pinus caribaea* Morelet var. *caribaea* en diferentes ambientes," *Revista Forestal Baracoa* 26(1), 19-28. <https://www.forestbaracoa.edicionescervantes.com/index.php/fb/article/view/626>
- Gonçalves, J. C., Soares Vieira, F., Alves Camargos, J. A., and Zerbini, N. J. (2015). "Influence of site on properties of wood of *Pinus caribaea* var. *hondurensis*," *Cerne* 15(2), 251-255. <https://cerne.ufba.br/site/index.php/CERNE/article/view/210/180>
- González-Cruz, I., Lazo, D. Á., Quintero, A., Alves, A., and Rodríguez, J. (2007). "Comportamiento de algunas propiedades físicas en la dirección radial de la madera de la especie *Pinus caribaea* Morelet var. *caribaea*," *Revista Forestal Baracoa* 26(1), 37-43. <https://www.forestbaracoa.edicionescervantes.com/index.php/fb/article/view/628>
- González-Cruz, I., Álvarez-Lazo, D. A. and Velázquez-Abad, L. (2019). "Influence of some parameters on the warping of the sawn wood of *Pinus caribaea* Morelet, var. *caribaea*," *Revista Cubana de Ciencias Forestales* 7(1), 17-27. <http://cfores.upr.edu.cu/index.php/cfores/article/view/401>
- Gundogan, R., Bektas, I., Hakki, M. A., and Yuksel, A. (2005). "Relationship between site index and some physical properties of calabrian pine," *Forest Products Journal* 55(1), 45-48.
- Hara, E., Missanjo, E., and Kadzuwa, H. (2023). "Variation of wood density and shrinkage characters of *Pinus oocarpa* in Malawi," *Journal of Global Ecology and Environment* 18(2), 19-31. <https://doi.org/10.56557/jogee/2023/v18i28297>
- Harris, J. M. (1977). "Shrinkage and density of radiata pine compression wood in relation to its anatomy and mode of formation," *New Zealand Journal of Forestry Science* 7(1), 91-106. https://www.scionresearch.com/_data/assets/pdf_file/0005/59514/NZJFS7191.pdf
- Hughes, J. F. (1968). "Utilization of the wood of low altitude tropical pines," in: *FAO*

- World Symposium on Man-Made Forests and Their Industrial Importance*, FAO, Rome, Italy.
- IAWA Committee (2004). "IAWA list of microscopic features for softwood identification," *IAWA Journal* 25(1), 1-70. <https://doi.org/10.1163/22941932-90001616>
- ISO 3129 (2012). "Wood – Sampling methods and general requirements for physical and mechanical testing of small clear wood specimens," International Organization for Standardization, Geneva.
- ISO 13061-2 (2014). "Physical and mechanical properties of wood – Test methods for small clear wood specimens – Part 2: Determination of density for physical and mechanical tests," International Organization for Standardization, Geneva.
- ISO 13061-13 (2016). "Physical and mechanical properties of wood – Test methods for small clear wood specimens – Part 13: Determination of radial and tangential shrinkage," International Organization for Standardization, Geneva.
- ISO 13061-14 (2016). "Physical and mechanical properties of wood – Test methods for small clear wood specimens – Part 14: Determination of volumetric shrinkage," International Organization for Standardization, Geneva.
- Kiaei, M. (2011). "Anatomical, physical, and mechanical properties of eldar pine (*Pinus eldarica* Medw.) grown in the Kelardasht region," *Turkish Journal of Agriculture and Forestry* 35(1), 31-42. <https://doi.org/10.3906/tar-1001-552>
- Kollmann, F. P., and Côté, W. A. (1984). "Solid wood," in: *Principles of Wood Science and Technology*, Vol. 1, Springer-Verlag, Berlin, 180 pp. <https://link.springer.com/book/10.1007/978-3-642-87928-9>
- Leng, C., Wang, J., Dong, L., Yi, M., Luo, H., Zhang, L., Chen, T., Xie, W., Xie, H., and Lai, M. (2024). "Radial variation and early prediction of wood properties in *Pinus elliottii* Engelm. plantation," *Forests* 15(5), 1-13. <https://doi.org/10.3390/f15050870>
- Leonardon, M., Altaner, C. M., and Jarvis, M. C. (2010). "Wood shrinkage: influence of anatomy, cell wall architecture, chemical composition and cambial age," *European Journal of Wood and Wood Products* 68(3), 87-94. <https://doi.org/10.1007/s00107-009-0355-8>
- Loiola, P. L., Klitze, R. J., Rocha, M. P., and Vidaurre, G. B. (2021). "Physical properties of wood *Pinus caribaea* var. *caribaea*, *Pinus caribaea* var. *hondurensis* and *Pinus oocarpa* for pencil production," *Floresta* 51(2), 354-362. <https://doi.org/10.5380/rf.v51i2.68955>
- Luis, J. A. (2004). *The Study of Relief. Contributions to Sustainable Development in Cuba*, Ph.D. Dissertation, Instituto de Geografía Tropical, La Habana, Cuba.
- Márquez-Carrero, G., Valero, S. W., León-Hernández, W. J., Gutiérrez-Gotera, I. J., and Maldonado-Rangel, J. C. (2022). "Density variability in radial direction and in growth ring of *Pinus caribaea* var. *hondurensis* from plantations of 25 years old," *Tecnología en Marcha* 35(2), 115-124. <https://doi.org/10.18845/tm.v35i2.5866>
- Meier, E. (n.d). "Caribbean Pine," *The Wood Database*, (<https://www.wood-database.com/caribbean-pine/>), accessed 5 August 2026.
- Muller, B. G., Louw, J. H., and Malan, F. S. (2017). "Variation in selected solid wood properties of young *Pinus patula* from diverse sites in the Mpumalanga escarpment area in South Africa," *Southern Forests: A Journal of Forest Science* 79(4), 317-327. <https://doi.org/10.2989/00306525.2016.1255376>
- Ofori, J. (1999). "The effect of mycorrhizae on some physical properties of the wood of *Pinus caribaea*," *Ghana Journal of Forestry* 8, 15-21.

- <https://www.cabidigitallibrary.org/doi/full/10.5555/20000616463>
- Panshin, A. J., and de Zeeuw, C. (1980). "Structure, identification, properties, and uses of the commercial woods of the United States and Canada," in: *Textbook of Wood Technology*, 4th Ed., McGraw-Hill, New York.
- Plumptre, R. A. (1984). *Pinus caribaea. Volume 2: Wood Properties and Utilization, Tropical Forestry Papers No. 17*, Commonwealth Forestry Institute, University of Oxford, UK. <https://ora.ox.ac.uk/objects/uuid:38bd34d8-5c78-4184-a161-184add410cf0>
- Reyes Hernández, A., Cairo Cairo, I., Machado de Armas, J., Fundora Herrera, O., Ríos Albuérne, C., Ana Belkis Manes Suárez, A. B., Reyes Hernández, J., Quesada Iznaga, J. E., Lino Fleites, G., and Domínguez León, L. (2007). "Several agroforestry system effect about fertility indicators in ferrallitic red yellowing lixiviated soil in Topes de Collantes," *Centro Agrícola* 34(3), 5-9.
- Riesco Muñoz, G., and Barrio Anta, M. (2010). "Physical properties of thinning wood in maritime pine (*Pinus pinaster* Ait.): Case study," *European Journal of Wood and Wood Products* 129, 1021-1029. <https://doi.org/10.1007/s10342-010-0388-x>
- Riki, J. T. B., Adeyemo, S. M., Majekobaje, A. R., Oyelere, A. T., and Oluwadare, A. O. (2022). "Density variation in axial and radial positions of Caribbean pine (*Pinus caribaea* Morelet) grown in Afaka, Nigeria," *Journal of Agriculture and Environment* 15(2), 163-171.
- Ruano, A., García de Ceca, J. L., Cabrero, J. C., and Hermoso, E. (2022). "Shrinkage pattern assessment for black pine juvenile wood delimitation," *European Journal of Wood and Wood Products* 80, 131-138. <https://doi.org/10.1007/s00107-021-01736-9>
- Ruwanpathirana, N. D., Amarasekera, H. S., and de Silva, M. P. (1996). "Variation of *Pinus caribaea* wood density with height in tree and distance from pith, in different site classes," in: *Proceedings of the Second Annual Forestry Symposium*, Sri Lanka, 45-58. <https://doi.org/10.31357/fesympos.v0i0.1200>
- Sawilowsky, S. S. (2009). "New effect size rules of thumb," *Journal of Modern Applied Statistical Methods* 8(2), 597-599. <https://doi.org/10.22237/jmasm/1257035100>
- Schimleck, L., Dahlen, J., Mora, C., Antony, F., Eberhardt, T. L., and Onakpoma, I. (2025). "Maps depicting the within-tree wood property variation of some North American conifers: A review," *Canadian Journal of Forest Research* 55, 1-14. <https://doi.org/10.1139/cjfr-2024-0142>
- Schulgasser, K., and Witztum, A. (2015). "How the relationship between density and shrinkage of wood depends on its microstructure," *Wood Sci. Technol.* 49, 389-401. <https://doi.org/10.1007/s00226-015-0699-7>
- Timell, T. E. (1986). *Compression Wood in Gymnosperms*, Vols. 1-3, Springer-Verlag, Berlin. <https://www.scirp.org/reference/referencespapers?referenceid=1764789>
- Tomazello Filho, M., and Silva, J. C. (1987). "Formação e caracterização da madeira de compressão em *Pinus caribaea* var. *hondurensis*," *Instituto de Pesquisas e Estudos Florestais* (35), 41-48. <https://www.ipef.br/publicacoes/scientia/nr37/cap06.pdf>
- Trianoski, R., De Matos, J. L. M., Iwakiri, S., and Prata, J. G. (2013). "Evaluation of dimensional stability of tropical pine species," *Floresta e Ambiente* 20(3), 398-406. <http://dx.doi.org/10.4322/floram.2012.071>
- Trocones Boggiano, A. G., Gurau, L., Porojan, M., and Stanciu, M. D. (2025). "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," *BioResources* 20(3), 6242-6266. <https://doi.org/10.15376/biores.20.3.6242-6266>

- Udoakpan, U. I. (2013). "An evaluation of wood properties of *Pinus caribaea* (Morelet) in Oluwa Forest Reserve, Ondo State, Nigeria," *Ethiopian Journal of Environmental Studies and Management* 6(2), 159-169. <https://doi.org/10.4314/ejesm.v6i2.6>
- Vázquez-Cuecuecha, O. G., Zamora-Campos, E. M., García-Gallegos, E., and Ramírez-Flores, J. A. (2015). "Densidad básica de la madera de dos pinos y su relación con propiedades edáficas," *Madera y Bosques* 21(1), 129-138.
- Vidaurre, G., Lombardi, L. R., Oliveira, J. T. D. S., and Arantes, M. D. C. (2011). "Juvenile and mature wood and the properties of wood," *Floresta e Ambiente* 18(4), 469-480. <http://doi.org/10.4322/floram.2011.066>
- Wang, E., Chen, T., Pang, Sh., and Karalus, A. (2008). "Variation in anisotropic shrinkage of plantation-grown *Pinus radiata* wood," *Maderas, Ciencia y Tecnología* 10(3), 243-249. <https://dx.doi.org/10.4067/S0718-221X2008000300007>
- Zanuncio, A. J. V., Possato, E. L., Carvalho, A. G., Lopes, O. P., and Castro, V. R. (2022). "Basic density and scaling of juvenile and mature wood in *Pinus caribaea* trees," *Cellulose Chemistry and Technology* 56(5-6), 473-479.
- Zobel, B. J., and van Buijtenen, J. P. (1989). "Wood variation and wood properties," in: *Wood Variation*, Springer-Verlag, Berlin. https://doi.org/10.1007/978-3-642-74069-5_1

Article submitted: August 28, 2026; Peer review completed: September 20, 2026;
Revised version received and accepted: October 3, 2026; Published: October 19, 2026.
DOI: 10.15376/biores.21.4.11719-11746