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RESEARCH ARTICLE

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Age trends and within-site effects in wood density and radial growth in *Quercus faginea* mature trees

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Abstract

Aim of the study: This paper aims to valorize the wood of *Quercus faginea* Lam. for high quality end uses (e.g. furniture) by studying growth and quality properties using mature trees. Age trends in tree-ring width and wood density are shown and the main factors responsible for variations in tree-ring width and wood density within and between trees are investigated.

Area of study: The study site is in the center of Portugal within the natural species distribution area.

Material and methods: Radial samples from ten mature trees were collected at 6 heights (from base to 9.7 m) and prepared for X-ray microdensity.

Main results: Wood density showed high values, ranging from 0.868 g/cm^3 to 0.957 g/cm^3. Wood density decreased from pith to bark and with stem height. Cambial age showed a linear relationship with wood density and most of the variation in wood is explained by age. Intra-ring and axial within-tree homogeneity was good.

Research highlights: Mature trees of *Q. faginea* showed high wood density and a high potential for high quality end uses, comparable to other oaks. Wood density is influenced by cambial age and tree-ring width. Wood quality may be improved by tree growth rates adjustment e.g. through an adequate tree stand density (e.g. thinning operations).

Keywords: *Quercus faginea*; wood density components; cambial age; wood quality; variation.

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Introduction

Oak wood is a highly prized wood for a wide variety of valued products, such as indoor flooring, furniture, and cabinets, due to its strong textural features, density and mechanical properties. In central Europe, native oaks such as *Quercus robur* and *Q. petraea* are the most frequently studied in relation to wood anatomical characteristics and properties due to their present market value (e.g. Zhang *et al*., 1993; Guilley *et al*., 1999, 2004; Bergès *et al*., 2008), but other oaks have also attracted attention, namely species growing in more southern regions (e.g. Knapič *et al*., 2008; Leal *et al*., 2012).

Quercus faginea Lam. (Portuguese or Lusitanian oak) is native to the Iberian Peninsula and Maghreb Africa and its wood was used in the past in industry such as shipbuilding. However intensive exploitation and replacement by plantation species such as *Pinus pinaster* and *Eucalyptus globulus* have led to declining areas, abandonment of silvicultural management and low value wood utilization, meaning nowadays that it is mainly used as fuel. There are serious concerns regarding the sustainability of such endogenous oak forests and the overall forest diversity (e.g. Goicoechea & Agúndez, 2000). Valorization of *Q. faginea* wood is important in this context contributing to fight species' decline by giving an economic value for such potential multifunctional forests that will go beyond conservation (Habitat Directive).

Density is one of the main properties of wood, largely used to evaluate its quality and technological characteristics. Wood density varies between and within species, and also shows within-tree variability that includes axial, radial and within growth ring variation (Panshin & Zeeuw, 1980; Zobel & van Buijtenen, 1989; Saranpaa, 2003). The latter is essentially related to cellular structure, earlywood and latewood characteristics and proportion. In ring-porous species, growth rate affects wood properties through earlywood and latewood proportion, and high growth rates generally result in higher density in spite of some controversy (Zobel & van Buijtenen, 1989; Walker, 2006). Heartwood proportion is also an important characteristic in determining wood quality and in the case of mature trees of *Q. faginea* it represented 73% of the cross-sectional area at 1.3 m of height (Sousa *et al.*, 2013). Additional aspects such as absence of branches and presence of reaction wood and straight grain are also relevant characteristics in determining quality of wood.

The study of wood density variation is therefore one supporting line for the effort of valorizing *Q. faginea*. A previous study with young adult trees (on average 40 year old trees, with a dbh of 21 cm) showed favorable features in what regards the high density (ca. 0.848 g/cm^3) and a within-tree density variation of small magnitude, leading to a fairly homogenous wood (Knapič *et al.*, 2011). However, knowledge is still lacking on mature trees at longer rotation ages with ca. a dbh class of 40 cm that would correspond to the typical trees managed for timber products. It is known that wood formation is closely related to foliage or crown in the young trees compared to older ones (Larson, 1969). So, this approach on long-term effects in *Q. faginea* wood technological properties is needed to clarify its quality and suitability for the timber industry.

This issue is the object of the present paper which addresses the question of the within-tree variation of ring width and wood density components. Although a decreasing pattern from pith to bark, and from base to top may be expected as it occurs in other *Quercus* spp. (e.g. Lei *et al.*, 1996; Bergès *et al.*, 2000), the wood density range is quite diverse within this genus and there is little information on variation patterns in high density woods such as *Q. faginea* (Nepveu, 1984; Dilem, 1995; Woodcock & Shier, 2002). The knowledge obtained will be important broadly in the size-and age- related changes in hardwoods quality context, and locally for forest management of the actual *Q. faginea* stands targeted towards solid wood products, and for increasing the interest in the economic exploitation of this autochthonous species in the future.

Material and methods

Quercus faginea trees were selected in the center of Portugal, at Vimeiro (39º 29' N, 9º 01' W, 100 m mean altitude) from an unmanaged stand of public nature kept for conservational targets, essentially constituted by *Q. faginea* and some *Q. suber*, *Castanea sativa* and *P. pinaster* sparse trees. Vegetation is diverse with ferns, gorses, heather and grass among others. The climate is Mediterranean with Atlantic influence, with a mean annual temperature of 15 ºC and annual precipitation of 890 mm. The highest temperatures occur during July-August (19 ºC) and the precipitation is concentrated from October to February (77 mm to 99 mm monthly rainfall). Soils are classified as chromiccambisoils.

Ten dominant or co-dominant trees aged on average 125 years and free of visible signs of decay were harvested. Total tree height, crown height, crown diameter and tree diameter (over bark) at 1.3 m were measured on the standing trees (Table 1). These trees were felled and sampled at stem base, and at 1.3 m, 3.4 m, 5.6 m, 7.7 m and 9.7 m above ground level. Only 8 trees attained the 7.7 m height level and 6 trees the 9.7 m height level. A disk of approximately 10 cm thickness was collected at each of the sampling heights of each tree.

A wood sample from pith to bark was selected from each disk avoiding tension wood. After, radial strips

Table 1. Estimated age (number of rings at stem base) and biometric characteristics of the 10 sampled *Quercus faginea* trees. Standard deviation in brackets.

Tree number	Estimated Age	Diameter at 1.3 m (cm)	Total height (m)	Stem height (m)	Heartwood radius* (cm)	Sapwood width* (cm)
1	122	42.2	17.1	11.2	12.8	2.7
2	120	29.0	14.2	6.5	8.4	2.9
3	122	31.1	13.7	5.0	12.1	1.6
4	128	42.0	16.2	8.9	13.1	2.3
5	121	33.5	15.6	6.0	9.9	2.5
6	132	46.3	18.0	6.5	11.6	4.3
7	132	40.8	15.5	2.7	11.5	2.9
8	112	37.1	14.2	6.3	11.6	3.0
9	112	30.4	13.0	4.7	9.9	2.3
10	150	34.8	10.0	4.4	10.5	2.4
Mean	125 (11)	36.7 (5.9)	14.8 (2.3)	6.2 (2.4)	11.0 (3.6)	2.7 (9.5)

* Mean of 6 height levels.

with 5 mm on the tangential direction and 2 mm of thickness (axial direction), using especially designed dual-saw equipment, were prepared and conditioned at 12% moisture content. These radial samples were then X-rayed perpendicularly to the transverse section and their images scanned by microdensity analysis as described by Louzada (2000). For each ring measured, the following determinations were made: average ring density or wood density (RD), average earlywood (EWD) and latewood density (LWD), heterogeneity index (HI), ring width (RW), earlywood width (EWW), latewood width (LWW) and latewood percentage or proportion (LWP). For further details see also the previous co-work by Knapič *et al*. (2011). The heartwood and sapwood were identified by visual natural color differences and whenever necessary methylorange solution was applied to highlight the contrast. Then, rings were counted and cross-examined with the densitometry profiles of ring width, and 10 rings (common between samples) were analyzed in four radial regions: inner heartwood (IH) i.e. close to the pith, mid heartwood when its color was well defined (HW), heartwood-sapwood transition wood (TW) when color contrast was not so clear, and sapwood (SW) near to the bark.

To measure and analyse the relationship between ring density and radial growth parameters, the cambial age or ring age (from the pith) was used as a reference for arranging the data obtained from the microdensity profiles.

Analysis of variance for all ring and wood density components was performed according to the model presented in Table 2 to find significant differences between trees, height levels, rings and their interactions. In order to perform the analysis, 100 rings from pith to bark were analysed within the first four stem heights of each tree adding up a total of 4000 rings. Expected variance was calculated to identify the contribution of the sources of variation. Pearson correlation analysis was performed between wood density and ring number, and distance from pith as well as between the wood density and ring width components. Duncan Multiple range test was performed to compare means in the analysis of variance. Regression analysis was applied to wood density and ring width models as function of cambial age. All statistical analysis was performed using commercial software (JMP, SAS Institute Inc.).

Results

Age related profiles

Tree ring boundaries were identified by differences in wood density as well as by the abrupt transition of pore size between latewood and earlywood (Figure 1). The less distinct rings were very narrow, more frequent at the lower stem height levels and near the bark (Figure 1b).

Overall ring width decreased with cambial age at each height level (Figure 2). The higher variation was found in the first 80 years of cambial age and was present at all height levels. Linear and nonlinear models fitted quite well at breast height level ($0.74<R^2<0.76$) and 5.6 m ($0.77<R^2<0.84$). There was a gradual decrease of ring width from the stem base to 5.5 m of tree height (Table 3). Between-tree variation of ring width showed higher ring-to-ring fluctuations compared to height level differences (Table 3, Figure 2).

Latewood proportion was similar between all height levels (Table 3).

Quercus faginea wood showed high density values ranging between 0.868 g/cm^3 and 0.957 g/cm^3 (Table 3). Mean ring density decreased gradually from pith to bark with some ring-to-ring fluctuations (Figure 2). Both linear ($0.75<R^2<0.90$) and nonlinear ($0.76<R^2<0.90$) models fitted quite well the radial variation of wood density according to cambial age (Figure 2). Major differences were observed over 60 years of cambial age at the higher height levels (Figure 2, Table 3). Differences between the lower (base and

Table 2. Model for analysis of variance for the ring and density components.

Source of variation	Degrees of freedom	Expected variance	Error Term
(1)Trees (T)	t-1	$s^2\varepsilon + lr\, s^2\, T$	(7)
(2)Levels (L)	l-1	$s^2\varepsilon + r\, s^2TL + rt\, s^2\, L$	(3)
(3)T x L	(t-1)(l-1)	$s^2\varepsilon + r\, s^2TL$	(7)
(4)Rings (R)	r-1	$s^2\varepsilon + l\, s^2RT + lt\, s^2R$	(5)
(5)R x T	(r-1)(t-1)	$s^2\varepsilon + l\, s^2RT$	(7)
(6)R x L	(r-1)(l-1)	$s^2\varepsilon + t\, s^2RL$	(7)
(7)Residual (R x L x T)	(r-1)(l-1)(t-1)	$s^2\varepsilon$	

1. t= trees (10); l= height levels/tree (4); r= rings/level/tree (100). 2. s^2 T, s^2 L, s^2TL, s^2R, s^2RT, s^2RL and $s^2\varepsilon$ are variance components due to trees, levels, trees x levels, rings, rings x trees, rings x levels and residual.

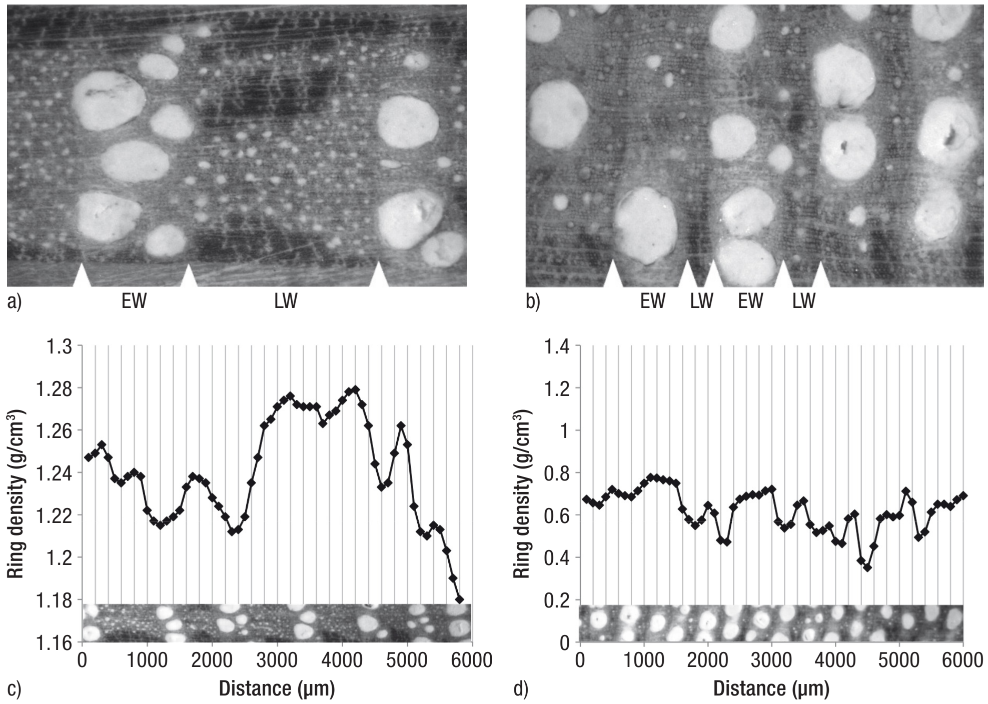

Figure 1. Growth ring distinctiveness within a) wide and b) narrow rings in *Quercus faginea* wood, and c), d) two density profiles showing those types of rings. EW = earlywood, LW=latewood. Scale bar = 1mm.

Table 3. Mean values for wood density and ring width components for the studied *Q. faginea* trees. Mean values by stem height level (1= base, 2= 1.3 m, 3= 3.4 m and 4= 5.6 m) plus standard deviation for the maximum rings common at each level (n=1000) for RD= ring density, EWD= earlywood density, LWD = latewood density, HI = heterogeneity index, EWW = earlywood width, LWW = latewood width, RW = ring width and LWP = latewood percentage. Average values on the same column with the same letter are not statistically different by Duncan Multiple test with alpha 0.05.

level	RD (g/cm³)	EWD (g/cm³)	LWD (g/cm³)	HI (g/cm³)	EWW (mm)	LWW (mm)	RW (mm)	LWP (%)
4	0.851 ± 0.166 a	0.783 ± 0.181 a	0.901 ± 0.164 a	0.064 ± 0.052 a	0.41 ± 0.29 a	0.57 ± 0.51 a	0.98 ± 0.70 a	54.9 ± 16.0 a
3	0.868 ± 0.180 a	0.799 ± 0.189 a	0.913 ± 0.178 a	0.062 ± 0.050 a	0.43 ± 0.31 a	0.65 ± 0.58 ab	1.08 ± 0.79 a	57.2 ± 15.6 ab
2	0.932 ± 0.169 b	0.859 ± 0.189 b	0.975 ± 0.163 b	0.061 ± 0.049 a	0.45 ± 0.30 ab	0.73 ± 0.61 b	1.18 ± 0.78 a	58.0 ± 16.6 bc
1	0.957 ± 0.147 b	0.880 ± 0.17 b	0.998 ± 0.148 b	0.061 ± 0.054 a	0.51 ± 0.36 b	0.91 ± 0.80 c	1.42 ± 1.00 b	60.3 ± 16.4 c
Mean	0.899 ± 0.169	0.826 ± 0.186	0.944 ± 0.166	0.063 ± 0.052	0.44 ± 0.32	0.70 ±0.62	1.14 ± 0.81	57.6 ± 16.3

1.3 m) and the higher (3.4 m and 5.5 m) stem levels were statistically significant (Table 3).

Earlywood and latewood density showed low values at higher height levels (Table 3).

The ring heterogeneity index was very low and relatively constant along the stem and over the years (Figure 2b, Table 3).

Wood density was significantly different between the inner heartwood and the mid heartwood and between the transition wood and the sapwood at all height levels (Table 4).

Tree, height and cambial age effects

The analysis of variance was performed for the first 100 rings that were common to all trees and the first four stem height levels (till 5.6 m). The total expected variance by source of variation is shown in Figure 3. Almost all single effects and interactions were significant ($p<0.001$) with some exceptions for heterogeneity index, earlywood width and latewood percentage.

Cambial age, and tree x cambial age interaction were the most significant factors to explain ring width variation accounting for 19% and 10% of the total variation, respectively. Tree x level interaction accounted for 5%, level for 4%, tree for 3%, and level x ring interaction for 2% of the total variation. Latewood percentage was only slightly explained by cambial age, tree and level (2 to 3%).

Wood density was mainly influenced by cambial age (ring) accounting for 17 - 26% of the total variation. Tree, stem height (level) and their interaction effects

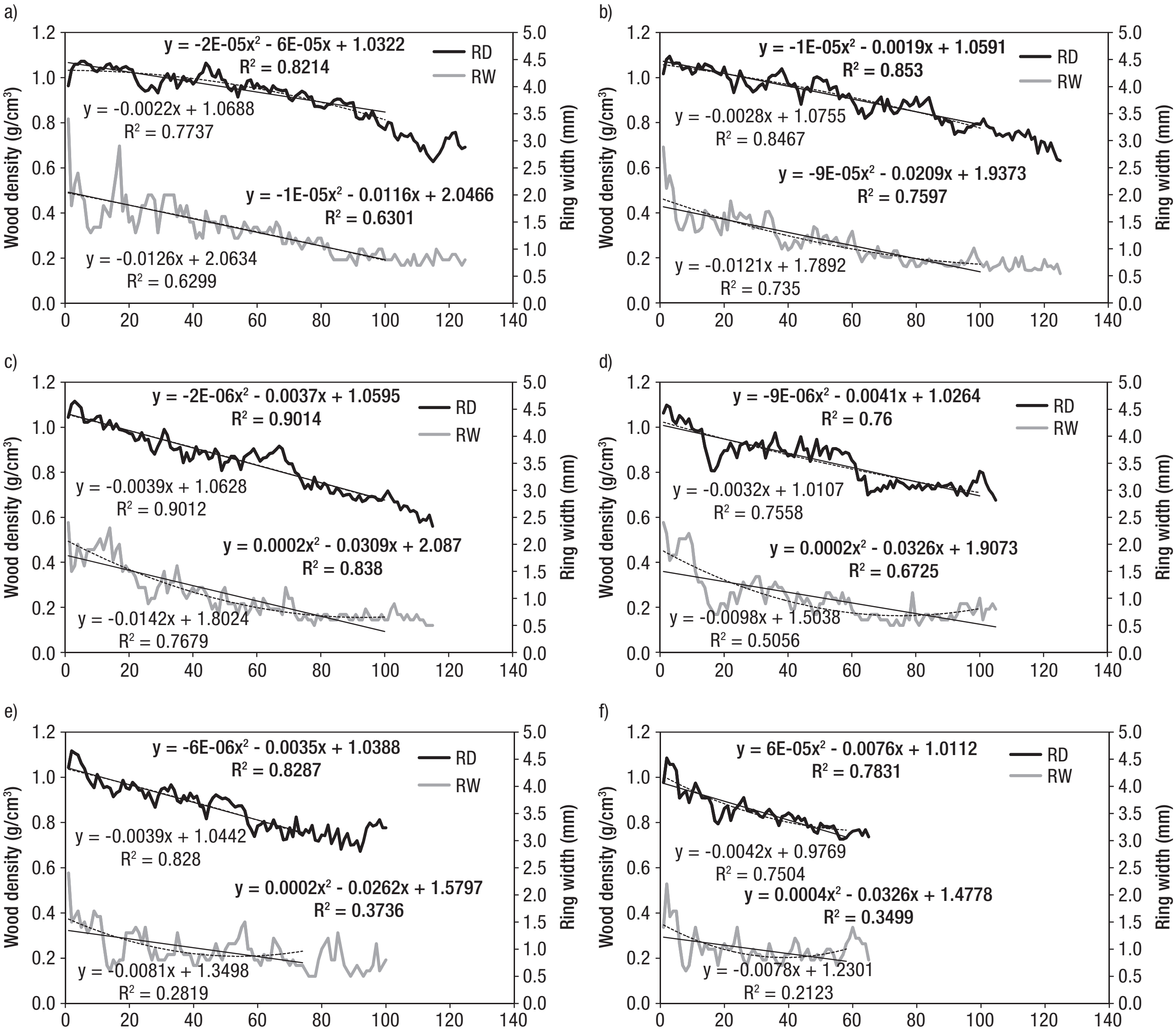

Figure 2. Ring width (RW) and wood ring density (RD) profiles for the 10 *Quercus faginea* mature trees at different height levels with linear and nonlinear fitted models: a) the base, b) 1.3 m, c) 3.4 m, d) 5.6 m, e) 7.7 m, and f) 9.7 m. Mean common values for 10 trees at each level. Note: Non-linear equations are in bold.

accounted for 5 - 9%; tree x ring interaction for 6 - 8%; and level x ring interaction for 1 - 2% of the total variation.

Overall the between-tree variation was smaller for ring width components (3%) than for wood density components (6 to 9%).

The intra-ring variation (heterogeneity index) was only slightly explained by tree and cambial age (8% and 4%, respectively) and height levels were not a significant factor of variation. Between-tree variation explained more than cambial age.

Overall the residual effect accounted for 42% to 53% of the total variation of the density components of *Q. faginea* wood and 57% of ring width variation. It was also the major responsible for latewood percentage and heterogeneity index variability.

Correlation with ring width was significant and positive for mean ring density (r = 0.432), earlywood density (r = 0.257) and latewood density (r = 0.464) (Table 5). The density components were not strongly correlated to latewood percentage. Latewood density showed the strongest correlation of all variables with mean ring density (r = 0.969).

Discussion

Growth rate values of *Q. faginea* were similar to other oaks as *Q. petraea* (0.8 to 3.9 mm at 61-224 years old) and *Q. robur* (1.5 mm at 151 years of age) usually under a classic silviculture (Zhang *et al*. 1993; Guilley *et al*. 1999; Guilley *et al*. 2004; Bergès *et al*.,

Table 4. Average values for the wood density at different regions from pith to bark (IW= Inner heartwood, HW= Mid heartwood, TW= Heartwood-sapwood transition wood, SW= Sapwood) at each height level (1= base, 2= 1.3 m, 3= 3.4 m, 4= 5.6 m; 5= 7.7 m and 6= 9.7 m). Average density values on the same column with the same letter are not statistically different by Duncan Multiple test with alpha 0.05. Cambial age in parenthesis is the mean of cambial age of the analysed data at each height level.

	Level					
	1	**2**	**3**	**4**	**5**	**6**
IW	1.048 (11) a	1.044 (11) a	1.023 (11) a	0.987 (11) a	0.974 (11) a	0.923 (11) a
HW	0.988 (47) b	0.953 (47) b	0.876 (45) b	0.910 (39) b	0.915 (37) b	0.823 (31) b
TW	0.955 (80) c	0.910 (79) b	0.810 (74) c	0.838 (67) c	0.908 (63) b	0.843 (50) b
SW	0.678 (121) d	0.700 (119) c	0.639 (114) d	0.704 (104) d	0.712 (97) c	0.743 (82) c

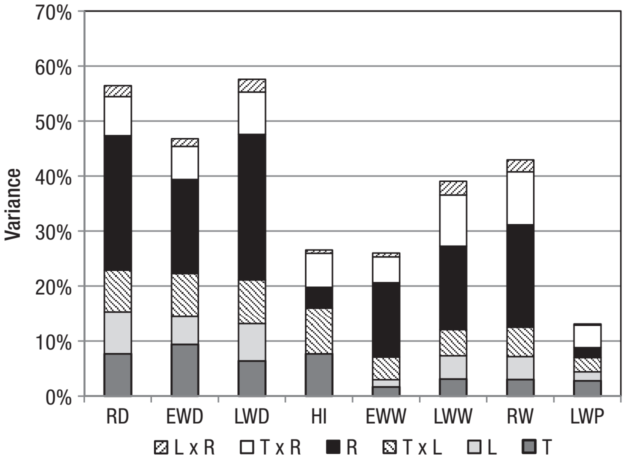

Figure 3. Percentage of total expected variation by source of variation (T= Tree, L= level, R=rings and respective interactions) according to the ANOVA model. Average of the first 100 rings at 4 height levels for the 10 studied *Q. faginea* trees. Note: RD= ring density, EWD= earlywood density, LWD = latewood density, HI = heterogeneity index, EWW = earlywood width, LWW = latewood width, RW = ring width and LWP = latewood percentage.

Table 5. Correlation matrix for density components and ring width (average values of the first 100 rings at 4 height levels from 10 *Q. faginea* trees, n=4000). Values marked in bold are significant at P<0.05. Note: RD - ring density, EWD - earlywood density, LWD - latewood density, EWW - earlywood width, LWW - latewood width, RW - ring width and LWP - latewood percentage.

	RD	**EWD**	**LWD**	**EWW**	**LWW**	**RW**	**LWP**
RD	1.000						
EWD	**0.920**	1.000					
LWD	**0.969**	**0.839**	1.000				
EWW	**0.319**	**0.292**	**0.385**	1.000			
LWW	**0.403**	**0.190**	**0.412**	**0.447**	1.000		
RW	**0.432**	**0.257**	**0.464**	**0.725**	**0.940**	1.000	
LWP	**0.234**	0.019	**0.188**	**0.331**	**-0.262**	**0.331**	1.000

2008). It is interesting to note that the average dbh of the studied trees is in line with Loewenstein *et al.* (2000) age models for white oaks under a managed uneven-aged oak forest. There is a previous study using the same microdensitometric methodology focusing on younger *Q. faginea* trees with 34-60 years of age for which 2.4 mm wide rings were reported (Knapič *et al.* 2011). For the same cambial age period i.e. the first 30 years, the mean ring width was smaller in the present study. This difference may be the consequence, at least partially, of the fact that the forest from where the trees were taken had no silvicultural management and was kept as a conservation area, from which a slow tree radial growth is expected; differences in soil and climate conditions probably are also involved. Age and size of *Q. faginea* mature trees showed a linear relation according to Table 1 that emphasis the tree competition for site resources. However age-related growth limitations were found as shown by the levelling of the growth rate that occurred for these *Q. faginea* trees at an age of ca. 80 years.

Regarding wood density, *Q. faginea* mature trees showed high values that are similar to other oaks such as *Q. suber* (0.75 to 1.07 g/cm^3) (Knapič *et al.*, 2007, 2008) and *Q. cerris* (0.96 g/cm^3) (Dilem, 1995). Despite this similarity, *Q. faginea* wood density values are higher than those found for the currently highly valued oaks such as *Q. petraea* (0.66 - 0.83 g/cm^3) (Bergès *et al.*, 2008), *Q. rubra* (0.54 - 0.76 g/cm^3), and *Q. robur* (0.52 - 0.63 g/cm^3) (Nepveu, 1984; Genet *et al.*, 2012). The high average wood density of *Q. faginea* is in part explained by its fibre proportion (23 - 44%) and thicker cell-walls, and the wide and tall multiseriate rays (Sousa *et al.*, 2014).

The decreasing radial tendency was similar for wood density and ring width in *Q. faginea* mature trees. These patterns corroborate the results of previous studies in other oaks i.e. in 70 - 110-year-old *Q. suber* trees (Knapič *et al.*, 2008), in 80-year-old *Q. garryana* (Lei *et al.*, 1996), in 56 to 187-year-old *Q. petraea* (Bergès *et al.*, 2000) as well as in other mature American oaks (*Q. nigra*, *Q. rubra*, *Q. falcata*, *Q. velutina*) (Paul, 1963). This tendency was somehow expected since they are a common pattern in ring-porous species from a temperate climate (e.g. Paul, 1963; Lei *et al*., 1996; Zhang *et al*., 1993, Woodcock & Shier, 2002). These species are characterized by a ring-structure development during the growth year responsible for that tendency i.e. vessels size and arrangement, and latewood proportion. In the case of *Q. faginea,* vessels showed ca. 200 µm of diameter in earlywood and ca. 50 µm in latewood with a vessel radial proportion ranging from 13 to 23 % from pith to bark and wood density being strongly negatively correlated with both mean vessel area and proportion (Sousa *et al*., 2014, Sousa *et al.* 2015). Previous work with cork oak showed that 32% the total variation in wood ring density was also explained by changes in vessel size (Leal *et al.* 2011).

It is known that in ring-porous species, a retardation of radial growth brings the rows of large pores closer together in the successive annual rings, as seen in cross sections, and reduces the ring region of latewood containing the thicker latewood cells (Chauhan, 2006). Therefore these species show a positive correlation between latewood proportion and ring width (Polge & Keller, 1973; Zhang *et al*., 1993). In the present study, this correlation was significant with a positive trend, showing that latewood width was proportional to total ring width.

Since earlywood varies less in amount than latewood under unfavourable growth conditions, the narrow rings contain a higher earlywood proportion, leading to lower mean ring density (Paul, 1963). Bergès *et al.* (2008) noted that latewood radial proportion leaded to decrease in density in *Q. petraea* due to the influence of latewood density and earlywood density in mean ring density.

In contrast, Rao *et al.* (1997) found that density in *Q. robur* was independent of latewood width due to a relative uniformity of latewood width with cambial age. This is also the profile of the studied *Q. faginea* mature trees with latewood proportion tending to be more constant with tree ageing, and accounting for 58% of the ring. Latewood proportion was significantly correlated with ring width and less with latewood density and ring density. However, the main effects explaining latewood proportion might be related for instance with site characteristics and circumference heterogeneity.

Heartwood formation and accumulation of extractives during ageing may also increase density (Hillis, 1987). In the present case, the lower density region of the stem that corresponds to the outermost rings, namely after 80 years, approximately coincides with the measurements of sapwood width that ranged from 23 to 43 mm. The sapwood width tendency is to follow the stem profile adjusting to taper variations (Sousa *et al*., 2013). The abrupt wood density variation between the heartwood-sapwood transition region and the sapwood (0.879 and 0.692 g/cm^3 respectively) reinforces that hypothesis at all stem heights, as did the findings in *Q. suber* (Knapič *et al*., 2008).

The decreasing axial variation of ring width, representing the effect of tree age (maturation, juvenile versus mature wood), although highly significant, only contributed in a small degree to explain ring width variation and the mean values were not statistically different at most of the stem height levels. Stem analysis on other *Quercus* spp. corroborates these results (Lei *et al*., 1996; Guilley *et al*., 1999; Knapič *et al*., 2008). This is important from the point of view of wood processing and suitability since an axial homogeneity is favourable.

Similar observations on the axial profile of wood density were made in younger *Q. faginea* trees (Knapič *et al*., 2011) and in other *Quercus* spp.: *Q. suber* (Knapič *et al*., 2008), *Q. petraea* (Degron & Nepveu, 1996; Guilley *et al*., 1999) and *Q. garryana* (Lei *et al*., 1996). Explanations for the decrease in wood density with increasing tree age have been suggested to be related with the crown effects on latewood formation inhibition leading to lower values of density in the upper levels of the stem based mostly in softwoods (Saranpaa, 2003). However this subject is lacking in conclusions and no crown effects on wood density have been reported (Gartner *et al*., 2002). Moreover the maturation process should be more important to define wood density and growth rate profiles at younger phases than in later stages since the stem level effects accounted more than the double in younger than in mature trees. For instance growth rings with the same formation year would be considered mature wood if seen at the stem base e.g. located in mid heartwood, and at a higher stem level would be located in the heartwood-sapwood transition.

Cambial age was the most important factor explaining wood density variation as well as radial growth variability in these *Q. faginea* mature trees. Despite the scale applicability constraint these results are similar to Bergès *et al*. (2000) findings in *Q. petraea* mature trees from an even-aged high forest stand in France. Also Bergès *et al*. (2008) noted that cambial age influenced earlywood and latewood density and reduced latewood proportion, leading to a significant effect of age on mean density in *Q. petraea*. Cambial age did not contribute to latewood proportion variation but accounted to ring width variability, meaning that latewood is influenced by other factors as suggested before.

By comparing these *Q. faginea* mature trees to younger trees (44-year-old on average) from a different provenance in Portugal, studied previously by Knapič *et al*. (2011), it may be seen that cambial age effects represented only 3 to 8% of the total variation of wood density. It may be assumed that radial growth is not affected by cambial age within younger ages since tree competition is not yet very high. This effect becomes more important at longer rotation ages and therefore cambial age accounts more to total density variation and growth rate than individual tree characteristics. Between-tree variability explained mainly the wood density variation in the case of *Q. petraea* and *Q. robur* (Zhang *et al*. 1993; Ackermann, 1995; Guilley *et al*., 2004; Bergès *et al*., 2008). This variability is related to external factors, such as silvicultural practices, and internal factors, such as genotype (Zobel & van Buijtenen, 1989). In the case of *Q. faginea*, the tree affected more wood density than ring width under longer-rotations. Therefore, more homogenous wood might be obtained using tree selection and forestry breeding programs.

Correlation between ring width and density was significant and stronger when compared to younger trees (Knapič *et al*., 2011). These findings corroborate Paul (1963) studies in unmanaged stands of *Q. alba* and *Q. velutina*, where the variation in density was significantly related to changes in ring width with increasing tree age as well as in managed stands (Zhang *et al*., 1993; Degron & Nepveu, 1996; Guilley *et al*., 1999). Zhang (1994) concluded that in ring-porous species, ring width had little influence on density while other studies refer to inconsistent relationships between ring width and wood density for other oaks (Polge & Keller, 1973).

The residual effect in the analysis of variance was high. This shows the importance of factors that were not unaccounted in this study such as the heartwood and sapwood distinction and the extractive depositions (Zobel & van Buijtenen, 1989). Other factors could also be involved, for instance, the effect of the directions in the cross-section and the crown effects. The genetic factors also contribute to explain the high residual effect found in the *Q. faginea* mature trees, as suggested for *Q. petraea* by Guilley *et al*. (2004). Site effects i.e. edaphic and climatic factors, may or may not have an influence on ring density (Guilley *et al*., 2004; Bergès *et al*., 2008).

The possibility to study mature trees of *Q. faginea* showed the high density of this wood and an overall small magnitude of within-tree density variation. Such wood density characteristics confirm the value of *Q. faginea* as a timber species for use in solid products, comparable with other commercial oaks.

In practical terms, the results confirm that the effects of cambial age on wood density were the most important to explain its variability and that ring-width was also important to define wood density. Therefore adequate stand management, avoiding excessive tree competition e.g. through thinning operations, will improve *Q. faginea* growth rate. This means that future work is needed to detail the impact on ring width and wood density of forestry management operations. Nevertheless the results obtained here support that the *Q. faginea* mature trees already available and growing in unmanaged stands are valuable as high wood density timber and may be economically exploited.

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