RING WIDTH VARIATION AND HEARTWOOD DEVELOPMENT IN *QUERCUS FAGINEA*

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Abstract. High-value exploitation of endogenous forest species may help in fighting the threat to their sustainability, as is the case for *Quercus faginea* Lam. (Portuguese oak) for which research is underway to determine the wood potential for high-quality products. Ring widths were measured in 20 trees in two sites in Portugal and within-tree heartwood and sapwood development was determined. The wood shows distinct ring porosity. The mean annual radial growth at dbh was 2.3 and 1.0 mm for the two sites, respectively. Ring width decreased with cambial age, ie 3.1 ± 1.2 mm in the first 10 rings to 1.3 ± 0.8 mm at around 40 yr (site 1). Ring width decreased axially from the tree base upward but the variation was small. The trees showed a relatively high proportion of heartwood, ie 60-70% heartwood for 20-25 cm wood diameters that decreased with height, and followed the stem profile. Heartwood diameter was modeled as a function of stem diameter, to be used for heartwood estimation in standing trees. Sapwood width was relatively constant. Overall the stem quality was found to be good for production of solid wood products regarding ring and heartwood features.

Keywords: *Quercus faginea*, Portuguese oak, heartwood, sapwood, ring width, wood quality.

INTRODUCTION

Quercus faginea Lam. (Portuguese or Lusitanian oak) is a deciduous oak, belonging to the white oaks subgroup, that is a native species in the western Mediterranean part of the Iberian Peninsula and Maghreb Africa. *Q. faginea* forests have been subject to extensive destruction over the centuries and the long-term future of the species is under threat. The oak forests that once covered Portugal were intensively exploited for timber for various applications, for example for naval construction during the XV and XVI centuries or as railway sleepers in the last two centuries, and many stands were converted to agriculture or to industrial pine and eucalypt plantations (Capelo and Catry 2007). Now *Q. faginea* is restricted to only a few scattered stands. However, the wood potential and the environmental and cultural importance of the species are acknowledged (Fabião et al 2007; Paiva 2007). More knowledge on tree growth, stem development, and wood properties is an essential tool to strengthen the efforts of producing high-value wood products with this species, ie as in the EU Woodtech research project.

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Most studies on this species have dealt with seedling sensitivity and response to environmental conditions (eg Sanz-Pérez et al 2007) as well as with edaphic and environmental and climatic questions (eg Maltez-Mouro et al 2009). Villar-Salvador et al (1997) studied the response of xylem features to climate and Corcuera et al (2004) the effects of severe drought.

Knowledge of *Q. faginea* wood properties is scarce. It has distinct ring porosity and overall oak-type anatomical features, strong mechanical strength, and high density (Carvalho 1997; Knapič et al 2011). The utilization of *Q. faginea* wood, which currently is not commercially significant, and the acceptance of the species as providing high-value timber should help in guaranteeing the sustainability of *Q. faginea* forests. The detailed wood characterization requires evaluation of a number of anatomical, physical, and mechanical properties. Among them, two characteristics that are important for determining wood quality and performance are ring width and heartwood proportion. The width of annual growth rings and their within-tree variation is one of the primary wood quality factors since it is related to wood density variation and consequently to other physical and mechanical wood properties, especially in ring-porous woods (Nepveu 1984; Zhang et al 1993; Chauhan et al 2006).

Heartwood is also an important stem quality characteristic regarding its use value. Heartwood develops as a physiologically inactive region in the inner part of the stem while the outer region of sapwood remains active in storage and conduction (Hillis 1987). Heartwood and sapwood are very different in their extractives content, density, and some other physical properties (Pereira et al 2003). Heartwood is generally preferred for most timber applications because of its darker color and higher natural durability. Despite its economic importance, the heartwood development of *Q. faginea,* as for many other species, has not been fully characterized.

The present article reports data for *Q. faginea* on radial stem growth measured by ring analysis and its between-tree and within-tree variation, together with information on heartwood and sapwood within-tree distribution, based on 20 trees that were harvested in two stands in Portugal. Previous work on variation of wood density components within and between *Q. faginea* trees (at site 1) showed that density decreased with height and from pith to bark, ie the larger rings had higher wood density values (Knapič et al 2011). The present study adds knowledge on *Q. faginea* heartwood and sapwood within-tree distribution and on between-site and tree radial stem growth based on ring analysis. This information is a first step in the development of an understanding of the growth and wood mechanical quality of this tree. It is our objective to contribute to the efforts of preserving *Q. faginea* by determining its potential for high-quality end uses and simultaneously gathering information on the characteristics of its growth and development under the general rationale that a high-value exploitation of endogenous forest species is a method for fighting threats to their sustainability.

MATERIAL AND METHODS

For this study, two stands of *Q. faginea* were selected for sampling: Site 1 was located in the northeast of Portugal, near Macedo de Cavaleiros, Bragança (latitude 41°30′ N, longitude 7°01′ W, 554 m mean altitude) and site 2 in the center of Portugal, near Vimeiro, Alcobaça (latitude 39°29′ N, longitude 9°01′ W, 100 m mean altitude). The trees were aged 34-60 yr and 112-150 yr at site 1 and site 2, respectively. From each stand, 10 dominant or codominant trees free of visible signs of decay were randomly selected. Total tree height, crown height, crown diameter, and tree diameter at breast height (1.3 m) were measured on the standing trees. Site and tree characteristics are shown in Table 1. The stands were unmanaged and no records of eventual silvicultural operations exist.

The trees were felled and sampled along the stem: at stem base height, at 1.3 m, 3.4 m, 5.6 m, 7.7 m, and 9.7 m (site 2 only) above ground level. A disc of about 10 cm thickness was collected at each of the sampling heights of each tree. Each

Table 1. Site and *Quercus faginea* trees characteristics.[a]

	Site 1	Site 2
Location	Bragança (Macedo de Cavaleiros) Latitude 41°31′ N, longitude 6°51′ W	Alcobaça (Vimeiro) Latitude 39°29′ N, longitude 9°01′ W
Altitude (m)	540	100
Soil	Orthic Dystric and Eutric Leptosols	Chromic Cambisols
Annual precipitation (mm)	700 ± 141 (289-1299)	890 ± 249 (469-1477)
Annual mean temperature (°C)	12 ± 1 (11-13)	15 ± 3 (10-19)
Köppen-Geiger Climate Classification	Csa	Csb
Tree height (m)	10.5 ± 0.7 (9.5-11.7)	14.8 ± 2.3 (10.0-18.0)
Diameter at 1.3 m (cm)[b]	20.9 ± 4.2 (15.5-29.0)	36.7 ± 5.9 (29.0-46.3)
Crown height (m)[c]	8.3 ± 1.3 (6.1-11.2)	8.5 ± 2.3 (5.6-12.8)
Radius crown (m)	2.4 ± 0.7	4.4 ± 1.1
Tree age[d]	40 ± 8 (34-60)	125 ± 11 (112-150)

[a] Mean values and standard deviation with minimum–maximum values in parentheses.
[b] Over bark diameter.
[c] Crown height = tree height – trunk height.
[d] Measured at stem base.

disc surface was prepared by sanding. Tree ring widths were measured with 0.1 mm precision along three approximately equidistant radial directions (≈120°) on each disc in successive images with 7× optical magnification (1 pixel = 0.0217 mm) using a microscope coupled to a digital camera and image analysis software (Leica Q Win Standard).

Heartwood was visually distinct from sapwood (Fig 1) but for measurement distinction was enhanced by applying a methylorange solution to the disc surface. The images of the discs were acquired using image analysis software (Analysis software, Version 3.2; AnalySIS Soft Imaging System GmbH) and measurements of total disc area and heartwood area were taken. Calculations were made of sapwood area, sapwood mean radial width, and heartwood mean diameter. The number of rings included in the heartwood and in the sapwood was also determined. The height limit of the heartwood was calculated as the intercept of the linear regression of heartwood areas with tree height levels.

Figure 1. Stem cross-section of *Quercus faginea* showing the natural color differences between heartwood and sapwood (bar = 2 cm).

Statistical and correlation analysis were performed at the 0.05 confidence level using SPSS for Windows Version 19.0 (LEAD Technologies, Inc.). Analysis of variance was made considering tree, ring, and height level as fixed effects as well as their interactions. The relationship among the studied variables was assessed through correlation analysis.

RESULTS AND DISCUSSION

The sampled *Q. faginea* trees showed similar characteristics to those reported for the species (Table 1). The trees were medium-sized with a maximum tree height of 18 m and an average diameter at breast height of 37 cm for 125-yr-old trees (site 2). The trees had a short stem and on average 8 m of crown height.

Q. faginea showed distinct tree rings that were visible to the naked eye. It is a ring-porous wood (Fig 2) with very wide pores in the earlywood

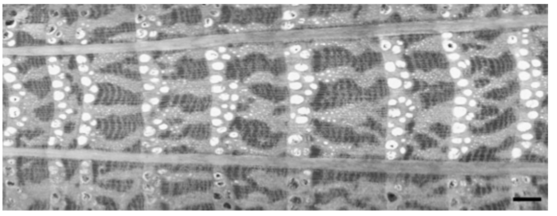

Figure 2. *Quercus faginea* wood observed in cross-section showing the wood vessels and ring porosity (scale bar = 1 cm).

in comparison with the pores in the latewood. The pores were arranged in lines, usually up to three lines, producing distinct ring boundaries. Rings were eccentric to undulating, and sometimes very narrow, but discontinuous rings were not frequent. Overall ring distinction was very good and allowed easy ring counting and measurement.

Ring Width and Radial Growth

The radial variation of the average tree ring width at 1.3 m height is shown in Fig 3 for sites 1 and 2. The pattern of radial variation was similar at both sites with a higher growth rate in the first 10 yr of cambial age (2.8 and 1.2 mm for site 1 and site 2, respectively) that decreased gradually at about 30-40 yr of cambial age (1.5 and 1.0 mm, respectively, for site 1 and site 2) and from this age on remained relatively constant. Overall growth rate was higher at site 1 compared with site 2 for similar cambial ages. The between-tree variability of ring width was high within site 1, as shown by the deviation of the mean with differences that were statistically significant ($p < 0.0001$) during the first 30 yr of growth. At site 2, the between-tree variability of ring width for growth during the first 30 yr was not significant.

Figure 4 plots the mean accumulated radial growth for the 10 *Q. faginea* trees at each site. The pattern of radial growth variation was similar in both sites although with differences in the absolute values with a tree mean radial growth that was higher at site 1. For instance, at an age of 50 yr, the underbark diameter of *Q. faginea* trees was 21.2 cm (site 1) and 13.4 cm (site 2).

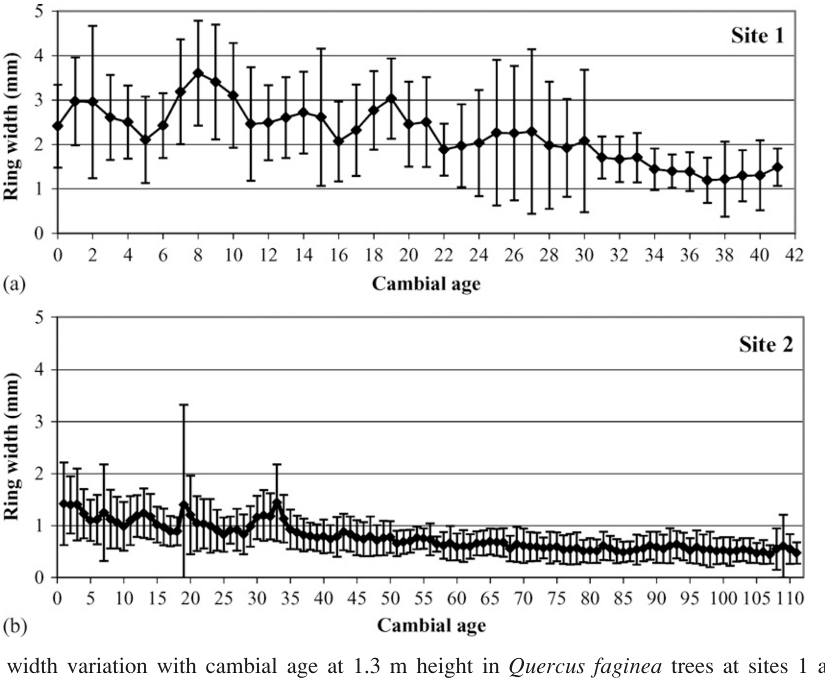

Figure 3. Ring width variation with cambial age at 1.3 m height in *Quercus faginea* trees at sites 1 and 2. Average of 10 trees with error bars representing standard deviation. Note that the XX scale differs between sites.

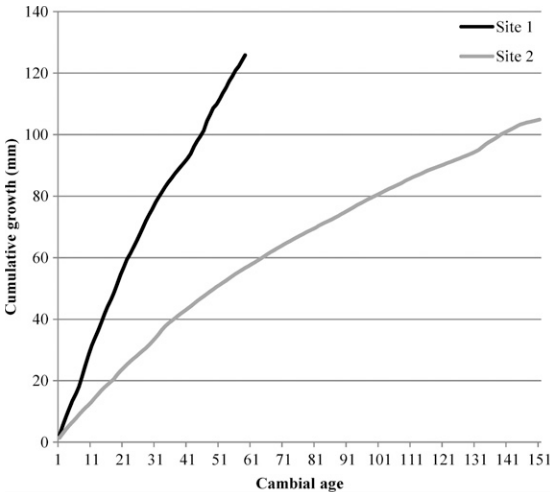

Figure 4. Accumulated radial growth with cambial age at 1.3 m height in *Quercus faginea* trees at sites 1 and 2. Mean values for 10 trees per site.

The within-tree variation is shown in Table 2 by summarizing the mean ring width for different cambial age classes (radial variation) at the different tree height levels (axial variation). Ring width varied with height in the tree for the same cambial age with an overall decreasing trend, ie the mean annual ring width was highest at the stem base and lowest at the top of the stem. The radial variation showed a decrease with cambial age at all height levels, which was more accentuated in the regions near the pith.

Heartwood and Sapwood Development

The heartwood of *Q. faginea* was clearly visible on the wood discs because of its brown color and generally well-defined borders (Fig 1). Heartwood area decreased within the tree from the base upward and the heartwood vertical profile within the tree followed approximately the stem profile, resulting in a uniform thickness of sapwood along the tree. This also happened when there were clear taper variations along the stem (for example, see Fig 5 representing one tree at each site).

The heartwood content differed considerably between sites (Fig 6). At site 1, the heartwood proportion was relatively constant in the lower part of the stem, representing 35.0 and 37.1%

Table 2. Within-tree variation of ring width according to cambial age classes and stem for *Quercus faginea* trees at sites 1 and 2.[a]

		Ring width (mm)					
Site	Age class	0 m	1.3 m	3.4 m	5.6 m	6.7 m	9.7 m
1	[0-10]	2.8 ± 0.7	2.8 ± 0.7	2.4 ± 0.6	2.0 ± 0.6	1.5 ± 0.3	
	[10-20]	3.1 ± 0.5	2.6 ± 0.4	2.4 ± 0.6	2.0 ± 0.6	1.5 ± 0.3	
	[20-30]	2.8 ± 0.8	2.1 ± 1.1	2.4 ± 0.9	1.5 ± 0.9	1.0 ± 0.0	
	[30-40]	2.0 ± 0.6	1.5 ± 0.4	1.6 ± 0.3	1.5 ± 0.3	— ±	
	[40-50]	1.9 ± 0.7	1.6 ± 0.5	2.0 ± 0.6	1.5 ± 0.3	— ±	
	Mean	2.6 ± 0.8	2.3 ± 0.8	2.3 ± 0.7	1.9 ± 0.7	1.4 ± 0.3	
2	[0-10]	1.9 ± 0.5	1.9 ± 0.6	1.8 ± 0.3	2.1 ± 0.4	1.9 ± 0.3	1.2 ± 0.6
	[10-20]	1.8 ± 0.3	1.2 ± 0.2	1.5 ± 0.4	0.8 ± 0.3	0.9 ± 0.3	1.1 ± 0.2
	[20-30]	1.5 ± 0.3	1.2 ± 0.4	1.0 ± 0.2	1.4 ± 0.3	1.0 ± 0.2	1.1 ± 0.3
	[30-40]	1.7 ± 0.4	1.1 ± 0.1	1.3 ± 0.2	1.3 ± 0.3	0.8 ± 0.2	0.8 ± 0.1
	[40-50]	1.5 ± 0.2	1.3 ± 0.2	1.1 ± 0.3	1.0 ± 0.1	0.8 ± 0.2	0.8 ± 0.2
	[50-60]	1.4 ± 0.2	1.0 ± 0.2	1.0 ± 0.1	1.1 ± 0.1	0.8 ± 0.2	0.7 ± 0.1
	[60-70]	1.5 ± 0.3	0.7 ± 0.2	1.0 ± 0.2	0.7 ± 0.1	0.8 ± 0.2	0.6 ± 0.1
	[70-80]	1.2 ± 0.2	0.6 ± 0.1	0.7 ± 0.1	0.6 ± 0.1	0.7 ± 0.3	1.1 ± 0.6
	[80-90]	0.9 ± 0.1	0.8 ± 0.1	0.6 ± 0.1	0.5 ± 0.1	0.8 ± 0.3	0.7 ± 0.1
	[90-100]	1.1 ± 0.1	0.9 ± 0.2	0.7 ± 0.2	0.6 ± 0.1	0.6 ± 0.2	0.9 ± 0.2
	[100-110]	0.9 ± 0.1	0.9 ± 0.1	0.6 ± 0.1	0.6 ± 0.2	0.5 ± 0.2	0.5 ± 0.2
	[110-120]	0.7 ± 0.2	0.8 ± 0.2	0.7 ± 0.2	0.7 ± 0.2	0.6 ± 0.4	- ±
	[120-130]	0.9 ± 0.3	0.7 ± 0.1	0.7 ± 0.2	0.5 ± 0.1	0.3 ± 0.1	— ±
	Mean	1.3 ± 0.4	1.0 ± 0.3	1.0 ± 0.4	0.9 ± 0.5	0.8 ± 0.4	0.9 ± 0.2

[a] Average of 10 trees at each site plus standard deviation.

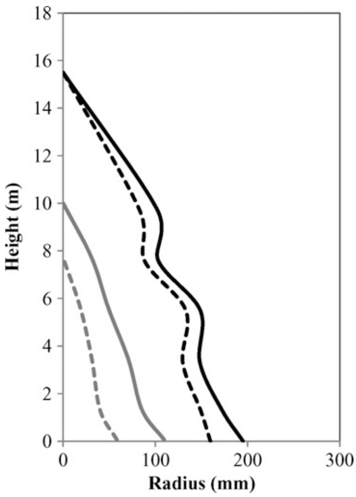

Figure 5. Tree radius (full line) and heartwood (dashed line) profiles for one tree at site 1 (gray lines) and site 2 (black lines).

of the cross-sectional area at tree base and 1.3 m height, respectively, and decreased regularly up the stem to 11.3% at 5.6 m, whereas at 7.7 m, none of the trees contained heartwood. At site 2, the proportion of heartwood was considerably higher: 67.9% at the base, 73.1% at 1.3 m, 69.9% at 3.4 m, and then decreasing to 54.5% at 7.6 m height and 45.6% at 9.7 m. The within-tree heartwood variation was statistically significant ($p < 0.001$ at site 1 and $p < 0.05$ at site 2) as well as the differences between sites ($p < 0.001$).

The sapwood width was relatively constant along the height axis of the tree (Fig 6) and varied between 47.6 and 37.2 mm (site 1) and 31.2 and 23.1 mm (site 2). The within-tree sapwood variation was not statistically significant in either case. The sapwood contained, on average, 21 rings at the tree base and 17 rings at 5.6 m height at site 1 and 31 rings at the base and 31 at 7.7 m height at site 2. The difference in sapwood width between sites were statistically significant ($p < 0.001$).

Heartwood diameter was related to tree size with the smallest trees having less heartwood (Fig 7a). In fact, the diameter of heartwood in *Q. faginea* was strongly correlated with stem diameter ($R^2 = 78.3$ and 92.9% at sites 1 and 2, respectively, $p < 0.0001$). The sapwood width was independent of stem diameter while ($p < 0.001$) the sapwood area showed a tendency to increase with tree diameter ($R^2 = 83.6$ and 57.2% at sites 1 and 2, respectively, $p < 0.001$) (Fig 7c).

The results show that in *Q. faginea* heartwood starts to form when the stem diameter reaches about 10-20 cm and subsequently increases with tree diameter, maintaining a constant sapwood width at about 2-4 cm (Fig 6a).

Only one reference was found in the literature regarding *Q. faginea* growth rate with a report of 1.5 mm/year^{-1} over 31 yr (Oliveira et al 2001). In the present study, the growth rate for a similar period of 30 yr (Table 2) was 2.5 mm year^{-1} and 1.4 mm year^{-1} for samples taken from sites 1 and 2, respectively. The annual growth rate (Table 2) found in this study of *Q. faginea* is similar to other oak species, namely *Q. suber,* another native oak species from Portugal, both in terms of mean ring width and radial variation (Gourlay and Pereira 1998; Costa et al 2003; Knapič et al 2007; Leal et al 2008). In *Q. pyrenaica*, Corcuera et al (2006) found that the radial ring width decreased from approximately 1.6 to 0.5 mm from the inner to the outer part of the stem at a cambial age of 35-41 yr. *Q. petraea* produces annual rings of 2 mm or more in the first 30 rings (Helińska-Raczkowska and Fabisiak 1991), which is similar to *Q. cerr*is with a growth rate of 2.2-2.9 mm in the first 15 yr and 1.5-1.7 mm afterward until 25 yr of age (Manetti 2002).

Overall the radial growth rate of *Q. faginea* was in the range of values reported for other oak species and larger for site 1. This leads to the inference that under favorable conditions, growth of *Q. faginea* is comparatively high. In this case, commercial stems for the solid wood industry would require a rotation of 70-80 yr for a stem diameter of 30-35 cm. The within-tree radial and axial variation of ring width that was found in the *Q. faginea* trees was of moderate

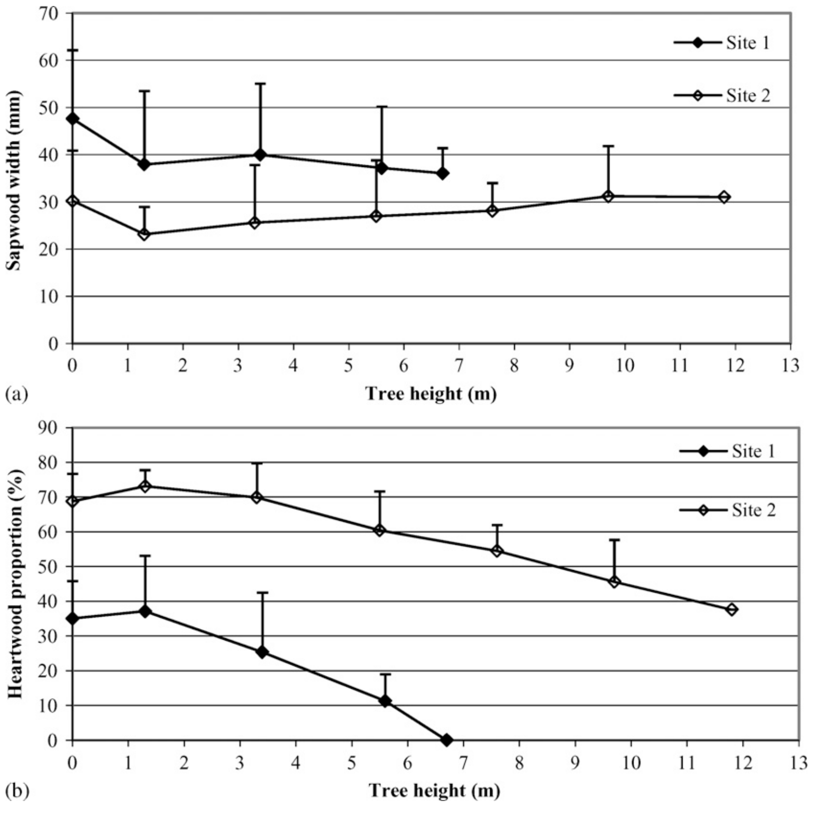

Figure 6. Sapwood width and heartwood proportion variation along the stem at sites 1 and 2. Mean of 10 trees with bars as standard deviation.

magnitude as shown by coefficients of variation of the radial and axial means of, respectively, 30-40% and 30-50% (Table 2). These differences are not sufficient to produce excessive heterogeneity within the stem and a variation in properties that would be detrimental to product performance and value.

There are no results published for *Q. faginea* regarding heartwood content. In fact, scant information is available in the bibliography regarding the amount of heartwood and sapwood in other oak species. Most works on oak heartwood deals with durability and chemical and color properties (eg Mosedale et al 1996; Humar et al 2008), while sapwood area is related to leaf area (eg Meadows and Hodges 2002) or sap flow (eg Granier et al 1994).

The patterns of within-tree axial variation of heartwood and sapwood (Fig 6) are in agreement with previous results on heartwood development for most species (Hillis 1987). The slight increase in percentage of cross-sectional area corresponding to heartwood at 1.3 m of tree height is found in some species where an enlargement of heartwood from the base to a point in the lower part of the stem has been reported (Pinto et al 2004; Knapič and Pereira 2005), although not all species show this tendency (Knapič et al 2006).

A number of studies report a positive relationship between tree growth measured by diameter and heartwood dimension while the sapwood maintains a relatively constant width range independent of tree diameter (Gominho and Pereira

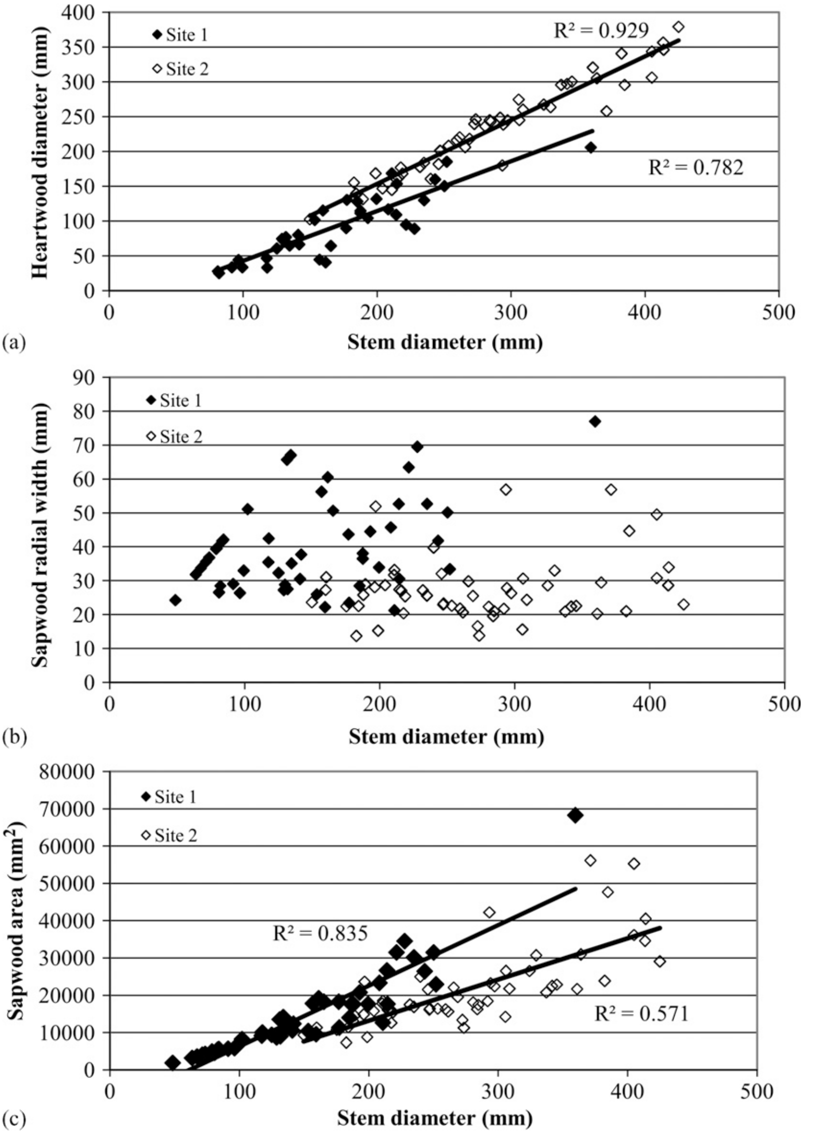

Figure 7. Scatterplots representing the relationship between stem diameter and: (a) heartwood diameter, (b) sapwood radial width, and (c) sapwood area at sites 1 and 2.

2000, 2005; Pinto et al 2004, 2005; Knapič and Pereira 2005; Knapič et al 2006). These results support the theory that heartwood formation is a cumulative process that increases during tree growth at the pace required to maintain an approximately constant sapwood width as required by the physiological conditions of the species (Bamber 1976). In the case of the *Q*. *faginea* trees in this study, the results support this theory. The sapwood width followed the stem profile (Fig 5) without a significant within-tree axial variation (Fig 6) and showed no correlation with tree diameter (Fig 7b) while the sapwood area (at 1.3 m) that ranged between 87 and 345 cm^2 at site 1 and between 133 and 405 cm^2 at site 2 was correlated with tree diameter (Fig 7c).

The heartwood of *Q. faginea* was well correlated with tree diameter (Fig 7) and represented a substantial proportion of the stem cross-section, ie 20-25 cm wood diameters correspond to a 60-70% heartwood proportion. The previous conclusions on wood density from trees at site 1 as reported by Knapič et al (2011) and more recent data (not shown) from trees at site 2 corroborate the decrease tendency of wood density, ie heartwood is denser compared with sapwood and is related to ring width. An important practical consequence for the high-value utilization of *Q. faginea* timber is the possibility of modeling and estimating heartwood content in standing trees from the measurement of tree diameter.

CONCLUSIONS

Q. faginea trees show a mean annual radial growth at 1.3 m height of between 2.3 and 1.1 mm, depending on site. The ring width decreased radially within the tree with cambial age and axially from the base upward but the magnitude of the ring width variation was small and allows a stem homogeneity that is valued for technological processing.

Q. faginea showed substantial heartwood development that follows the stem profile and allows prediction of heartwood area based on the stem diameter in standing trees. The sapwood width was small and rather constant along the stem.

Overall the stem wood quality of *Q. faginea* trees appears to be good for production of solid wood products with regard to its ring and heartwood distribution features. Other characteristics, ie color and chemical composition, should be studied in the future because they largely contribute to appearance and durability properties of wood products.

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