TITLE

Intra-species variation in maximum moisture content, cell-wall density and porosity of hardwoods

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SHORT TITLE

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ABSTRACT

Some properties of wood, such as maximum moisture content, cell-wall density and porosity, are not well known, even though they affect the performance of chemical preservatives, glues and coatings on wood. This knowledge gap was addressed in the present study by analysing these physical properties in laurel (*Laurus nobilis* L.) wood. Laurel is a common hardwood tree in southern Europe. Seventeen laurel trees were felled for the study, and 300 defect-free specimens were obtained from the trees for analysis. The following mean values were obtained: wood maximum moisture content, 114 %; cell-wall oven-dry density, 1198 kg m^{-3}; and oven-dry wood porosity, 45 %. Significant inter- and intra-tree variations in the three properties were observed. The inter-tree variation was mainly attributed to the tree age, and the trend suggests that wood maximum moisture content and porosity are expected to be lower in older trees than those under study. The values of the three properties were slightly, but statistically significantly, lower at the highest positions in the tree. Harvesting of the basal logs of young trees is therefore advisable only if more porous wood is required, and commercial exploitation of the whole trunk of mature trees is recommended if more compact wood is required. The variation in cell-wall density was not negligible, although this variable is often assumed to be approximately constant for all wood species. Maximum moisture content and wood porosity can be estimated using bulk or apparent density as a predictor variable.

KEYWORDS

hardwood; *Laurus nobilis*; physical property; wood technology.

INTRA-SPECIES VARIATION IN MAXIMUM MOISTURE CONTENT, CELL-WALL DENSITY AND POROSITY OF WOOD

1. Introduction

Information about wood properties is useful for wood manufacturing and is essential for optimizing the use of this raw material. However, some wood properties are not well described in the literature. This applies to maximum moisture content, cell-wall density and porosity, which are not usually included in wood species databases (e.g. Gutiérrez Oliva and Plaza Pulgar 1967; Glass and Zelinka 2010; Wagenführ and Wagenführ 2022).

The inter- and intra-tree variation in properties should also be analysed if the aim is to provide foresters with guidelines or practical rules about the type of tree or the part of the tree that is harvested to supply the transformation industry with raw wood material of a particular quality. The inter- and intra-tree sources of variation have generally been studied for some indicator or proxy wood variables, such as apparent wood density (Lachenbruch and McCulloh 2014). Analysis of variables related to porosity, such as axial conduit widening in broadleaved plants is a topic of more recent interest (Anfodillo et al. 2013).

1.1. Maximum moisture content

In wood, water occurs as bound water, in the cell walls, of hygroscopic nature, and as free or capillary water, in the void spaces of wood (Prichananda 1966). The pores are filled with air when the moisture content falls below the fibre saturation point (cell-wall saturation point) (Rosner et al. 2010), which usually ranges between 25 and 35 % (Gutiérrez Oliva and Plaza Pulgar 1967). The cell lumina begin to fill when the moisture content rises above the fibre saturation point, and the maximum moisture content is reached when the cell lumina are filled with water. Theoretically, full saturation of all voids in the wood can be reached (Siau 1995).

Estimation of the maximum possible moisture content is useful in relation to impregnation of wood with preservatives, for determining the maximum quantity of preservative that can be forced into a piece of wood in terms of liquid retention (weight of liquid preservative per unit volume of water saturated wood) and also for determining incomplete retention of the preservative as the percentage of voids filled (Siau 1995). The maximum retention of liquid preservative can be computed if the maximum moisture content, wood basic density and liquid preservative density are known. The main interest in estimating maximum moisture content is related to the full-cell impregnation process by immersion or autoclaving, with initial vacuum and further pressure (e.g. Tripathi 2012).

Quantifying the maximum moisture content is potentially very useful for calculating the dose of liquid preservative in laurel wood that protects against biotic decay agents, because laurel wood is very sensitive to fungal infections, which cause intense darkening of the material (Pulgar Lorenzo and Riesco Muñoz 2018).

The maximum moisture content can range from about 30 % to above 200 % (Glass and Zelinka 2010) and is always higher than the moisture content of wood from newly felled trees, which is 80-90 % for sapwood and 70-80 % for heartwood in European hardwoods (Fernández-Golfín Seco and Conde García 2007). The maximum moisture content of the sapwood of Norway spruce has been reported to be 169 % (Rosner et al. 2010).

1.2. Cell-wall density

Variation in cell-wall density and the influence on the apparent density of wood (bulk density, including cell-walls and voids) are important in relation to manipulating wood to supply the transformation industry with a more homogenous material, in terms of apparent density and related properties. Controlling the sources of variation in cell-wall density is especially useful in wood in which density and quality vary widely depending on genetic factors (Zobel and Van Buijtenen 1989; Riesco Muñoz and Remacha Gete 2017).

Cell-wall density is expressed relative to the amount of wood material excluding the voids represented by the cell lumina. However, cell-wall density can also be expressed relative to the wood substance excluding microvoids within the walls of the cells or relative to the material which includes microvoids not filled by water because their diameter is smaller than that of water molecules. Estimation of cell-wall density and porosity therefore depends on the fluid used for the displacement in testing methods, as a fraction of the total porosity is due to microvoids (Siau 1995).

It is commonly accepted that cell-wall density in the dry state is somewhat constant in a particular type of wood, with little variability between tree species (Desch and Dinwoodie 1996; Usta 2003; Lachenbruch and McCulloh 2014). Indeed, it has been reported that measuring the cell-wall oven-dry density of wood by water displacement yields similar results for all wood species tested, with an overall average of 1,560 kg m^{-3}, a lower average of 1,400 kg m^{-3} for resinous wood tissues and a higher average of 1,620 kg m^{-3} for very lignified woods (Kollmann 1951). The range is 1,500-1,550 kg m^{-3} for Sitka spruce (*Picea sitchensis* (Bong.) Carr.) (Weatherwax and Tarkow 1968a, b), but decreases to 1,497-1,517 kg m^{-3} in some hardwood species (Kellogg and Wangaard 1969). The following mean values have also been reported: 1,200 kg m^{-3} (Peraza Sánchez 2001) and 1,343 kg m^{-3} for European oak (*Quercus robur* L.) (Riesco Muñoz and Remacha Gete 2017), 1,500 kg m^{-3} for all timbers (Hearmon and Paton 1958; Freas 1995; Desch and Dinwoodie 1996; Frihart and Hunt 2010), 1,530 kg m^{-3} for wood substance (Smith 1954; Lachenbruch and McCulloh 2014), 1,533 kg m^{-3} for white spruce (*Picea glauca* (Moench) Voss) (Stamm and Hansen 1937) and 1,540 kg m^{-3} (Glass and Zelinka 2010). As cell-wall oven-dry density exhibits low variation, the large range in apparent oven-dry density (e.g. Freas 1995; Desch and Dinwoodie 1996; Glass and Zelinka 2010) can mainly be attributed to variations in wood porosity related to species, tree and position in the stem.

1.3. Porosity

Wood porosity or wood specific porosity (percentage of wood tissue occupied by pores) is an anatomical variable influencing some types of industrial transformation of wood, such as preservation, gluing and coating. A high degree of porosity makes wood more wettable, which can facilitate impregnation of the wood by preservative or coating liquids; however, wettability can also increase the probability of colonization by wood-decay fungi (Carol and Clausen 2010; Sadiku 2018). In addition, porosity is decisive in gluing-related processes (wood surface sanding intensity, glue dosage, bonding pressure, bonding temperature, etc.) and in the strength of the glued joints when mechanical adherence is involved (Packham 1992).

Porosity is closely related to the surface roughness of wood, which is an important characteristic in manufacturing settings in relation to e.g. sanding, finishing and adhesion (Bao et al. 2016). Surface roughness strongly affects the texture, appearance and sensory perception of the wood surface, with the subsequent impact on the user's experience in numerous end-use applications (furniture, benches, tabletops, frames, floors, etc.) (Aydin et al. 2006; Coelho et al. 2008; Li et al. 2010).

Porosity is also related to the performance of the hydraulic and mechanical functions of wood tissues in the tree (Lachenbruch and McCulloh 2014). Regarding the species under study, the traits of the xylem influencing vulnerability to cavitation of trees belonging to the genus *Laurus* have recently been studied (e.g. Rodríguez-Zaccaro et al. 2019).

Oven-dry wood porosity can be as low as 6 % for the heaviest woods and it can reach 93 % for the lightest wood (Kollmann 1951). A value of 85 % porosity has recently been reported for *Paulownia* sp., a light hardwood (Kozakiewicz et al. 2020). Differences in porosity may arise from differences in the anatomy of the wood (abundance of different cell types, thickness of cell walls and size of cell lumina) (Mitchell and Denne 1997; Usta 2003), which can be modified by the effect of extractives (Polge 1966; Fries 1986).

1.4. Laurel wood

Information on wood maximum moisture content, cell-wall density and porosity is scarce, even though these variables have important technological repercussions in wood processing. As far as authors know, no information has been published on these physical variables in laurel wood, a phylogenetically ancient hardwood exhibiting physical properties similar to softwoods (Pulgar Lorenzo and Riesco Muñoz 2018). Laurel is a common tree species of the *Lauraceae* family that grows in Spain and other Mediterranean countries, as a remnant of the subtropical evergreen lauroid forests that covered the Mediterranean Region in the past, when the climate was more humid (Rozas Ortiz et al. 2005). The increasing aridity of the laurel distribution area is related to the high resistance of the xylem to formation of drought-induced embolisms, as a key adaptation of laurel trees in response to seasonally dry environments (Maatallah et al. 2010; McAdam and Cardoso 2019).

Laurel is an evergreen broadleaf tree that forms arboreal scrublands with forest structure (Ruiz de la Torre 1979). It can reach up to 28 m in height (Rozas Ortiz et al. 2005) and has straight stems. The wood has white-yellow sapwood and darker heartwood. The growth rings are visible to the naked eye, and the wood tends to form semiporous rings (García Esteban and Guindeo Casasús 1989). The density is moderately high and homogeneous along the stem. The wood is machinable, allowing a decorative finish to be achieved. It is used to craft small marquetry objects and also for carving and turnery (García Esteban and Guindeo Casasús 1990; Pulgar Lorenzo and Riesco Muñoz 2018).

The main objectives of the present study were to assess the maximum moisture content, cell-wall oven-dry density and oven-dry wood porosity of laurel wood, as well as the inter- and intra-tree variations in these variables, and also to determine the relationships between these and other physical properties. The findings will help to provide values for the process variables in wood manufacturing and will also aid decisions regarding how to manage this wood to reduce variations in apparent density and thus produce a more homogeneous raw material in terms of density and other properties related to quality.

2. Material and methods

Several properties related to density and dimensional stability of laurel wood in response to changes in moisture content were evaluated in a previous study (Pulgar Lorenzo and Riesco Muñoz 2018). The wood analysed in the earlier study consisted of a sample of 958 small, defect-free specimens obtained from 17 young laurel trees (ranging from 24 to 41 years old, breast height diameter ranging from 13.7 to 28.9 cm and total height ranging from 5.1 to 13.1 m), selected and felled for analysis, in a stand located in Galicia (north-western Spain). Cross-sectional slices were obtained at the stem base and at stem heights of 1, 2 and 3 m (when the stem diameter was large enough) in each felled laurel. Slices were cut to a thickness of approximately 15 cm and were sawn to produce standard prismatic specimens (Pulgar Lorenzo and Riesco Muñoz 2018). The methods used for representative sampling, data acquisition and determination of physical properties, according to domestic and international standards, were described in the aforementioned study. Methodological aspects related to the number of sampled trees and gravimetric variable correct mensuration (Williamson and Wiemann, 2010) and to sampling height in the tree (Anfodillo et al., 2013) were also considered.

In the present study, a subsample of 300 specimens obtained from the material analysed in the previous study were immersed in water in an open tank, at laboratory temperature, for a period of 13 months. The temperature of the water was always 20 ºC or slightly higher. The moisture content of the water-saturated specimens was then determined as the difference in mass of the soaked and oven-dried samples, and expressed as a percentage of the mass in the oven-dry state, according to the EN 13183-1:2002 standard (CEN 2002). The value obtained was assumed to be the maximum moisture content (*MM*), and full saturation of the lumens and cell-walls was assumed to have occurred. The *MM* values, together with data from the previous study (density of water, volumetric shrinkage of wood, apparent oven-dry density and fibre saturation point) (Pulgar Lorenzo and Riesco Muñoz 2018), were used to calculate the cell-wall oven-dry density according to equation (1), in which the following assumptions were made: that wet wood contains bound water dissolved or adsorbed in the cell-wall and bound water therefore contributes to wood moisture content; that cell-wall dimensions vary in response to changes in moisture content (cell-walls are subject to shrinkage and swelling) (Siau 1995; Rosner et al. 2010); and that the density of bound water is the same as the density of free water:

$$CWD = WD\frac{100 + VS}{WD\frac{100 + VS}{OD} - MM + FSP} \qquad (1)$$

where

CWD is the cell-wall oven-dry density, in kilograms per cubic metre, *WD* is the density of water in the voids of wood at laboratory temperature, in kilograms per cubic metre,

VS is the volumetric shrinkage of wood, expressed as a percentage,

OD is the apparent oven-dry density, in kilograms per cubic metre,

MM is the maximum moisture content, expressed as a percentage,

FSP is the fibre saturation point, expressed as a percentage.

The cell-wall oven-dry density was used to compute oven-dry wood porosity (*P*), defined as the percentage of void volume of oven-dry wood, according to equation (2):

$$P = 100 - 100\frac{OD}{CWD} \tag{2}$$

The density of water was considered to be approximately 1,000 kg m^{-3} as compaction of bound water is negligible (Siau 1995). Volumetric shrinkage, apparent oven-dry density and fibre saturation point, which are required to compute the variables in equations (1) and (2), were obtained from the previous study for each of the 300 tested specimens (Pulgar Lorenzo and Riesco Muñoz 2018). The volumetric shrinkage was obtained from water saturation to dry state, as a percentage of dry volume. The apparent oven-dry density was obtained as the ratio between the mass and volume of the specimen in the dry state. Ring width, basic density and air-dry density (adjusted to a moisture content of 12 %) were also obtained in the previous study and were included here to describe the tested material in context, because of the value of density variables as tools for describing the plant functionality (Williamson and Wiemann 2010), beyond the classical role of density as wood quality index (e.g. Zobel and Van Buijtenen 1989; Glass and Zelinka 2010; Lachenbruch and McCulloh 2014). Basic density is used as an "apparent density" estimator in this study, although it is not, sensu stricto, a measure of wood density because its value (dry biomass in a unit volume of green wood) does not represent any actual state of wood. It most closely corresponds to an ecological trait (Williamson and Wiemann 2010).

The descriptive statistics of the physical properties were obtained after validating and refining the test results. The wood properties assigned to the laurel wood were calculated as the arithmetic mean values of all the valid data from the specimens obtained in the sampled trees, considering specimens as sampling units, all of the same weight in the sample. Dispersion of the values the properties analysed was quantified using the coefficient of variation (quotient of standard deviation and mean, expressed as a percentage). The coefficient of variation represents an estimate of relative dispersion and it is useful for comparing the scatter of different variables.

Exploratory analysis of the relationships between quantitative variables was conducted by graphical inspection of the plotted pairs and examination of the Pearson's or Spearman´s correlation coefficients. The analyses were applied to the overall data and to each sub-sample of specimens grouped by qualitative variables (namely tree and height in the stem). One-way analysis of variance (ANOVA) was used to search for relationships between quantitative variables (namely maximum moisture content, cell-wall density and oven-dry wood porosity) and qualitative variables (namely tree and height in the stem). LSD post-hoc analysis was used to identify any significant differences between means. The Kruskal-Wallis test, with pairwise multiple comparisons using Wilcoxon rank sum test and *p*-value adjustment by Bonferroni´s method, was applied when the assumptions for ANOVA were not fulfilled.

Test results were considered statistically significant at $p < 0.05$ and highly significant at $p < 0.01$. All statistical analyses were carried out using Microsoft Excel 2013 and IBM SPSS Statistics software (version 25).

3. Results and discussion

3.1. Basic descriptive statistics

The main statistics of the physical properties under study are summarised in Table 1. Cell-wall oven-dry density was nearly two times higher than the oven-dry density, as approximately half of wood apparent volume (45 %) corresponded to pores. Cell-wall oven-dry density was lower than all of the previously reported values mentioned in the Introduction. Maximum moisture content was much higher than the fibre saturation point. This was expected because, in the water absorption process, the saturation point of wood fibre is reached when the cell lumina are still free of water, while the maximum moisture content is reached when the cell lumina are filled with water (Prichananda 1966; Siau 1995).

Table 1.

Decay and the inherent loss of material from the vessel cell-walls and loss of parenchyma cells were expected because of the long saturation time. It was therefore assumed that some of the natural substances impregnating the wood were extracted and dissolved in water during the long period of immersion of the specimens. The cell-wall density obtained was therefore that of partially extracted wood (extraction of part of the water-soluble substances impregnating the wood). The value was lower than the density of non-extracted cell walls, although removal of part of the extractive content reduces the bulking effect of the low hygroscopicity of cell wall materials (Siau 1995). In addition, it is possible that not all of the cell lumina were filled, despite the long immersion period. Some air may remain in some of the cell voids, and therefore the moisture content determined would not be the theoretical maximum. Rosner et al. (2010) concluded that “after refilling small air bubbles might have been trapped in the conduits”. Consequently, cell-wall density, computed by equation (1), underestimates the real cell-wall density, and the wood porosity, computed by equation (2), also underestimates the real value.

Moreover, as the specimens were oven dried in a previous test (Pulgar Lorenzo and Riesco Muñoz 2018), the maximum achievable moisture content of the wood would be lower due to the modification of the hydrophilic behaviour of the wood surface. A study with fresh and pre-dried Norway spruce sapwood revealed that only one cycle of wood dehydration, without a sequence of repeated rounds of wetting-drying leading to hysteresis phenomena, increases the vulnerability of hydraulic conduction and may modify the structure of the cell walls and the shrinkage behaviour (Rosner et al., 2010). These possible changes influence the cell-wall density estimation with equation (1), in which volumetric shrinkage is an input variable.

It is also possible that low molecular weight compounds were volatilized during the standardised drying at 103 ºC in the previous test (Pulgar Lorenzo and Riesco Muñoz 2018). Dry mass would be therefore underestimated and maximum moisture content would be overestimated, partly compensating for the effect described in the previous paragraph, although only a small amount of mass is expected to be lost due to the drying process (Williamson and Wiemann 2010).

Finally, the equilibrium moisture content depends on the shape and size of the samples because the moisture content is higher in thin sections than in larger specimens (Siau 1995). Underestimation of maximum moisture content, cell-wall density and porosity is considered in the discussion, although it did not influence analysis of the inter-tree and intra-tree variation in the variables under study.

As previously mentioned, the values of apparent air-dry density, basic density, volumetric shrinkage, fibre saturation point and ring width were obtained for each of the specimens tested in a previous study (Pulgar Lorenzo and Riesco Muñoz 2018). Regarding apparent air-dry density, the sampled wood was homogeneous and moderately heavy according to the interpretation criteria in the UNE 56528:1978 standard (IRANOR 1978a) and the UNE 56540:1978 standard (IRANOR 1978b). The three apparent density variables analysed (air-dry, oven-dry and basic density) were remarkably homogeneous, as occurs in conifer wood, and less variable than is usual in hardwood species (e.g. Wagenführ and Wagenführ 2022). The cell-wall density was also homogeneous, but it was expected to be much more homogenous than the apparent density variables because it is not influenced by the porosity as a source of variation. Wood moisture content is not a source of variation for any of the four density variables under study.

Apparent density is calculated as the ratio between the mass (wood fibre matter and water) and the volume of wood, considering the whole volume: volume of wood substance and volume of voids (cell lumina and intercellular spaces), partly filled with water (Lachenbruch and McCulloh 2014). The apparent density of wood therefore depends on the amounts of water, air and wood fibre matter, together with the cell-wall density and the density of the water inside the wood. Analysis of oven-dried wood (absence of water in cell-walls and lumina) is simpler because the apparent oven-dry density only depends on the quantity of cell walls and the cell-wall oven-dry density.

The value of volumetric shrinkage was high according to the interpretation criterion in the UNE 56540:1978 standard (IRANOR 1978b), and the fibre saturation point was intermediate according to the interpretation criterion proposed by Gutiérrez Oliva and Plaza Pulgar (1967).

The growth ring width was much more variable (range 2-10 mm) than the other quantitative properties analysed (see coefficients of variation in Table 1). This can be attributed to the diversity of dimension and ages of the trees included in the sample.

The relative error in the estimation of the means for all the analysed variables was below 5 %, the upper threshold proposed in the UNE 56528:1978 standard (IRANOR 1978a). This finding was attributed to the overall homogeneity of the variables, except for ring width. The sample size was therefore sufficient to obtain accurate estimators for the means given the dispersion exhibited by the variables.

3.2. Relationships between wood properties

Maximum moisture content, cell-wall oven-dry density and oven-dry wood porosity were not normally distributed or even symmetrically distributed. Spearman´s correlation coefficients were therefore computed in order to quantify the relationships between the wood quantitative variables under study (Table 2). The lack of high correlations for ring width and other wood properties at stand-level scale may be partly explained by the high variation in ring width and the low variation in maximum moisture content, density variables and porosity (Table 1). However, the correlations were highly significant, probably due to the large amount of data considered.

Table 2.

The homogeneous density observed in the laurel wood is more usual for mature conifer wood, and the negative correlations between growth ring width and density (Table 2) are also typical of conifer wood (e.g. Kollmann 1951).

Maximum moisture content and porosity were highly significant and inversely related to oven-dry, air-dry and basic density. The values of the Spearman's correlation coefficients were considered suitable for modelling purposes, with basic density being a good predictor of maximum moisture content, and air-dry density being a good predictor of porosity. Graphical analysis of the plotted pairs of maximum moisture content versus basic density and oven-dry wood porosity versus air-dry density (density at 12 % moisture content) revealed that a linear or linearizable function would be suitable for describing the relationships between variables (Figure 1). A small number of specimens exhibited lower porosity and maximum moisture content than expected considering the density and the general trends observed in the rest of the data (Figure 1). This outlier group of specimens corresponded to the base of a stem with the widest rings of the sample (mean ring width 7.9 mm, compared to a mean ring width of 4.8 mm for the rest of the trees). Ring width and apparent density were negatively related (Table 2) and an abnormal group of specimens -in relation to ring width- were therefore also expected to be outliers for apparent density, being lighter but with intermediate maximum moisture content and porosity.

Figure 1.

Considering the subsamples from each individual tree, the correlation coefficients for maximum moisture content and basic density in each tree were higher than for the whole sample only in 9 of the 17 trees, probably due to the smaller sample size per tree. Similarly, the correlation coefficients for porosity and air-dry density were higher than the coefficients for the whole sample only in 6 of the 17 trees. Development of individual-tree models was therefore not pursued, as the findings were not encouraging.

Cell-wall density was obviously related to the apparent density variables analysed (oven-dry, air-dry and basic density), but the correlation coefficients were not high enough to enable construction of predictive models of cell-wall density including apparent densities as possible predictor variables.

3.3. Inter-tree variation in the wood characteristics

Analysis of variance was not conducted as maximum moisture content, cell-wall oven-dry density and oven-dry wood porosity were not normally distributed. The Kruskal-Wallis test was therefore used, with tree as a factor. The test revealed that each physical property of the laurel wood differed significantly between trees (Table 3), as also reported for *Quercus robur* (Riesco Muñoz and

Remacha Gete 2017). The inter-tree variation was not attributable to genetic differences, because the genetic diversity was not expected to be high in sampled trees that were close to each other in the same stand. There was probably a reasonable degree of relatedness among individuals growing next to each other in the same plot. In addition, environmental conditions were almost constant for all sampled trees as there were no remarkable differences in site quality.

Table 3.

The inter-tree variation in wood characteristics may therefore be attributed to tree factors such as age, dimensions (breast height diameter, total height, over bark volume, slenderness) and growth rate. The correlation matrix for average per tree wood properties and dendrometric tree characteristics (not included here) showed that the closest relationships were those related to age. The highest values of the Pearson's correlation coefficient were as follows:

- r = -0.56* for cell-wall density and tree age
- r = -0.50* for oven-dry wood porosity and tree age.

As both relationships were negative, the cell-wall density and porosity values are expected be lower in trees older than those in the study. However, this is a tentative prediction as only 17 pairs of values (mean wood property and tree age) were used to compute the Pearson´s correlation coefficient. In fact, the Spearman´s correlation coefficient was not significant for any of the variables tested. The possible lower porosity in older trees is an important factor to be considered regarding the industrial use of laurel wood.

The box plots of cell-wall density and porosity distributed by tree are presented in Figure 2 and Figure 3. Graphical analysis of these and the post-hoc analysis by the Wilcoxon signed-rank test for paired data with the Bonferroni's correction (not included here because of the large number of differences of means analysed) showed that the cell walls were lightest in trees older than 35 years, except for tree number 15. In addition, trees that differed significantly from the others in terms of porosity (low) were those in which ring width was smallest (trees number 9 and 16). In fact, porosity and ring width were positively related, as indicated in Table 2. As laurel is a hardwood with marked, usually semiporous rings (García Esteban and Guindeo Casasús 1989; Pulgar Lorenzo and Riesco Muñoz 2018), a higher proportion of earlywood was expected in thin rings. Therefore, the low porosity in narrow rings found in this study led us to assume that the earlywood was less porous than latewood, although this contradicts the more porous nature of earlywood tissues. It must be assumed that the analysed hardwood tends towards the usual pattern of diffuse distribution of vessels in the ring (Figure 4) and the spring band width of the growth ring, very variable in laurel wood (García Esteban and Guindeo Casasús 1989), decreases in proportion as the ring width decreases, as is common in conifer wood (Kollmann 1951).

Figure 2.

Figure 3.

Figure 4.

Xylem tissue is under pressure to adapt to biotic and abiotic challenges (Lachenbruch and McCulloh 2014), and lower density values at older cambial ages are theoretically expected due to competition for resources over time (Zobel and Van Buijtenen 1989). The effect of competition on density was not observed in the present study, probably due to the young age of the sampled trees, in which competition responses were not yet reflected in the xylem.

The absence of significant correlations between apparent oven-dry density and age can be explained by the combined effect of a decrease in cell-wall density (lighter matter) and a decrease in porosity (more matter) leading to an almost constant oven-dry density in young and older trees.

The variation in apparent density is not only attributable to the balance between cell-wall density and porosity, because density and other physical properties are also influenced by the relative proportion of cell types. Lower wood density is explained by a smaller proportion of dense thick-walled cells and a larger number of pores in diffuse porous species (Paul 1963). The presence of wide vessels is more common in wetter sites and in trees relative to shrubs (Anfodillo et al. 2013). The abundance of thin-walled vessels with a large lumen relative to thick-walled, small lumen fibres is related to a smaller amount of cell wall material and lower density. In addition, the relative abundance of parenchyma cells affects wood density because of their relatively thick walls and the frequent presence of cross walls, due to the short length of this type of cell (Thomas 1991).

3.4. Wood variation along the stem

The intra-tree variation in the properties analysed was low but not negligible. The coefficient of variation for maximum moisture content was 2 % for the most homogeneous trees and 11 % for the most heterogeneous one, with the coefficients of variation of the 17 sampled trees averaging 5 %. Regarding cell-wall density, the coefficient of variation was 2 % for the most homogeneous trees and 9 % for the most heterogeneous ones, with the coefficients of variation of the 17 sampled trees averaging 4 %. Thus cell-wall density can be considered very homogeneous in the whole sample and in each tree, but not almost constant, as reported in previous studies (some of which are mentioned in the Introduction). Regarding the porosity, the coefficient of variation was 3 % for the most homogeneous trees and 10 % for the most heterogeneous ones, with the coefficients of variation of the 17 sampled trees averaging 6 %. The intra-tree coefficients of variation for both cell-wall density and porosity were significantly higher in the older trees.

The height in the stem was the source of intra-tree variation used in this work. This was justified because the expected pith-to-bark variation (Zobel and Van Buijtenen 1989; Williamson and Wiemann 2010; Anfodillo et al. 2013) was a negligible source of intra-tree variation, as demonstrated in a concurrent study of the authors with the same wood species (Pulgar Lorenzo and Riesco Muñoz, unpublished). Variation in maximum moisture content, cell-wall density and porosity along the stem was expected because the vascular network of the tree responds to the increase in plant height (Anfodillo et al. 2013). Analysis of variance considering height in the stem as a factor revealed that each of the physical properties of the laurel wood assessed varied significantly at different positions along the stem (Table 3). This was also checked with the Kruskal-Wallis test, although the variability in properties along the stem was rather small (Figure 5). In fact, the only remarkable variation was that of the cell-wall density, with a decrease of 18 kg m^{-3} per m between the root collar and a height of 3 m. The decrease in cell-wall density was accompanied by a decrease in porosity. This acted as a compensatory mechanism to maintain the apparent density almost constant along the stem: there was more matter (cell walls) per unit volume at higher positions in the stem, but the matter was lighter. This is an example of the frequent mutual compensation mechanism, in which the traits vary and the corresponding value of the property can remain unchanged (Lachenbruch and McCulloh 2014). However, the variations in this case are of no practical interest, and, from the point of view of harvesting, the wood maximum moisture content, cell-wall density and porosity can be assumed to be constant along the first three metres of the laurel stem. The trade-off mechanism stabilising the apparent density was the same used to explain the uniformity of apparent density throughout the lifespan of the tree.

Figure 5.

The inter- and intra-tree variation in the properties analysed was similar to the variation in other wood properties, apparently related to cambial age, although the cambial cell functionality depends directly on the distance from the cambial cells to the tree apex, as highlighted by Anfodillo et al. (2013). It was therefore expected that the variation in wood properties analysed in the study was also apparently related to the young age of the cambial tissues.

4. Conclusion

Maximum moisture content, cell-wall density and porosity are expected to be lower and more variable in older trees. Commercial exploitation of the complete trunk is recommended because values of all three variables were only slightly lower at higher positions in the stem, although specific harvesting of the basal log of young trees is advisable if more porous wood is required.

Porosity can be estimated by using air-dry density as a predictor variable. The variation in apparent density of wood was mainly attributed to variations in porosity because cell-wall density was homogeneous, although it was far from constant in the species. Further studies should examine whether cell-wall density differs significantly between species.

From a methodological point of view, the sample size was sufficient to yield accurate estimators for this type of hardwood.

5. Declarations

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Figure captions

Figure 1 Scatter plot of oven-dry wood porosity and maximum moisture content against density for the sample of laurel wood analysed. *RWm*: mean ring width.

Figure 2 Box plot of the cell-wall oven-dry density of laurel wood in each tree. Boxes are ordered by increasing age of the tree (scale not continuous). The trees are ordered by increasing breast height diameter for individuals of the same age. The boxes corresponding to the trees with the significantly lower cell-wall oven-dry density are highlighted.

Figure 3 Box plot of the oven-dry wood porosity of laurel wood in each tree. Boxes are ordered by increasing age of the tree (scale not continuous). The trees are ordered by increasing breast height diameter for individuals of the same age. The boxes corresponding to the trees with the significantly lower oven-dry wood porosity are highlighted.

Figure 4 Planed and sanded cross-section of a laurel wood specimen (target dimensions 20 × 20 mm), exhibiting the diffuse distribution of the larger vessels and axial parenchyma along the radial direction of the visible rings. The end-grain surface was photographed in incident light. Length of the reference bar: 25 mm. Photograph reproduced courtesy of M. Souto-Herrero.

Figure 5 Trends in the physical properties of laurel wood (cell-wall oven-dry density, maximum moisture content, apparent oven-dry density and oven-dry wood porosity) at different heights in the stem.

Table 1. Descriptive statistics of assessed physical properties of laurel wood. *n* = 300 valid tests; *CI* = confidence interval for the mean at 95 %; *CV* (%) = coefficient of variation; *e* (%) = relative error in estimating the mean.

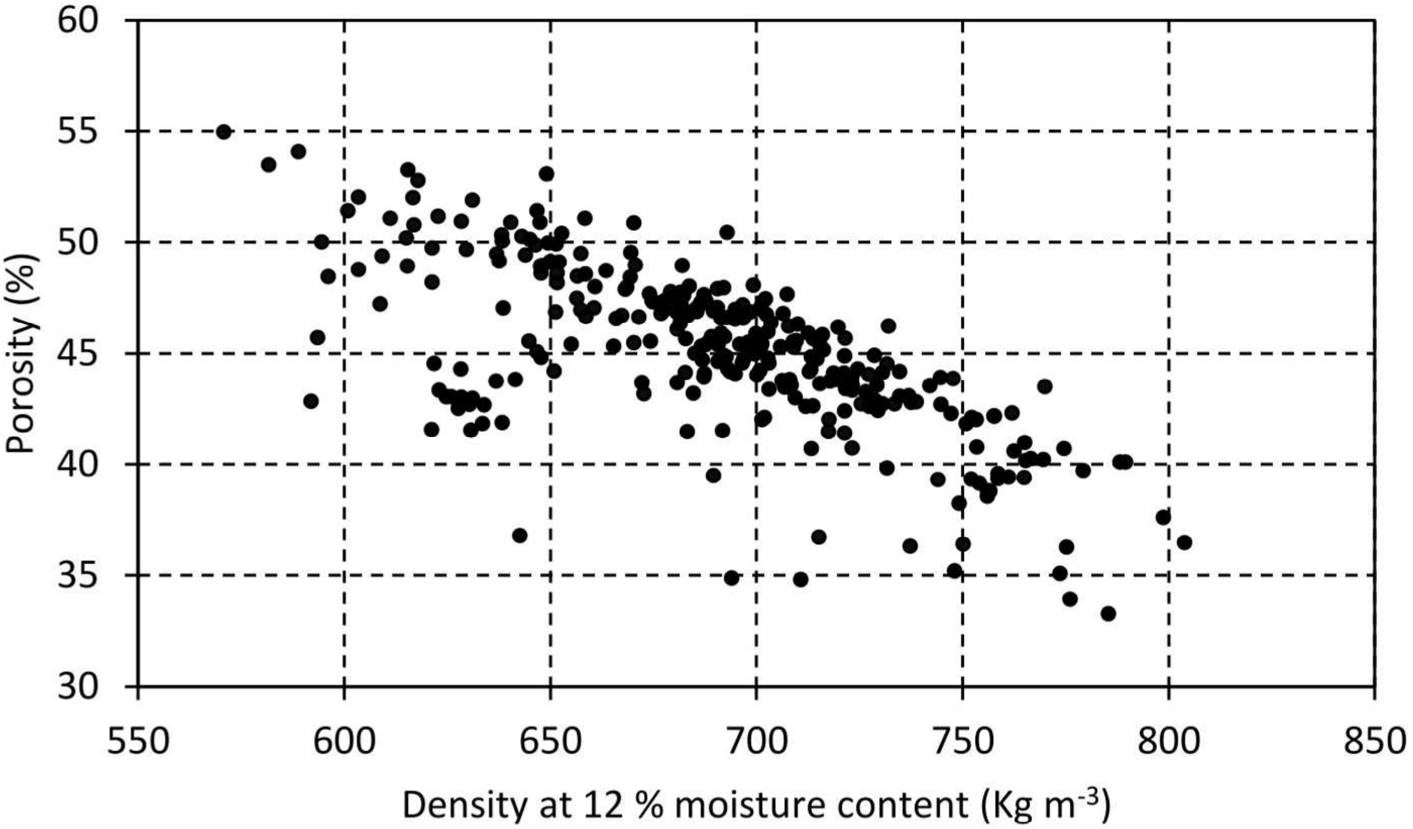
	mean	minimum	maximum	*CI*	*CV* (%)	*e* (%)
maximum moisture content (%)	114	90	146	112.6;114.8	9	0.5
cell-wall density (kg m^{-3})	1,198	942	1,360	1,189.8;1,205.5	6	0.3
oven-dry wood porosity (%)	45	33	55	44.6;45.5	8	0.5
oven-dry density (kg m^{-3})	657	542	772	651.6;662.0	7	0.4
air-dry density (kg m^{-3})	691	571	804	685.6;695.9	7	0.4
basic density (kg m^{-3})	560	470	640	555.9;563.3	6	1.9
volumetric shrinkage (%)	17.3	8.8	25.3	17.03;17.55	13	0.8
fibre saturation point (%)	33	20	53	32.2;33.1	13	0.7
ring width (mm)	5.0	1.8	9.9	4.73;5.18	40	2.3

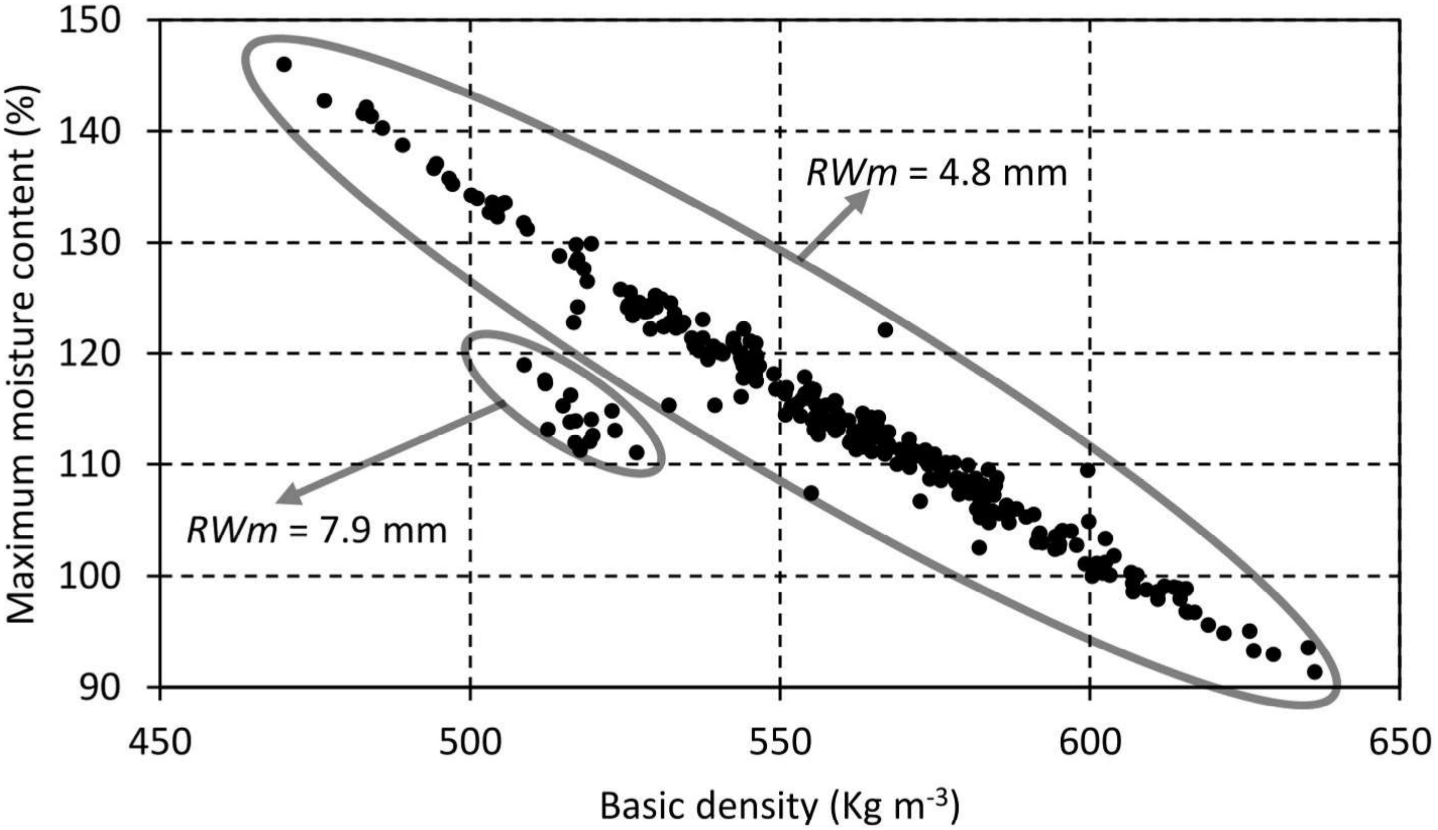
Table 2. Matrix of the Spearman's correlation coefficients (*r*) for the physical properties of laurel wood assessed. *n* = 300 valid tests; ** = significant at *p* > 99 %; n. s. = not significant.

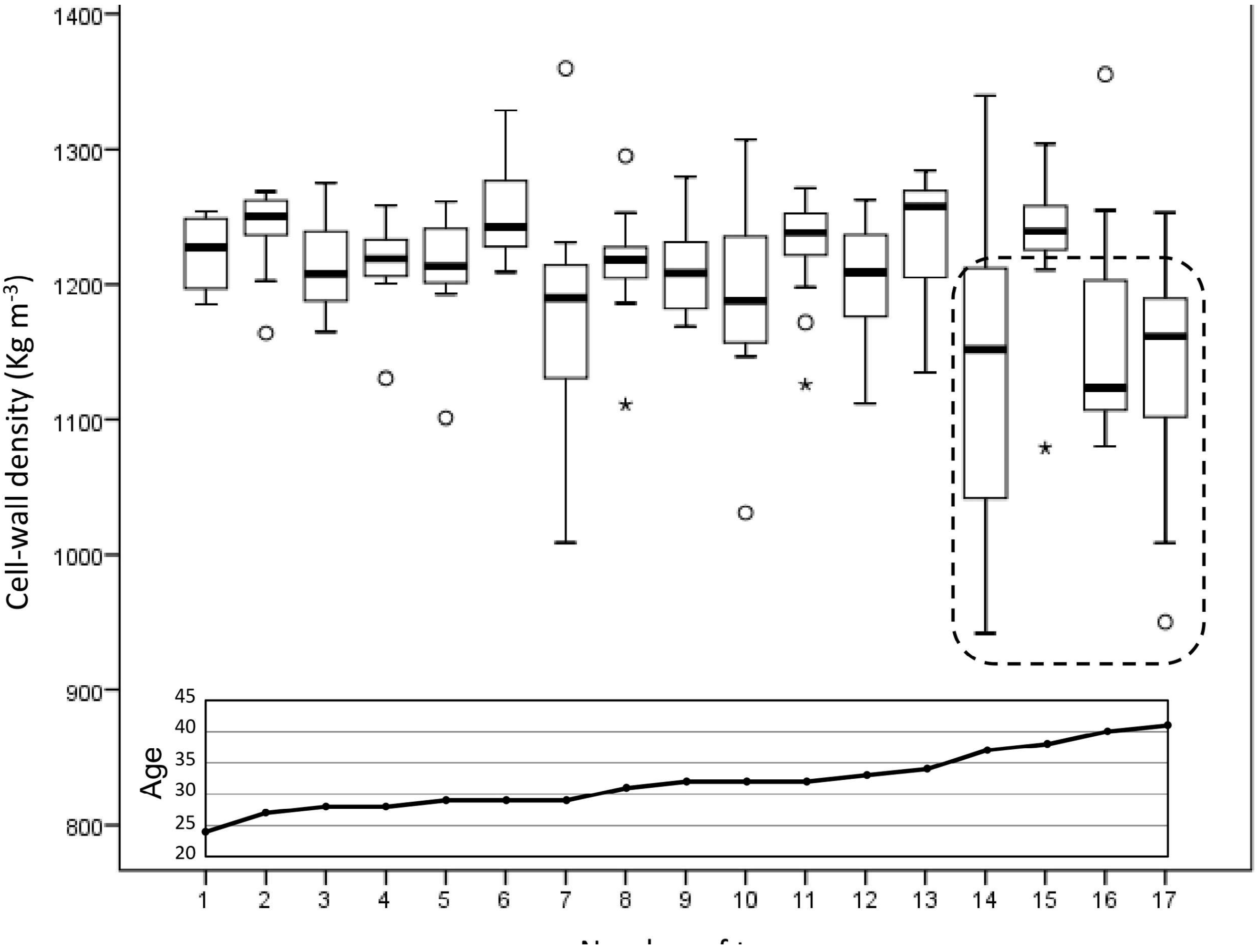
	RW	*OD*	*AD*	*BD*	*MM*	*CWD*	*P*
ring width (*RW*)	1.00						
oven-dry density (*OD*)	-0.30**	1.00					
air-dry density (*AD*)	-0.31**	0.99**	1.00				
basic density (*BD*)	-0.30**	0.96**	0.98**	1.00			
maximum moisture content (*MM*)	0.26**	-0.90**	-0.92**	-0.94**	1.00		
cell-wall oven-dry density (*CWD*)	n. s.	0.43**	0.33**	0.35**	-0.22**	1.00	
oven-dry wood porosity (*P*)	0.19**	-0.62**	-0.69**	-0.66**	0.78**	0.33**	1.00

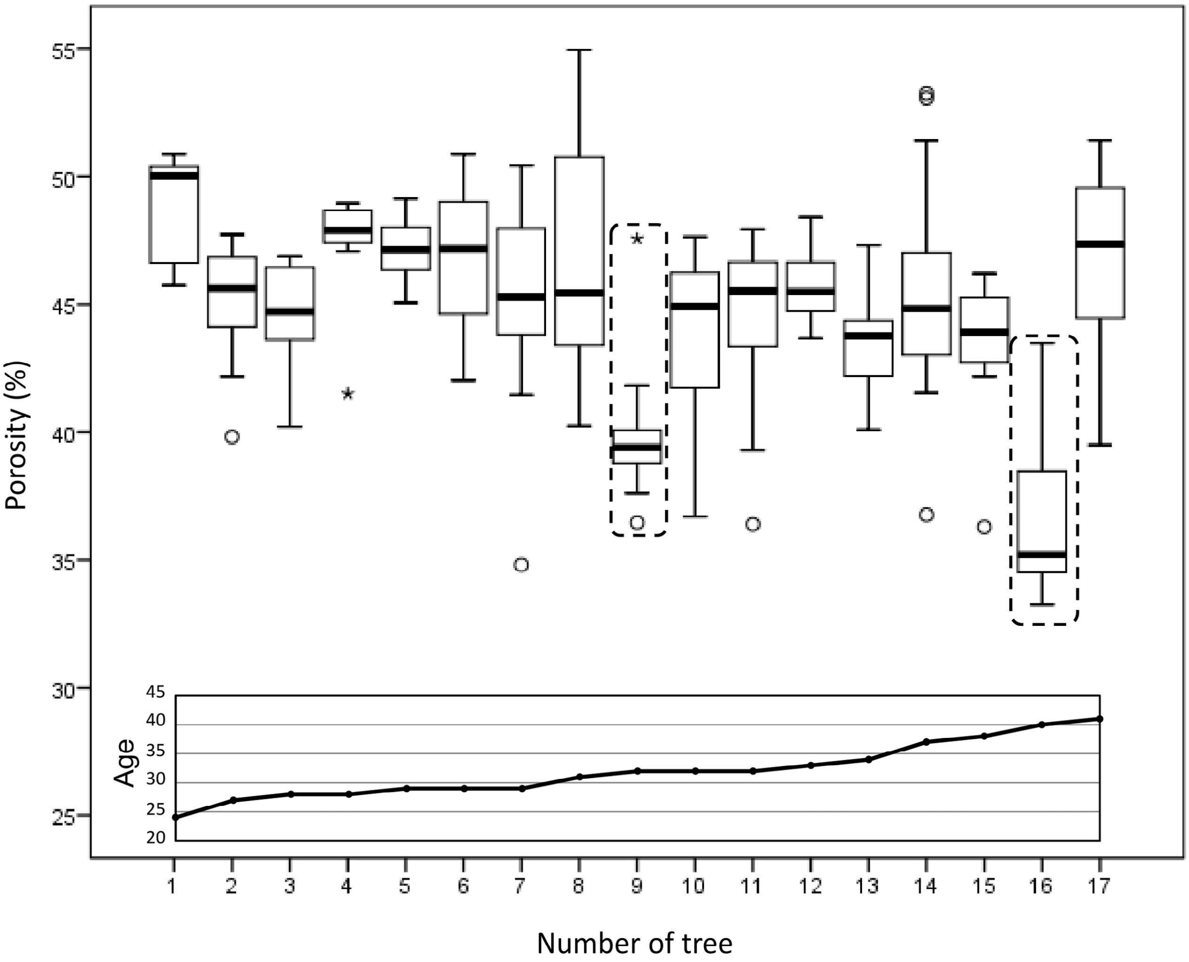
Table 3. Kruskal-Wallis Chi-squared statistic (K-W), degrees of freedom (df) and significance levels (*p*-values) in the Kruskal-Wallis group comparison for physical properties of laurel wood, considering the variables tree and height in the stem as factors.

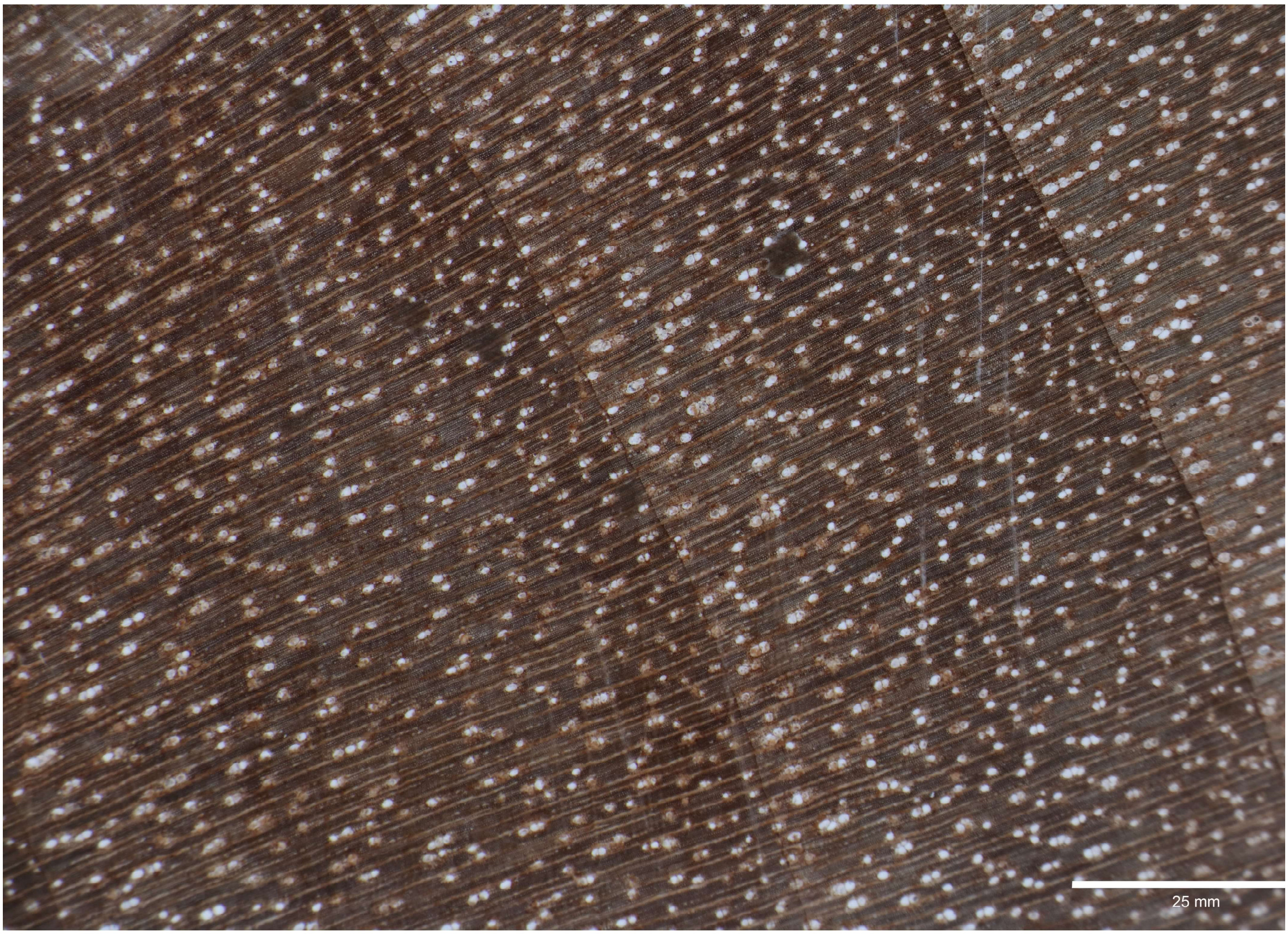
quantitative variable	tree factor			height in the stem factor		
	K-W	df	Sig.	K-W	df	Sig.
maximum moisture content (%)	151.960	16	< 0.01	28.633	3	< 0.01
cell-wall oven-dry density (kg m^{-3})	91.683	16	< 0.01	13.583	3	< 0.01
oven-dry wood porosity (%)	88.727	16	< 0.01	40.091	3	< 0.01

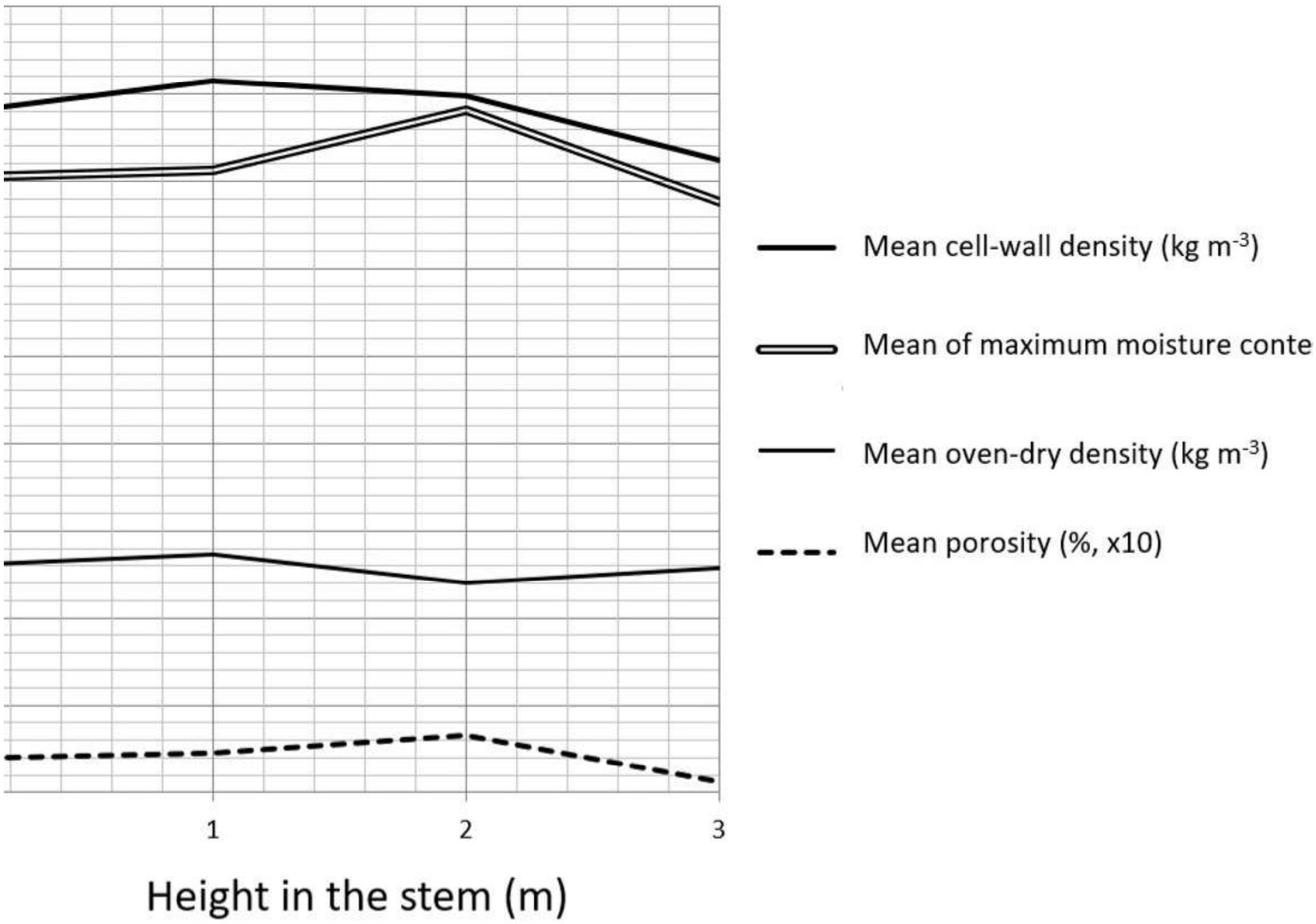

Porosity (%)
60
55
50
45
40
35
30
550
600
650
700
750
800
850
Density at 12 % moisture content (Kg m^{-3})


Maximum moisture content (%)
150
140
130
120
110
100
90
450
500
550
600
650
Basic density (Kg m^{-3})
RWm = 4.8 mm
RWm = 7.9 mm


Cell-wall density (Kg m^{-3})
1400
1300
1200
1100
1000
900
800
Age
45
40
35
30
25
20
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17


Porosity (%)
55
50
45
40
35
30
25
Age
45
40
35
30
25
20
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
Number of tree


25 mm


Mean cell-wall density (kg m-3)
Mean of maximum moisture conte
Mean oven-dry density (kg m-3)
Mean porosity (%, x10)
1
2
3
Height in the stem (m)