European Journal of Wood and Wood Products
https://doi.org/10.1007/s00107-021-01758-3

ORIGINAL ARTICLE

Wood description and timber use investigation of *Pachyelasma tessmannii* (Harms) Harms

Robin Doucet[1] · **Jean-Louis Doucet**[1] · **Philippe Lejeune**[1] · **Cécile Verheyen**[2] · **Tom De Mil**[1] · **Patrick Martin**[3] ·
Paul Lagoute[4] · **Benoit Jourez**[2]

Received: 23 October 2020 / Accepted: 8 October 2021

Abstract

In Central Africa more than 75% of the total log production is focussed on only four timber species, whose populations are progressively being depleted. Reducing the impact on those flagship species by diversifying the exploitation could lead to better forest management in the long term. *Pachyelasma tessmannii* is a species whose trees are among the largest in the forests of Central Africa. Yet the properties of its wood are poorly documented. The aim of this study is to evaluate the possibility of using this species with a view to diversify forest production in Central Africa. Its physical and mechanical properties, its natural durability, and quantified radial variation were investigated. By using Hierarchical Clustering on Principal Component (HCPC), heartwood was classified among 98 other Central African timber species. *P. tessmannii* has a wavy grain and a coarse texture with a wide well-discernible sapwood. The wood is "heavy" with disadvantageous dimensional stability parameters. All mechanical properties are "medium", except for "low" impact bending strength. Heartwood is very durable against white and brown rot. All properties were significantly influenced by radial variation, except for axial compression strength. According to the HCPC, *P. tessmannii* should be suitable for stairs (inside/outside), flooring, decking, veneer (back and face of plywood), sliced veneer, furniture (inside/outside), exterior panelling, cabinetry, and joinery (inside/outside). The results obtained concerning the radial variation of basic density could suggest that the species is light-demanding. Considering that the sustainable exploitation of light-demanding species is often confronted with the problem of their lack of regeneration in closed-canopy rainforests, further studies are needed before promoting this species on international markets.

1 Introduction

For several years, the future of tropical forests has become a critical issue (Lamb et al. 2005; Alroy 2017; Mitchard 2018), highlighting the need for sustainable management of these ecosystems (Karsenty et al. 2008; FAO 2011). The Congo Basin hosts the second largest continuous forest block in the world, after the Amazon Basin, with an area close to 170 million hectares. In Central Africa, 28% of that area is allocated to timber production (FRM 2018) and generally logging is the main source of direct or indirect employment (Bayol et al. 2012). To sustainably manage their forests, Central African countries have adapted their laws and encouraged forest companies to produce and respect a sustainable management plan. Among other things, the aim is to combine production and forest resource recovery after a cutting cycle (25 years on average).

Despite these measures, a progressive impoverishment of some flagship timber species (*Entandrophragma cylindricum* (Sprague) Sprague, *Triplochiton scleroxylon* K. Schum., *Lophira alata* Banks ex C.F. Gaertn.) is observed (Karsenty and Gourlet-Fleury 2006; Biwolé 2015). In Africa, the number of tree species has been estimated to be around 4600 (Slik et al. 2015). However only four species (*Aucoumea klaineana* Roxb. ex Colebr., *Entandrophragma cylindricum* (Spraque) Sprague, *Triplochiton scleroxylon* K. Schum. and *Erythrophleum suaveolens* (Guill. & Perr.) Brenan) account for more than 75% of the total log production in

---

✉ Robin Doucet
robin.doucet@uliege.be

[1] Forest is Life, TERRA Teaching and Research Centre,
Gembloux Agro-Bio Tech, Université de Liège,
5030 Gembloux, Belgium

[2] Centre Wallon de Recherche Agronomique (CRA-W),
5030 Gembloux, Belgium

[3] Expertise Bois (EXB), 258 Chemin de la Fontaine Martin,
33290 Le Pian Médoc, France

[4] Pallisco SARL, Avenue des Cocotiers 478, BP 394, Douala,
Cameroon

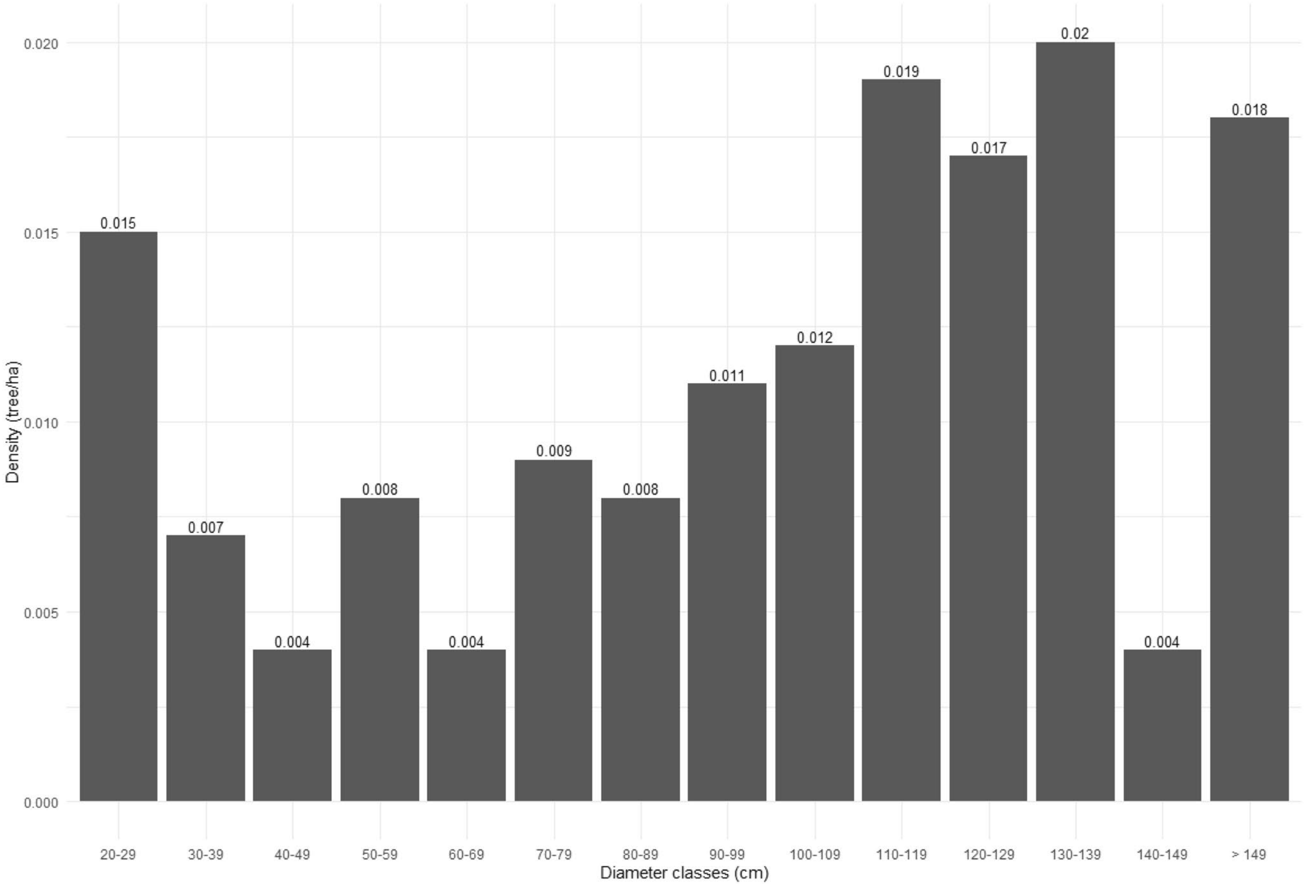


Fig. 1 Tree density by diameter class among the study site, highlighting lower densities in lower diameter classes

the Congo Basin (BAD 2019). Because most of them are light-demanding, their regeneration is generally absent in the forest understory and long-term recovery rates of their populations are low (Morin-Rivat et al. 2017). Diversifying timber production could reduce the impact on logging flagship species (Karsenty and Gourlet-Fleury 2006). As knowledge of wood properties is the main factor for accepting lesser-known timber species on international markets (Chaowana 2013; Boampong et al. 2015), those properties need to be investigated in a wide range of understudied species.

Pachyelasma tessmannii (Harms) Harms (commercial name: Eyek or Mekhogo) is a tree from the *Fabaceae* family, *Caesalpinioideae* sub-family. Although among the biggest trees of the African rainforest, only low volumes were exported from Central Africa: 5 and 1 m^3 of sawing, from Cameroun respectively in 2005 and 2006 (ATIBT 2006, 2007). Those very low exportation rates could be due to a lack of knowledge about this species. Indeed only few data such as density or heartwood/sapwood ratio and observations are documented (Lemmens et al. 2012).

The aims of this study are to (i) describe physical, mechanical and natural durability properties of *P. tessmannii* wood, (ii) quantify their radial variation, (iii) compare observed properties with those of better-known species in Central Africa in order to estimate main end uses and (iv) investigate the feasibility of a sustainable production considering ecological features of the species.

2 Material and methods

2.1 Study species and study site

Pachyelasma tessmannii can reach a height of 60 m and diameter of 2.5 m with a straight, cylindrical bole, sometimes deformed, with well-developed plank-buttresses. Its crown spreads like an umbrella. Leaves are 35 to 38.5 cm long. Its fruits are 4 angled pods that can reach 15–37 cm length, 2–2.5 cm width and 3.5–4 cm thickness Figure 1 (CJBG 2018). It occurs in secondary evergreen rainforest from south Niger to Central African Republic and from Gabon to Democratic Republic of Congo (Schmelzer and Gurib-Fakim 2008).

Following national regulations, minimum cutting diameters range from 50 cm in Cameroon to 70 cm in Gabon. Studied trees were collected in the Forest Management Unit (FMU) 10–044 granted to Pallisco, an FSC-certified logging company located in east Cameroon. The forest is moist and semi-deciduous (Fayolle et al. 2014). The climate is equatorial with an average temperature of 23.2 °C and an average annual rainfall of 1629 mm. The density of *P. tessmannii* trees (dbh, diameter at breast height > 20 cm) is 0.156 per ha. The density of harvestable trees following regulations of Cameroon is 0.132 per ha. Figure 1 gives the density of trees distribution by diameter classes in the study site (Nature + asbl 2015).

2.2 General description and preparation of samples

Four trees were harvested. Straightness and defects of the logs were determined. First boles were quarter sawn and the central planks of 10 cm thickness were collected on each tree (Table 1). To avoid deformation, they were slowly air-dried. Planks were divided into 5 equidistant segments, where sapwood thickness was recorded on each side of the planks. Colour, grain and texture were also determined for both sapwood and heartwood on the transversal plan. Finally, the transversal plane was sanded up to 1200 grit to visualize macroscopic anatomical traits.

After natural air-drying, planks were cut into 11–16 battens for Part A, 4–6 battens for Part B (Fig. 2), depending on planks' minimum width. These battens were finally cut into test samples following the process explained in Fig. 2. Defect-free samples were selected according to the ISO 3129 standard (ISO 2012) for physical and mechanical tests. Their dimensions are given in Table 2.

To study the influence of radial position on the wood properties, each sample was classified into one of the following wood parts:

i. Juvenile wood: samples within 10 cm from the pith and containing at least the 10 first years of the tree (Zobel and Sprague 1998; Ishiguri et al. 2007);
ii. Heartwood: samples containing heartwood out of juvenile wood;
iii. Sapwood: samples containing only sapwood.

Table 1 Dimension of *P. tessmannii* planks, in centimetres

Id plank	Length	Thickness	Maximum width	Minimum width
E1	318	10	114	111
E2	329	10	122	119
E3	326	10	79	72
E4	317	10	145	128

Since no study has yet been carried out on the wood moisture content (MC) behaviour of *P. tessmannii* under different environmental conditions, selected samples were stored at a standard atmosphere of 20 ± 2 °C and 65 ± 5% air relative humidity in order to reach an MC of 12% (ISO 2012). MC was regularly calculated on independent samples using the following equation: $MC = (mh - ma)/ma*100$ where mh = humid sample mass (g), ma = anhydrous sample mass after drying at 103 °C (g).

2.3 Wood properties

Wood properties, calculations for their determination and standards used are summarized in Table 2.

FSP calculation consisted in oven-drying samples of 5 different MC rankings from 0 to 60%. For each MC, the sample surface was calculated as the product of tangential and radial dimensions. The FSP, considered as the MC at which shrinkage begins during drying, was extrapolated using the linear regression modelled on the surface shrinkage induced by MC variation of the sample (Kollmann and Coté 1968; Bossu et al. 2016).

All strength properties were determined using an Instron-5582 machine, with the exception of the impact bending strength, which was determined with an Amsler machine. Due to lack of knowledge about *P. tessmannii* drying, some tests were not carried out at a 12% MC (Table 3). Once the MC is lower than the FSP, mechanical properties increase with decreasing MC (Kollmann and Coté 1968; Gerhards 1982; Kretschmann and Green 1996), therefore obtained values are probably underestimating values at 12% MC.

Natural durability was considered as the resistance of wood against attack of basidiomycete fungi. In this study, a white-rot fungus, *Trametes versicolor* (L.) Lloyd (CTB 863 strain), and a brown-rot fungus, *Coniophora puteana* (Schumach.) P. Karst. (BAM Ebw. 15 strain), were used.

Wood impregnation was assessed with regard to CEN/TR 14734: 2004 (CEN 2004). Impregnation classes were determined by measuring mean lateral penetration, minimal lateral penetration and minimal axial penetration of a copper sulphate solution in the wood after an impregnation cycle in a sealed chamber.

2.4 Data analyses

Analysis of variance (ANOVA) was performed to study the role of the radial position in wood properties. To verify

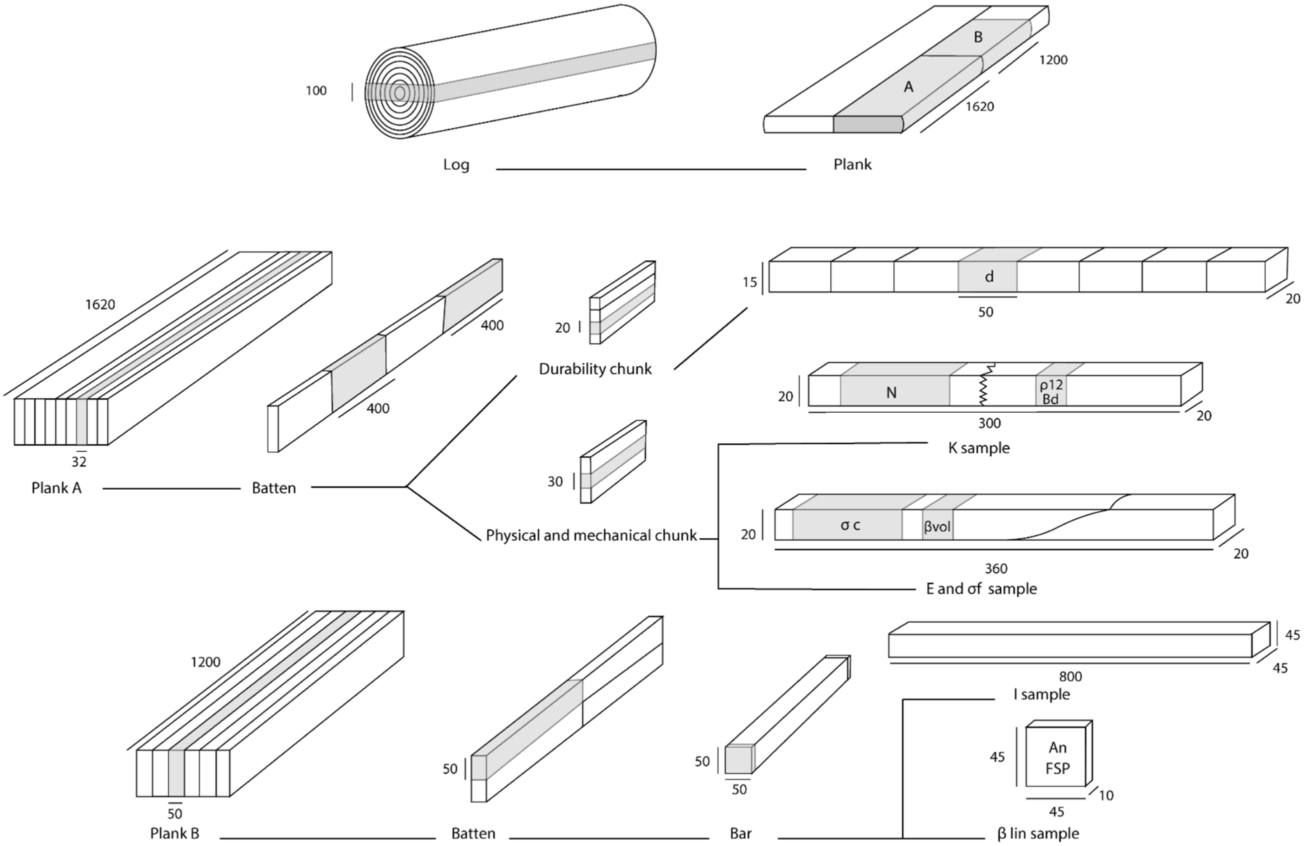


Fig. 2 Cutting process, dimensions in mm; natural durability (d); dynamic bending strength (K); density at 12% MC (ρ12); basic density (Bd); Monnin hardness (N); total volumetric shrinkage (βvol); Young's modulus (E); static bending strength (σ_f); axial compression strength (σ_c); impregnation (I); total linear radial/tangential shrinkage (β_{lin}); anisotropy (An); fiber saturation point (FSP)

normality and homoscedasticity, the Ryan-Joiner and the Levene tests were used respectively. If means were unequal then they were compared by using the t-test post-HOC test at a 95% confidence level. If homoscedasticity was not verified, the non-parametric test of Kruskall–Wallis was used and medians were structured by using Wilcoxson–Mann–Whitney test at a level of confidence of 95%.

The means of mechanical properties (E, σ_f, σ_c, and N) and physical properties (ρ_{12}, %V, β_{linR}, β_{linT}, $\beta_{linT}/\beta_{linR}$ and FSP) of *P. tessmannii* heartwood were compared with those of other African timber obtained from the CIRAD (2015) database. All values mentioned in this database, except for FSP, were determined according to the same standards used in this study (personal communication). As this database presents properties at 12% MC, our measurements that were not performed at 12%, were converted using the equation from USDA (2010): $P = P_{12} * (P_{12}/P_g)^{((12-M)/Mp-12)}$, where P is the property at M moisture content (%), P_{12} is the same property at 12% MC, P_g is the property for green wood and M_p here corresponds to the FSP. To identify the species with similar properties, a Principal Component Analysis (PCA) and a Hierarchical Clustering on Principal Components (HCPC) were carried out. This unsupervised method makes it possible to reduce the number of variables to few non-correlated variables, named Principal Components (PCs) which efficiently summarize the information (Lever et al. 2017). However, this statement is only verified if the number of selected components is optimal. Indeed, the cumulative variance explained by selected PCs should represent most of the dataset variability, while avoiding selecting too many components that could induce statistical noise. Then, Euclidean distance between species was calculated on selected PCs scores to create the dissimilarity matrix used to cluster species with the Unweighted Pair Group Method with Arithmetic mean (UPGMA) aggregation method.

All analyses and graphics were processed with RStudio software 1.2.5001 (RStudio team 2020) with the following packages: *FactoMineR* (Lê et al. 2008), *ggplot2* (Wickham 2016) and *Tidyverse* (Wickham et al. 2019).

Table 2 Calculation methods of wood properties

Properties	Symbols	Calculations	Units	Standards/references used	H	W	L	Ns	Nh	Nj
Wood density at 12% MC	ρ_{12}	$\rho_{12}=m_{12}/V_{12}$	kg/m^3	NF B51-005 (AFNOR 1985a)	20	20	20	24	59	24
Fibre saturation point	FSP	y in lm (MC ~ S)	%	Kollmann and Coté (1968), Bossu et al. (2016)	45	45	10	8	24	8
Basic density	Bd	$Bd=ma/Vs$	kg/m^3	NF B51-005 (AFNOR 1985a)	20	20	20	24	59	24
Volumetric shrinkage from saturated samples to oven dry	β_{vol}	$\beta_{vol}=(Vs-Va)/Vs*100$	%	NF B51-006 (AFNOR 1985b)	20	20	20	24	59	24
Volumetric coefficient	%V	$\%V=\beta_{vol}/FSP$	%/%	NF B51-006 (AFNOR 1985b)	–	–	–	–	–	–
Linear shrinkage from saturated samples to oven dry	β_{linT} and β_{linR}	$\beta_{lin}=(Ls-La)/Ls*100$	%	NF B51-006 (AFNOR 1985b)	45	45	10	24	76	27
Anisotropy	AN	$AN=\beta_{linT}/\beta_{linR}$	no units	NF B51-006 (AFNOR 1985b)	45	45	10	24	76	27
Young's modulus	E	$E=3P(l-t)\,m^2/8ba^3f$	Mpa	NF B51-016 (AFNOR 1987a)	20	20	360	24	62	24
Static bending strength	σ_f	$\sigma_f=3Pl/2ba^2$	Mpa	NF B51-008 (AFNOR 1987b)	20	20	360	24	62	24
Dynamic bending strength	K	$K=W/ab$	kg/cm^2	NBN 225 (IBN 1956)	20	20	300	24	59	24
Axial compression strength	σ_c	$\sigma_c=P/ab$	Mpa	NF B51-007 (AFNOR 1985c)	20	20	60	24	62	24
Monnin hardness	N	$N=(15-(\sqrt{900-p^2})/2)^{-1}$	no units	NF B51-013 (AFNOR 1985d)	20	20	60	24	59	24
Natural durability	d	$d=(m_0-m_{16})/m_0$	%	CEN/TS 15083-1 (CEN 2005)	15	25	50	16	32	32
Impregnation	I	–	classes	CEN/TR 14734 (CEN 2004)	45	45	800	12	15	-

m_{12} = mass 12% MC (kg), V_{12} = volume 12% MC (m^3), y in = y axis interception of lm = linear model, MC = moisture content, S = sample surface (m^2), ma = anhydrous mass (kg), Vs = volume above FSP (m^3), Va = anhydrous volume (m^3), Ls = linear length above FSP (m), La = anhydrous length (m), P = maximum load before breaking (N), l = distance between two support points (m), t = distance between two loading points (m), m = distance between the two arrow measuring points (m), a = sample height (cm), b = sample width (cm), f = arrow induced by the load (m), W = breaking unitary work (kgm), p = cylinder print width on sample (mm), m_0 = dry mass before fungus exposition (g), m_{16} = dry mass after 16 weeks of fungus exposition; Units; standards used for their determination; dimensions of samples: height (H), width (W) and length (L) and number of selected samples: sapwood (Ns), heartwood (Nh) and juvenile wood (Nj)

Table 3 Mechanical properties tested mean MC

Property	MC	Juvenile wood	Heartwood	Sapwood	Analysis	Significance	Heartwood (12% MC)
E (Mpa)	12	$16{,}941^a \pm 2382$ (22)	$17{,}005^a \pm 3698$ (61)	$14{,}326^b \pm 2792$ (24)	Anova	F = 6.134; p-val = 0.003	17,005
σ_f (Mpa)	15.3	$56^b \pm 12$ (22)	$79^a \pm 19$ (62)	$74^a \pm 21$ (24)	Anova	F = 13.19; p-val < 0.001	89
K (kgm/cm^2)	13.2	$0.13^b \pm 0.05$ (21)	$0.20^a \pm 0.08$ (59)	$0.27^a \pm 0.16$ (21)	Kruskal–Wallis	$\chi^2 = 28.73$; p-val < 0.001	–
σ_c (Mpa)	12	$55^a \pm 6$ (24)	$55^a \pm 7$ (59)	$52^a \pm 7$ (24)	Anova	F = 1.62; p-val = 0.204	55
N	14.6	$3.7^c \pm 0.8$ (24)	$4.3^b \pm 0.7$ (62)	$4.8^a \pm 1.0$ (24)	Anova	F = 11.84; p-val < 0.001	4.9

Mean values, median in case of Kruskal–Wallis analysis (± standard deviation) for each section and t-test/Wilcoxon test grouping; analysis; significance and mean value converted at 12% MC of heartwood used in the HCPC analysis

3 Results

All results concerning physical properties, mechanical properties and natural durability of *P. tessmannii* are summarized in Electronic Supplementary Material.

3.1 Log description, visual aspect and macroscopic anatomy

Planks had three mains defects: heart shakes (3/4), ring shakes (2/4) and cup shake (2/4). These defects hamper peeling transformation (Fays 2008). No evidences of insects or fungus attacks were observed. The sapwood is 9.8 ± 3.2 cm wide, it is white and well discernible from the heartwood. The heartwood varies from light pink or brown pink to red brown (Fig. 3a). The wood has interlocked-grain and flamed figure patterns on quarter sawn due to a wavy grain on the tangential section (Fig. 3a). On the one hand, this kind of grain angle variation produces beautiful and particularly attractive figures on wood (Harris 1989; Hillaby 2000; Fays 2008). On the other hand, it could negatively impact mechanical properties (Weddell 1961; Marsoem and Kikata 1987; Hernández and Almeida 2003) by decreasing mean value of resistance and

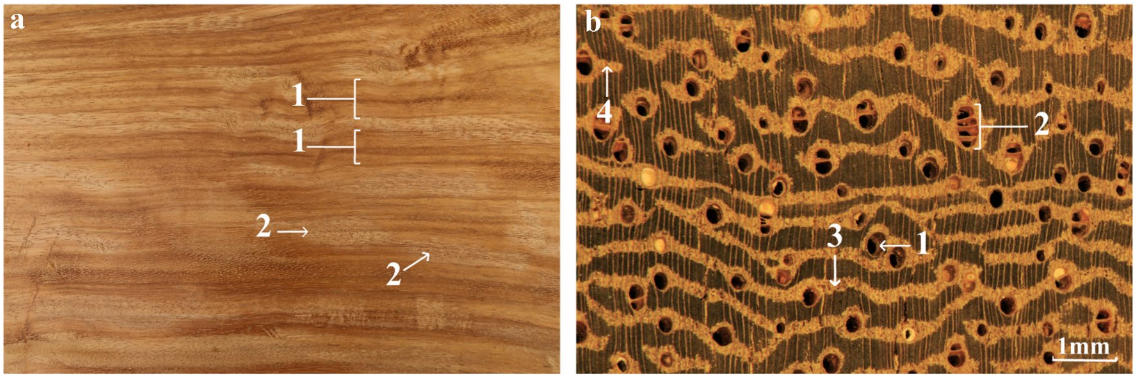


Fig. 3 *P. tessmannii* wood aspect **a** on quartersawn lumber showing large interlocked grain (a.1) and flamed aspect (a.2) due to the wavy grain in the tangential plane; **b** on the cross-section showing large vessels (b.1), diffusely distributed either isolated or grouped in groups of 2–3, up to 4 (b.2), an abundant axial confluent parenchyma (b.3) or winged-aliform (b.4)

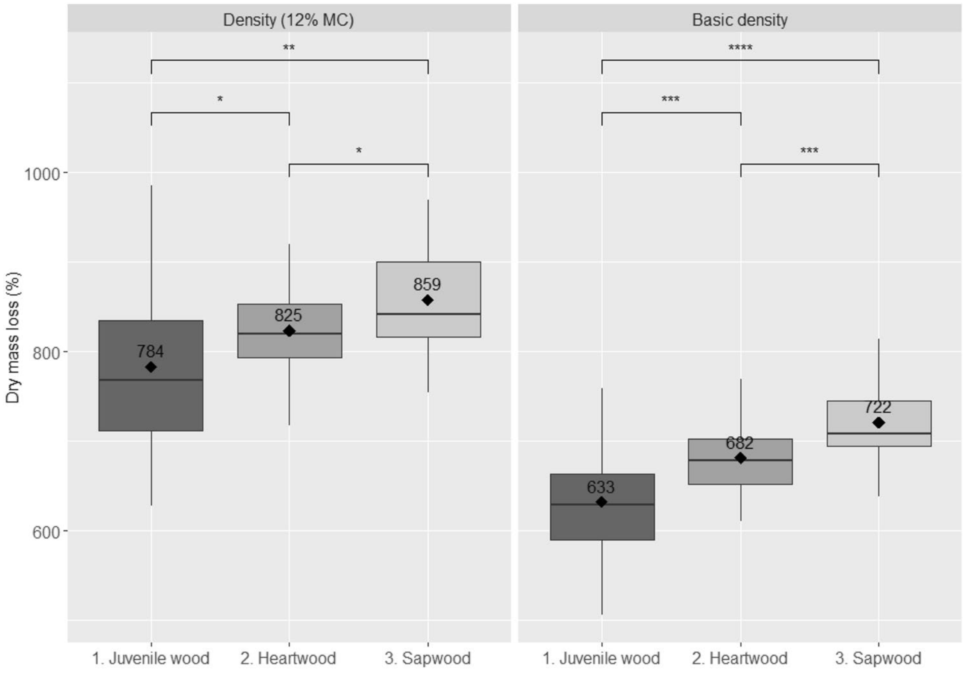
increasing variability (Hernández 2007). Those kinds of various grain angle finally induce surfacing difficulties and complicate planing and sanding operation during wood manufacturing. The wood texture is coarse due to wide vessels, diffusely distributed, either isolated or grouped in groups of 2–3, up to 4 (Fig. 3b). Axial parenchyma is abundant either confluent, aliform or winged-aliform.

3.2 Physical properties

Median density (12% MC) is significantly different ($\chi^2 = 10.984$; $p\text{-val} < 0.01$) between radial position: 768 ± 101 kg/m^3 ($n = 23$), 820 ± 51 kg/m^3 ($n = 47$) and 842 ± 62 kg/m^3 ($n = 22$), for juvenile wood, heartwood and sapwood, respectively (Fig. 4). The significant data dispersal in juvenile wood (Fig. 4) may be due to the definition we adopted, i.e. wood within 10 cm from the pith. As a consequence, samples may have included real juvenile wood and heartwood. Juvenile wood can be classified as “semi-heavy”, sapwood and heartwood can both be classified as “heavy” (Sallenave 1955). The observed ρ_{12} difference between mature (both sapwood and heartwood) and juvenile wood is particularly significant (Gartner et al. 1997; Bhat et al. 2001).

Basic density median follows the same pattern as ρ_{12} with significant variation along radial position ($\chi^2 = 25.43$; $p\text{-val} < 0.001$): 630 ± 68 kg/m^3 ($n = 22$), 679 ± 43 kg/m^3

Fig. 4 Increase in density at 12% MC and basic density from juvenile wood to sapwood of *P. tessmannii*; *, **, *** and **** correspond to p-value ≤ 0.05, p ≤ 0.01, p ≤ 0.001 and p ≤ 0.0001 respectively for Mann–Whitney test



(n = 58), 709 ± 46 kg/m^3 (n = 24), for juvenile wood, heartwood and sapwood, respectively.

Radial and tangential shrinkage are significantly influenced by radial position ($\chi^2 = 29.75$; p-val < 0.001 and $\chi^2 = 20.14$; p-val < 0.001, respectively). Radial shrinkages for juvenile wood, heartwood and sapwood are respectively 4.93 ± 0.62% (n = 18); 4.20 ± 0.64% (n = 60) and 3.75 ± 0.29% (n = 21). Radial shrinkage of juvenile wood and heartwood can be considered as "medium" and sapwood as "low" (Gérard et al. 2017). Tangential shrinkages are respectively 10.41 ± 0.24% (n = 14); 9.21 ± 1.24% (n = 55) and 9.03 ± 1.02% (n = 25) (Fig. 5) which correspond to a high tangential shrinkage for juvenile wood and medium shrinkage for both heartwood and sapwood (Gérard et al. 2017).

Volumetric shrinkage median is significantly influenced by radial position ($\chi^2 = 18.97$; p-val < 0.001): 15.66 ± 1.83% (n = 23), 13.75 ± 2.08% (n = 56) and 12.41 ± 0.90% (n = 19), for juvenile wood, heartwood and sapwood, respectively (Fig. 5). Volumetric shrinkage of juvenile wood is classified as "high" and it is "medium" for sapwood and heartwood (Sallenave 1955).

The mean anisotropy of shrinkage, which indicates the risk of deformation during drying (Spear and Walker 2006), is significantly different between radial positions (F = 3.41; p-val = 0.036): 2.10 ± 0.25 (n = 18), 2.20 ± 0.36 (n = 60) and 2.30 ± 0.25 (n = 21) for juvenile wood, heartwood and sapwood, respectively (Fig. 5).

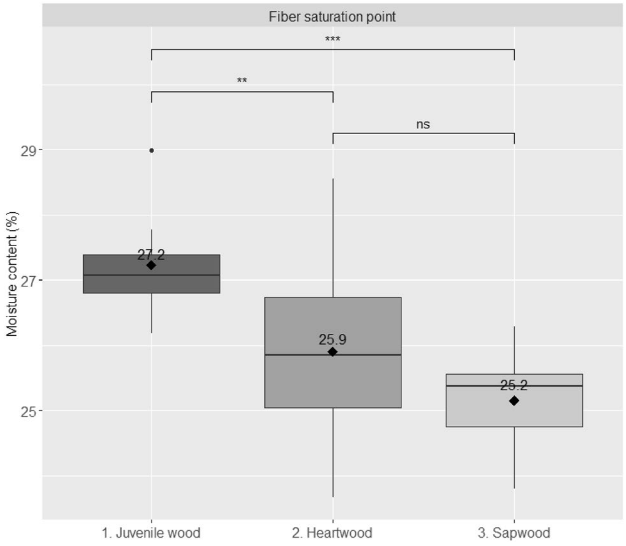


Fig. 6 Difference in fibre saturation point between juvenile wood, heartwood and sapwood of *P. tessmannii*; ns, ** and *** correspond to p-value > 0.05, p ≤ 0.01 and p ≤ 0.001 respectively for t-test

FSP can be classified as medium (Gérard et al. 2017) for all compartments even if its mean differs significantly (F = 6.49; p-val = 0.004) with radial variation (Fig. 6), 27.2 ± 0.8% (n = 7), 25.7 ± 1.5% (n = 23) and 24.9 ± 1.1% (n = 8) for juvenile wood, heartwood and sapwood (n = 8), respectively. All wood parts have a medium value of V_s: 0.55%/% for juvenile wood, 0.53%/% for heartwood and 0.50%/% for sapwood (Sallenave 1955).

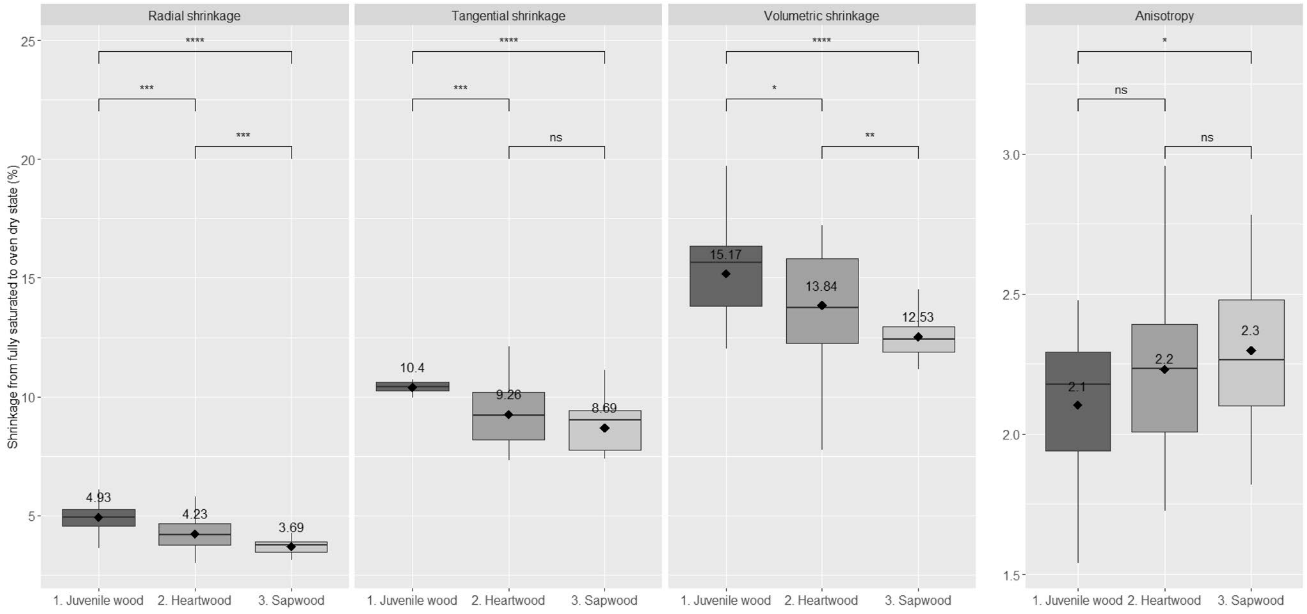


Fig. 5 Variation in linear, volumetric shrinkage and anisotropy (no units) across the stem of *P. tessmannii*; ns, *, **, *** and **** correspond to p-value > 0.5, p ≤ 0.05, p ≤ 0.01, p ≤ 0.001 and p ≤ 0.0001 for Mann–Whitney test (β_{linR}, β_{linT} and β_{vol}) and t-test (An), respectively

3.3 Mechanical properties

All mechanical properties results are summarized in Table 3. E mean is significantly different between wood parts but all remain classified as "medium" (Gérard et al. 2017). Values obtained for heartwood and juvenile wood (17,005 ± 3728 Mpa and 16,941 ± 2330 Mpa, respectively) were significantly higher than those of sapwood (14,326 ± 2792 Mpa) (Table 3). σ_f is significantly lower in juvenile wood (56 ± 12 Mpa) than heartwood and sapwood (79 ± 19 Mpa and 74 ± 21 Mpa, respectively). They are respectively "medium" and "weak" (Gérard et al. 2017). The K median is also significantly weaker for juvenile wood (0.13 ± 0.05 kg/cm^2) than heartwood (0.29 ± 0.17 kg/cm^2) and sapwood, (0.28 ± 0.08 kg/cm^2). According to Sallenave (1955), all wood parts can be considered as "low" impact strength. Compressive strength does not significantly differ among radial positions: 55 ± 6 Mpa, 55 ± 7 Mpa and 52 ± 7 Mpa for juvenile wood, heartwood and sapwood, respectively. All values can be considered as "medium" (Gérard et al. 2017). N is significantly different between the tree radial positions ($F = 11.84$; p-val < 0.001). Juvenile wood (3.7 ± 0.8) is less hard than heartwood (4.3 ± 0.7) which is less hard than sapwood (4.8 ± 1). All wood parts are considered as "mid-hard" (Gérard et al. 2017).

3.4 Natural durability and impregnation

For both white and brown rot, a significant variation among sample radial position is observed ($F = 6134$; p-val = 0.003 and $F = 13{,}19$; p-val < 0.001 respectively for *T. versicolor* and *C. puteana*). Considering two strains, the median dry mass loss (MDL) of heartwood (4.80 ± 3.17% and 0.57 ± 1.23% for *T. versicolor* and *C. puteana,* respectively) is significantly lower than for the two other radial positions (Fig. 7). As median is the parameter used to assess natural durability class, heartwood can be considered as very durable (CEN 2005). However, nearly half of samples could be classified as "durable" for *T. versicolor* and this ranking should be used carefully. Against *T. versicolor*, MDL of sapwood (16.06 ± 3.84%) is significantly higher than MDL of juvenile wood (12.15 ± 3.82%). They are respectively slightly and moderately durable. Against *C. puteana*, MDL of sapwood (3.72 ± 1.54%) was not significantly different from MDL of juvenile wood (2.06 ± 4.64%) and both are very durable. To confirm fungi virulence, beech samples were also tested. For those, MDL against *T. versicolor* and *C. puteana* was 30.17% and 40.37%.

Concerning wood impregnation, all samples of heartwood are classified as slightly to non-impregnable. The penetration of copper sulphate followed the interlocked grain on the surface but never covered the complete width of the specimen. Concerning sapwood, 42% of samples are considered as impregnable, 50% as moderately impregnable and 8% as slightly to non-impregnable. The copper solution also followed the interlocked grain and mainly covered the whole specimen's section.

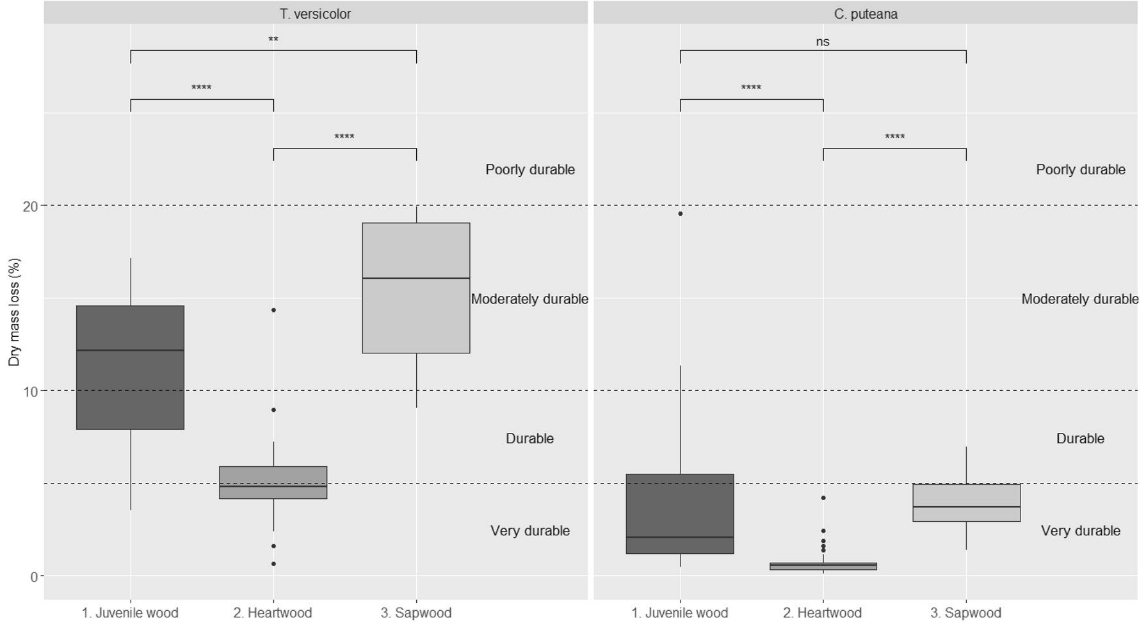


Fig. 7 Natural durability classes assessment according to CEN (2005) for *P. tessmannii* juvenile wood, heartwood and sapwood

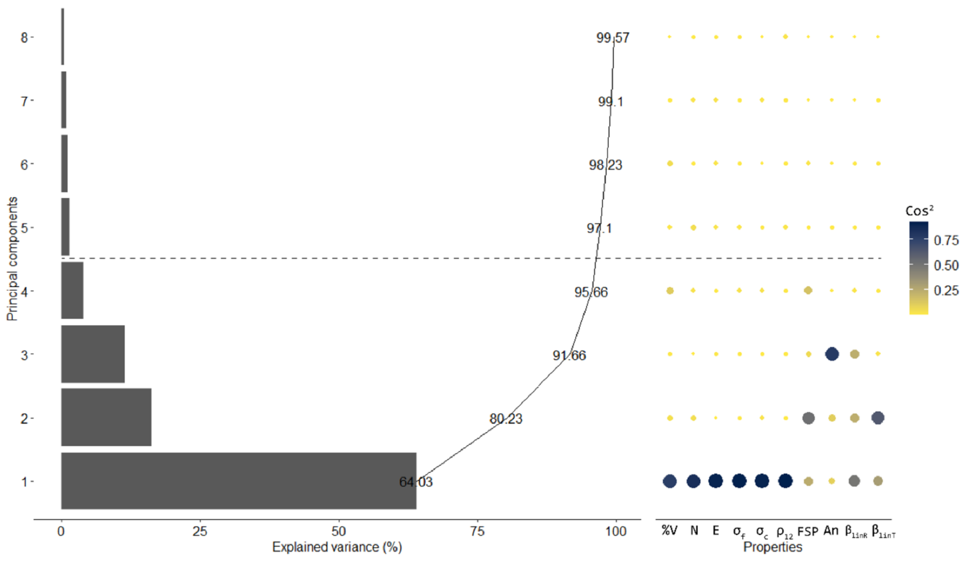


Fig. 8 On the left, bar plot of the percentage of the total variance explained by each component and the cumulative variance curve, on the right, the dot plot presents the quality of variable representation by the PCs, expressed as squared cosine. The dotted line corresponds to the limit number of components selected for the hierarchical clustering

3.5 Heartwood physical–mechanical classification

The cumulative percentage of total explained variance reaches 95.66% with the four first components (Fig. 8). The quality of variable representation on a PC is expressed as the squared cosine calculated between the variable and its projection on the PC in the multi-vector space created by the PCA. The first component is highly correlated with the ρ_{12}, E, N, σ_c, σ_f, and %V. The second one is correlated with stability parameters (FSP, β_{linR} and β_{linT}). AN is highly correlated and β_{linR} moderately correlated to the third one. Finally, FSP and %V are moderately correlated to the fourth component. Given the high cumulative variance explained by those four components and the weak representation quality of variables on PCs from the fifth component (minimal squared cosine < 0.1), only the four first components were kept for the hierarchical clustering.

The HCPC classifies *P. tessmannii* heartwood in the group composed of *Piptadeniastrum africanum* (Hook.f.) Brenan, *Scottellia klaineana* Pierre and *Pterygota* genus (*Pterygota bequaertii* De Wild and *Pterygota macrocarpa* K. Schum) (Fig. 9). Their pilot names are, respectively, Dabema, Akossika and Koto (ATIBT 2016). According to Fig. 8, those species appear to be similar based on the following properties: %V, β_{linR}, $\beta_{linT,}$ An, FSP and σ_c. However, *P. tessmannii* has a higher $\rho_{12,}$ E, N and a lower σ_f than those three other species. This classification also emphasizes the difference between *P. tessmannii* wood and that of the 4 main flagship species in Central Africa.

4 Discussion

4.1 Physical properties

Pachyelasma tessmannii presents a significant increase in ρ_{12} and Bd from the pith to the bark (Fig. 4). Dimensional stability parameters also variate with the radial gradient. Indeed, all shrinkage and FSP significantly decrease from juvenile wood to sapwood (Fig. 5). The anisotropy is not significantly different between heartwood and sapwood but seems to rise from juvenile wood to sapwood. The %V is not significantly different between wood parts, but there also is a decreasing trend from juvenile wood to sapwood. In this case, all stability properties seem to be correlated to the Bd as reported by some authors (Kollmann and Coté 1968; Mantanis et al. 1994; Kord et al. 2010). More recent studies highlight that those publications are based on temperate hardwood and softwood and do not match with the tropical wood anatomy complexity (de Almeida et al. 2017). Multi-species studies on tropical wood even present a poor relation between density and shrinkage (de Almeida et al. 2017; Deklerck et al. 2019). According to Schulgasser and Witztum (2015), shrinkage is mainly explained by wood microstructure. As microstructure of wood is affected by cambial maturity (Lichtenegger et al. 1999; Evans et al. 2000), it could explain the variation in physical properties between juvenile wood and mature wood. Deklerck et al. (2019) also show that vessels lumen area per mm^2 affect swelling more than wood density. Rungwattana and Hietz (2018) show significant increase in vessel fraction from pith to bark (independent of cambial maturity) for 5 tropical species. Considering these results, the furthest sapwood distance could explain the difference in dimensional properties observed among mature wood. Regardless of the radial variation of

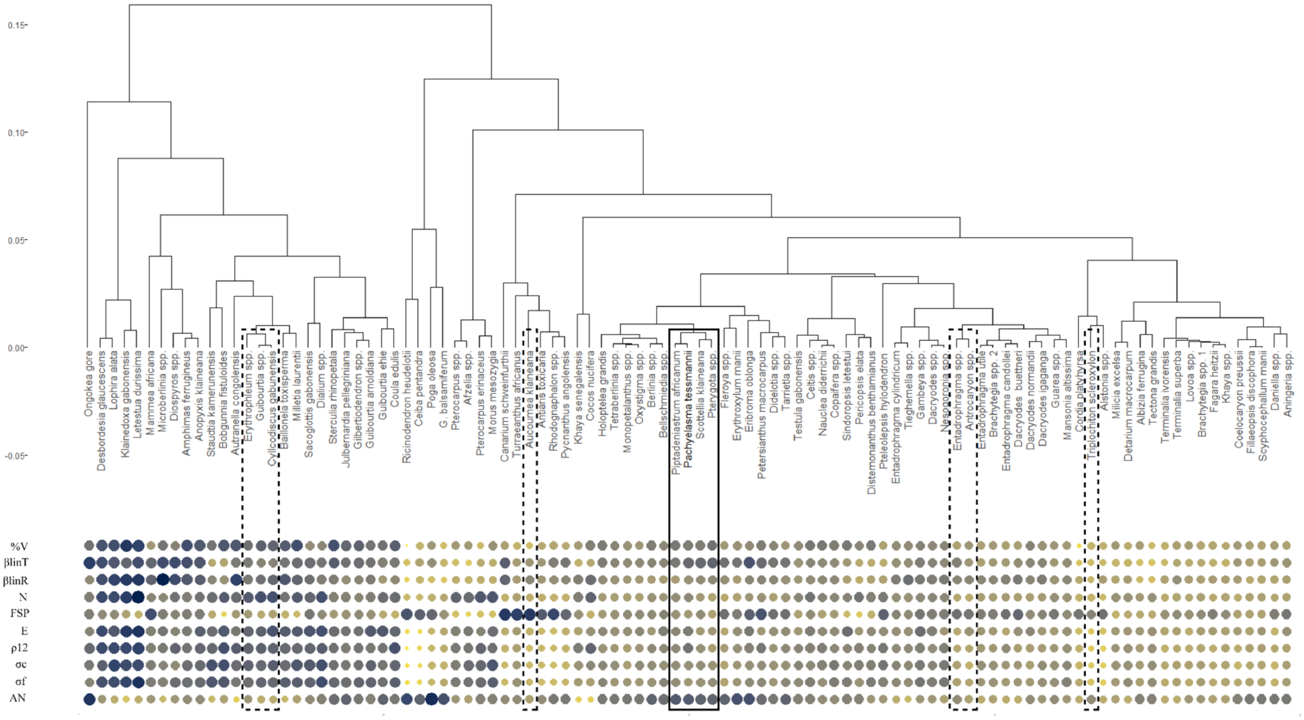


Fig. 9 On top, hierarchical classification by using the "UPGMA" aggregation method on "Euclidean" distance based on the 4 main PCs from the PCA (which represents 95.66% of variance). At the bottom, the dot plot presents all standardized physical and mechanical properties corresponding to each species. For each property, the smallest dots correspond to the lowest value observed in the database and the biggest one to the highest value. The branch containing the 3 closest species to *P. tessmannii*'s wood is fully circled. At the same cutting height in the classification, groups containing the 4 main flagship species in Central Africa (*A. klaineana*, *E. cylindricum*, *T. scleroxylon* and *E. suaveolens*) are dotted circled

shrinkages, the wide vessels (Fig. 3b) and their density (5 per mm^2 according to Normand and Paquis (1976) could explain high shrinkage in all wood parts for *P. tessmannii*).

Dimensional parameters provide information on lumber behaviour with MC variation. For *P. tessmannii*, juvenile wood will shrink/swell more than other wood parts but with a lower risk of deformations during drying due to an inferior AN. Sapwood will present the opposite behaviour: less shrinkage/swelling and a higher risk of deformation. FSP decreasing from juvenile wood to sapwood means that juvenile wood will start shrinking before other wood parts during drying. This can lead either to a high risk of checking or splitting for large wood pieces made up of two or three wood parts. It is therefore advised to saw narrow lumber during sawing process. %V expresses the lumber volumetric variation due to a variation of 1% MC. Juvenile wood will react more to MC variation than heartwood and sapwood.

Considering all wood parts, *P. tessmannii* shows disadvantageous dimensional parameters. Its high anisotropy and its interlocked grain strongly increase the risk of warping during wood drying (Dalois 1993). This wood deformation either leads to losses in planing operations or prevents lumber use (Fays 2008). As this risk is mainly linked to plain sawn lumber, quarter sawing which reduces the ratio of tangential and radial dimensions must be promoted (Dalois 1990).

4.2 Mechanical properties

Despite a quite high density, the mechanical properties are medium overall (Fig. 9) and go against the widely accepted statement about the interspecific relation between wood strength and density (Kollmann and Coté 1968; Zhang 1997; Ocloo and Laing 2003; Keller 2009; Sholadoye et al. 2016). The grain deviation pattern (Fig. 3) could explain this. As mechanical properties are tested parallel to wood rings, the wavy grain directly affects wood strength (Tsehaye and Walker 1995; Brémaud et al. 2011b). According to Kollmann and Coté (1968), a grain deviation between 15° and 20°, as observed on all samples, could lead to a decrease of 20 to 35% in bending strength and 10 to 20% in compressive strength. Impact bending strength is particularly influenced by sloping grain. Wilson et al. (cited in Harris 1989) suggest a slope lower than 2° for impact uses.

Considering that all wood parts present the same grain deviation pattern, mechanical strength is generally higher for mature wood (Table 3). However, E is significantly lower for sapwood and σ_c does not significantly vary with the radial gradient. E variation could be explained by a higher extractives content in juvenile wood and heartwood that positively affects the Young's modulus (Brémaud et al. 2011a).

4.3 Use classes

White rot was the most decaying fungus. As a precaution, natural durability against this strain can be used to assess *P. tessmannii* use classes. According to the NF EN 335 standard and the EN 460 standard, natural durability of juvenile wood covers use class 3 (outdoors, MC sometimes > 20%, quick drying after moisture exposure), the natural durability of heartwood covers use class 4 (outdoors, MC always > 20%, direct contact with the soil or water without any treatments), and that of sapwood covers the 2 first working classes (interior with no humidification or sheltered with occasional humidification). As sapwood soaking with decay preservative agent can be considered, it could be used until use class 4 with an appropriate treatment.

This use class assessment is only valid for situations where no other wood pests occur. Lemmens et al. (2012) mentioned a good resistance of *P. tessmannii* heartwood against termite and marine borers, but it can be attacked by pinhole borers. However, observations are not sufficient and further scientific work is needed to assess its natural durability against those pests before any use in areas where these pests occur. Moreover, every situation is different and this grading might be adapted.

4.4 Potential uses of heartwood

Potential heartwood uses can be proposed by crossing the actual uses of the identified three closest species (Table 4) and other *P. tessmannii* properties not included in the HCPC analysis. The coarse grain mainly does not allow mouldings (Martin and Vernay 2016). Low impact bending strength combined with a high density prevents use for vehicle or container flooring, boxes and crates, mobile items, seats, industrial or heavy flooring and carpentry. With a weak density-strength ratio, framing cannot be done. Unlike the three other species, *P. tessmannii* heartwood could be used until working class 4 and allow exterior uses as decking or exterior stairs. Hence, *P. tessmannii* is potentially suitable, according to the HCPC analysis and all properties studied, for the following end uses: stairs (inside/outside), flooring, decking, veneer (back and face of plywood), sliced veneer, furniture (inside/outside), exterior panelling, cabinetry, joinery (inside/outside) and turned goods.

This list can be compared to the one proposed by Lemmens et al. (2012): heavy construction, boat building, vehicle bodies, furniture and cabinet work, joinery, sporting goods and implements, interior trim, toys, turnery and very thin veneer. Considering medium to low mechanical properties (Table 3) observed and the weak density/mechanical strength ratio, heavy construction, boat building, vehicle bodies and sporting goods are not recommended. Interior trim is not recommended as discussed before. Interestingly only toys, turned goods and veneer (already in the HCPC potential use list) seems to meet *P. tessmannii* wood properties. This huge difference emphasizes the need to study wood properties before assessing uses. The wavy grain pattern observed on the 4 studied trees (Fig. 3a), which probably strongly decreases mechanical strength, could be the cause of this difference observed between the HCPC list and the one proposed by Lemmens et al. (2012).

The difference observed within *P. tessmannii* and the four main flagship species shows that the species studied will not be appropriate to substitute them in the tropical wood market. However, it could be added to diversify it.

4.5 Ecological traits and management

Radial variation of wood density is known to be correlated to many morphological and ecological traits of trees (King et al. 2006; Iida et al. 2012; Plourde et al. 2015). The increase in basic density from the pith to the bark is often attributed to pioneer and light-demanding species (Wiemann and Williamson 1988, 1989; Woodcock and Shier 2002, 2003). Considering the high diameter this species can reach (Fig. 1), it is probably a long-lived pioneer species. Such species often have a lack of regeneration in undisturbed mature forests (Pena-Claros et al. 2008).

Table 4 Main end uses (Gérard et al. 2017) for the 3 closest species of *P. tessmannii* identified by the HCPC

Species	Main end uses
Piptadenastrum africanum (Hook.f.) Brenan	Heavy carpentry; stairs (inside); veneer; vehicle or container flooring; glued laminated; built-in furniture or mobile item; house framing; industrial or heavy flooring; exterior panelling
Scottellia klaineana Pierre	Turned goods; framing; cabinetry (high-end furniture); stairs (inside); veneer; panelling; interior joinery; built-in furniture and mobile item; moulding; flooring; sliced veneer; marquetry
Pterygota spp.	Framing; boxes and crates; veneer; panelling glued laminated; interior joinery; built-in furniture or mobile item; moulding; house framing; fibre or particleboards; sliced veneer; seats; marquetry

Figure 1, showing lower tree proportion in lower diameter classes, probably confirms this lack of regeneration. As a consequence, if this lack of regeneration is confirmed in other logging concessions, silvicultural methods such as logging gap enrichment (Doucet et al. 2009) or enrichment planting (Doucet et al. 2016; Martínez-Garza et al. 2013) should be investigated. If successful, those techniques should be systematically implemented in case of exploitation of *P. tessmannii* in the selective logging context. As light-demanding species are more competitive in high light situations, this species might be suitable for planting and reforestation operations.

5 Conclusion

Pachyelasma tessmannii wood has some interesting properties (beautiful grain patterns, medium shrinkages and FSP, good heartwood durability, impregnable sapwood) but also some drawbacks (high radial variation in physical properties, high anisotropy, and weak strength/density ratio). All properties, except for axial compression strength, were significantly more advantageous in mature wood (heartwood and sapwood) than juvenile wood. This assumption suggests to ensure removing juvenile wood during the sawing process. The HCPC analysis showed the heartwood is quite similar to *Piptadenastrum africanum*, *Scottellia klaineana* and *Pterygota* spp. By crossing end uses of those more marketed species and the other wood properties studied, not taken into account in the HCPC, *P. tessmannii* could meet the following end uses: stairs (inside/outside), flooring, decking, veneer (back and face of plywood), sliced veneer, furniture (inside/outside), exterior panelling, cabinetry, joinery (inside/outside) and turned goods. However, it would be necessary to study more practical properties, such as stability test, drying yields, and gluing to confirm the end uses proposed.

The results obtained concerning the radial variation of basic density suggest that the species is light-demanding. A large-scale logging could threaten population in mature forest where natural regeneration of these species is often low. The stem distribution we obtained confirms that large trees of this species are more abundant than small ones. Prior to large-scale logging of *P. tessmannii*, further investigations are needed to clarify species ecology and the possibility to enhance its regeneration with appropriate silviculture.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00107-021-01758-3.

Acknowledgements We are grateful to Pallisco-CIFM and Pasquet Menuiseries for sending the vegetal material. We would also like to thank Lhacen Hadiy, Yannick Delzant, Cécile Lesire from GEPROFOR asbl and Anne Bauvin, Cécile Verheyen, Jean-Marc Henin, Caroline Pollet from the CRA-W.

Funding The research was supported by the *Identification d'essences à haut potential de valorisation* (EHPval) project, funded by the *Programme de promotion de l'exploitation certifiée des forêts* (PPECF).

Code availability Wood physical, mechanical and durability data are available on request to authors. Database and code used for the HCPC analysis are available online at: https://github.com/DoucetRobin/African-wood-HCPC.git.

Declarations

Conflict of interest Authors declare that they have no competing financial interests.

Consent to participate Not applicable.

Consent to publish Not applicable.

Ethical approval Not applicable.

References

AFNOR (1985a) NF B51-005: Bois. Détermination de la masse volumique (Wood. Density determination). Association Française de Normalisation, Paris

AFNOR (1985b) NF B51-006: Bois. Détermination du retrait (Wood. Shrinkage determination). Association Française de Normalisation, Paris

AFNOR (1985c) NF B51-007: Bois. Essai de compression axiale (Wood. Axial compression strength determination). Association Française de Normalisation, Paris

AFNOR (1985d) NF B 51-013: Bois. Détermination de la dureté de Monnin (Wood. Monnin hardness determination). Association Française de Normalisation, Paris

AFNOR (1987a) NF B51-016: Bois. Détermination du module d'élasticité en flexion statique de petites éprouvettes sans défauts (Wood. Young modulus determination on defect-free samples). Association Française de Normalisation, Paris

AFNOR (1987b) NF B51-008: Bois. Essai de flexion statique (Wood. Static bending strength determination). Association Française de Normalisation, Paris

Alroy J (2017) Effects of habitat disturbance on tropical forest biodiversity. Proc Natl Acad Sci USA 114:6056–6061

ATIBT (2006) La lettre de l'ATIBT n°24: Statistiques 2005 (ATIBT letter n°24: 2005 statistics). Association Technique Internationale de Bois Tropicaux, Paris

ATIBT (2007) La lettre de l'ATIBT n°26: Statistiques 2006 (ATIBT letter n°26: 2006 statistics). Association Technique Internationale de Bois Tropicaux, Paris

ATIBT (2016) Nomenclature générale des bois tropicaux (Tropical timber nomenclature). ATIBT, Association Technique Internationale de Bois Tropicaux, Nogent-sur-Marne

BAD (2019) Développement intégré et durable de la filière bois dans le Bassin du Congo: Opportunités, défis et recommandations opérationnelles (Tropical timber market sustainable development in the Congo Basin: Opportunities, challenges and operational recommendations). Banque Africaine de Développement. https://www.afdb.org/fr/documents/document/rapport-strategique-regional-developpement-integre-et-durable-de-la-filiere-bois-dans-le-bassin-du-congo-109428

Bayol N, Demarquez B, De Wasseige C, Eba'a Atyi R, Fisher JF, Nasi R, Pasquier A, Rossi X, Steil M, Vivien C (2012) Forest

Management and the Timber Sector in Central Africa. In: De Wasseige C, De Marcken P, Bayol N, Hiol-Hiol F, Mayaux P, Desclée B, Billand A, Nasi R (eds) The forests of the Congo Basin: State of the forest 2010. Publications Office of the European Union, Luxembourg, pp 43–62

Bhat KM, Priya PB, Rugmini P (2001) Characterisation of juvenile wood in teak. Wood Sci Technol 34:517–532

Biwolé AB (2015) Origine et dynamique des populations d'arbres des forêts denses humides d'Afrique Centrale, le cas de Lophira alata Banks ex Gaertn C.F. (Ochnaceae) (Central Africa rainforest trees origin and population dynamic, the case of Lophira alata Bank ex Gaertn C.F. (Ochnaceae)). Ph.D. Thesis, Université de Liège - Gembloux Agro-Bio tech, Belgium

Boampong E, Effah B, Antwi K et al (2015) Factors influencing the choice of timber for furniture and joinery production in Ghana. Eur J Eng Technol 3:48–59

Bossu J, Beauchêne J, Estevez Y et al (2016) New insights on wood dimensional stability influenced by secondary metabolites: the case of a fast-growing tropical species *Bagassa guianensis* aubl. PLoS ONE 11:150777

Brémaud I, Amusant N, Minato K et al (2011a) Effect of extractives on vibrational properties of African Padauk (*Pterocarpus soyauxii* Taub.). Wood Sci Technol 45:461–472

Brémaud I, Gril J, Thibaut B (2011b) Anisotropy of wood vibrational properties: dependence on grain angle and review of literature data. Wood Sci Technol 45:735–754

CEN (2004) CEN/TR 14734:2004: Durability of wood and wood-based products—determination of treatability of timber species to be impregnated with wood preservatives—laboratory method. Comité Européen de Normalisation, Bruxelles

CEN (2005) CEN 15083-1: Durability of wood and wood-based products—determination of the natural durability of solid wood against wood-destroying fungi, test methods—Part1: Basidiomycetes. Comité Européen de Normalisation, Bruxelles

Chaowana P (2013) Bamboo: an alternative raw material for wood and wood-based composites. J Mater Sci Res 2:90

CIRAD (2015) Les principales caractéristiques technologiques de 245 essences forestières tropicales et tempérées. Tropix v 7.5.1 (The main technological characteristics of 245 tropical and temperate forest species. Tropix v 7.5.1). Software. Centre de cooperation Internationale de Recherche Agronomique pour le Développement, Paris, France

CJBG (2018) Base de données des plantes d'Afrique (African plants database). Conservatoire et Jardin Botanique de la ville de Genève http://www.villege.ch/musinfo/bd/cjb/africa/details.php?langue=fr&id=69634. Accessed 13 May 2020

Dalois C (1990) Manuel de sciage et d'affûtage (Sawing and sharpening guide). Quae, Versailles

Dalois C (1993) Le sciage sur quartier des bois tropicaux modèle de scierie (Quarter-sawing a model for tropical sawmill). Bois Forets Des Trop 237:61–67

de Almeida TH, de Almeida DH, De Araujo VA et al (2017) Density as estimator of dimensional stability quantities of Brazilian tropical woods. BioResources 12:6579–6590

Deklerck V, De Mil T, Kondjo P et al (2019) Sleeping beauties in materials science: unlocking the value of xylarium specimens in the search for timbers of the future. Holzforschung 73:889–897

Doucet JL, Kouadio YL, Monticelli D, Lejeune P (2009) Enrichment of logging gaps with moabi (*Baillonella toxisperma* Pierre) in a Central African rain forest. For Ecol Manag 258:2407–2415

Doucet JL, Daïnou K, Ligot G et al (2016) Enrichment of Central African logged forests with high-value tree species: testing a new approach to regenerating degraded forests. Int J Biodivers Sci Ecosyst Serv Manag 12:83–95

Evans R, Stringer S, Kibblewhite RP (2000) Variation of microfibril angle, density and fibre orientation in twenty-nine *Eucalyptus nitens* trees. Appita J 53:450–457

FAO (2011) The State of Forests in the Amazon Basin, Congo Basin and Southeast Asia. Food and Agriculture Organization. http://www.fao.org/3/i2247e/i2247e00.pdf.

Fayolle A, Picard N, Doucet JL et al (2014) A new insight in the structure, composition and functioning of central African moist forests. For Ecol Manag 329:195–205

Fays R (2008) Des forêts... Des bois... (Some forest… Some wood…). Richard Fays, Impribeau Sainte-Ode, Brussels. p 1022

FRM (2018) Vision stratégique et industrialisation de la filière bois dans les 6 pays du Bassin du Congo, Horizon 2030 (Strategic vision and industrialization of the timber sector in the 6 Congo Basin countries, Horizon 2030). Forest Resources Management, Montpellier

Gartner BL, Milota MR, Hua L (1997) Variation in the anatomy and specific gravity of wood within and between trees of red alder (*Alnus rubra* Bong.). Wood Fiber Sci 29:10–20

Gerhards CC (1982) Effect of moisture content and temperature on the mechanical properties of wood: an analysis of immediate effects. Wood Fiber Sci 14:4–36

Gérard J, Guibal D, Paradis S, Cerre JC (2017) Tropical Timber Atlas. Quae, Versailles

Harris JM (1989) Spiral grain and wave phenomena in wood formation. Springer, Berlin

Hernández RE (2007) Influence of accessory substances, wood density and interlocked grain on the compressive properties of hardwoods. Wood Sci Technol 41:249–265

Hernández RE, Almeida G (2003) Effects of wood density and interlocked grain on the shear strength of three Amazonian tropical hardwoods. Wood Fiber Sci 35:154–166

Hillaby A (2000) The visual context of wood. Gt Vancouver Woodturners Guild News L 1:1–6

IBN (1956) NBN 225: Bois. Méthodes d'essai de qualification (Wood. Qualification test method). Institut Belge de Normalisation, Bruxelles

Iida Y, Poorter L, Sterck FJ et al (2012) Wood density explains architectural differentiation across 145 co-occurring tropical tree species. Funct Ecol 26:274–282

Ishiguri F, Eizawa J, Saito Y et al (2007) Variation in the wood properties of *Paraserianthes falcataria* planted in Indonesia. IAWA J 28:339–348

ISO (2012) Wood. Sampling methods and general requirements for physical and mechanical testing of small clear wood specimens (ISO Standard No. 3129). International Organization for Standardization, Geneva

Karsenty A, Gourlet-Fleury S (2006) Assessing sustainability of logging practices in the Congo Basin's managed forests: the issue of commercial species recovery. Ecol Soc 11:13

Karsenty A, Drigo IG, Piketty MG, Singer B (2008) Regulating industrial forest concessions in Central Africa and South America. For Ecol Manag 256:1498–1508

Keller R (2009) Des caractéristiques nouvelles pour l'étude des propriétés mécaniques des bois: les composantes de la densité (New characteristics for the study of the mechanical properties of wood: density compenents). Ann Des Sci for 25:237–249

King DA, Davies SJ, Tan S, Noor NSM (2006) The role of wood density and stem support costs in the growth and mortality of tropical trees. J Ecol 94:670–680

Kollmann FFP, Coté WAJ (1968) Principles of wood science and technology. Springer, Berlin

Kord B, Kialashaki A, Kord B (2010) The within-tree variation in wood density and shrinkage, and their relationship in *Populus euramericana*. Turk J Agric for 34:121–126

Kretschmann DE, Green DW (1996) Modeling moisture content-mechanical property relationships for clear southern pine. Wood Fiber Sci 28:320–337

Lamb D, Erskine PD, Parrotta JA (2005) Restoration of degraded tropical forest landscapes. Science 310:1628–1632

Lê S, Josse J, Husson F (2008) FactoMineR: a package for multivariate analysis. J Stat Softw 25:1–18

Lemmens RHMJ, Roeland HMJ, Louppe D, Oteng-Amoako A, Corbière H (2012) Plant ressources of tropical Africa. Prota 7(2): timbers 2. PROTA, Wageningen

Lever J, Krzywinski M, Altman N (2017) Points of significance: principal component analysis. Nat Methods 14:641–642

Lichtenegger H, Reiterer A, Stanzl-Tschegg SE, Fratzl P (1999) Variation of cellulose microfibril angles in softwoods and hardwoods—a possible strategy of mechanical optimization. J Struct Biol 128(3):257–269

Mantanis GI, Young RA, Rowell RM (1994) Swelling of wood Part 1. Swelling in water. Springer, Belrin

Marsoem N, Kikata Y (1987) The effect of interlocked grain on the mechanical properties of white meranti. Bull Nagoya Univ 9:51–57

Martin P, Vernay M (2016) Guide d'utilisation des bois africains éco-certifiés en Europe (Guide to the use of eco-certified African woods in Europe). ATIBT, Paris

Martínez-Garza C, Bongers F, Poorter L (2013) Are functional traits good predictors of species performance in restoration plantings in tropical abandoned pastures? For Ecol Manag 303:35–45

Mitchard ETA (2018) The tropical forest carbon cycle and climate change. Nature 559:527–534

Morin-Rivat J, Fayolle A, Favier C et al (2017) Present-day central African forest is a legacy of the 19th century human history. Elife 6:e20343

Nature + asbl (2015) Plan d'aménagement: unité forestière d'aménagement N° 10–47, Région de l'Est (Management plan: forest management unit n°10–47, Est region)

Normand D, Paquis J (1976) Manuel d'identification des bois commerciaux (Guide for commercial timber identification). Centre Technique Forestier Tropical (CTFT), Nogent-sur-Marne

Ocloo J, Laing E (2003) Correlation of relative density and strength properties with anatomical properties of the wood of Ghanaian Celtis species. Discov Innov 15:186–196

Peña-Claros M, Peters EM, Justiniano MJ et al (2008) Regeneration of commercial tree species following silvicultural treatments in a moist tropical forest. For Ecol Manag 255:1283–1293

Plourde BT, Boukili VK, Chazdon RL (2015) Radial changes in wood specific gravity of tropical trees: inter- and intraspecific variation during secondary succession. Funct Ecol 29:111–120

RStudio Team (2020) RStudio: integrated development for R. RStudio, PBC, Boston

Rungwattana K, Hietz P (2018) Radial variation of wood functional traits reflect size-related adaptations of tree mechanics and hydraulics. Funct Ecol 32:260–272

Sallenave P (1955) Propriétés physiques et mécaniques des bois tropicaux de l'union française (Physical and mechanical properties of French union tropical timber species). Centre Technique Forestier Tropical (CTFT) Nogent-sur-Marne

Schmelzer GH, Gurib-Fakim A (2008) Medicinal plants 1. PROTA, Wageningen

Schulgasser K, Witztum A (2015) How the relationship between density and shrinkage of wood depends on its microstructure. Wood Sci Technol 49:389–401

Sholadoye IO, Abubakar I, Annafi QB, Ejeh SP (2016) Evaluation of some wood properties of Nigeria timber using four-point bending test. Adv Multidiscip Res J 2:133–144

Slik JWF, Arroyo-Rodríguez V, Aiba SI et al (2015) An estimate of the number of tropical tree species. Proc Natl Acad Sci USA 112:7472–7477

Spear M, Walker JCF (2006) Dimensional instability in timber. In: Walker JCF (ed) Primary wood processing: principles and practice. Springer, Doordrecht, pp 95–120

Tsehaye A, Walker JCF (1995) Spiral grain in Canterbury *Pinus radiata*: within- and between-tree variations and effect on mechanical properties. N Z J for Sci 25:358–366

USDA (2010) Wood handbook: wood as an engineering material. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison

Weddell E (1961) Influence of interlocked grain on the bending strength of timber, with particular reference to utile and greenheart. J Inst Wood Sci 7:56–72

Wickham H (2016) ggplot2: elegant graphics for data analysis. Springer, New York

Wickham H, Averick M, Bryan J et al (2019) Welcome to the Tidyverse. J Open Source Softw 4:1686

Wiemann M, Williamson G (1988) Extreme radial changes in wood specific gravity in some tropical pioneers. Wood Fiber Sci 20:344–349

Wiemann M, Williamson G (1989) Radial gradients in the specific gravity of wood in some tropical and temperate trees. For Sci 35:197–210

Woodcock D, Shier A (2002) Wood specific gravity and its radial variations: the many ways to make a tree. Trees Struct Funct 16:437–443

Woodcock DW, Shier A (2003) Does canopy position affect wood specific gravity in temperate forest trees? Ann Bot 91:529–537

Zhang SY (1997) Wood specific gravity-mechanical relationship at species level. Springer, Berlin

Zobel BJ, Sprague JR (1998) Juvenile wood in forest trees. Springer, Berlin