Within-tree and between-tree variation of wood density components in cork oak trees in two sites in Portugal

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Summary

The axial and radial variation of wood density was studied using microdensitometry in cork oaks (*Quercus suber*) in two sites in Portugal. The observations were made in mature trees under cork production and in juvenile trees before the first cork extraction, at three height levels (stem base, 1.3 m and before stem bifurcation). The cork oak wood revealed a very high mean density (0.884–1.068 g cm^{-3}). Differences between earlywood and latewood were small (0.866 and 1.061 g cm^{-3}, respectively). Latewood corresponded on average to 61 per cent of the total. The variation of density between trees was statistically highly significant, but no differences were found between the two sites. The within-tree axial variation was negligible but the radial direction within a cross-section was one of the main origins of variation of the density components (18 per cent of the total variation). The density decreased from pith to cambium and this radial variation corresponded to 19–24 per cent of the total variation of wood density. Overall, the magnitude of density variations between and within cork oaks was small and an advantageous factor for their use for quality wood products.

Introduction

Oaks are valuable timber species and oak wood is highly prized for indoor joinery and furniture, due to its mechanical properties and aesthetical value. Therefore, several research studies have been done to characterize oak wood properties and their variation (Schutz, 1993; Gurau *et al.*, 2003; Gartner, 2006; Kuzsella and Szabo, 2007).

Wood density is considered as a key criterion of quality because of its high correlation to other physical properties, namely, to mechanical strength and performance in use. Oak wood density has been extensively studied, i.e. for *Quercus robur* L. and *Quercus petraea* (Matt.) Liebl in France (Ackermann, 1995; Degron and Nepveu, 1996; Guilley *et al.*, 1999; Bergès *et al.*, 2000), and models of wood density variation with ring width and cambial age have been established by several authors (Ackermann, 1995; Degron and Nepveu, 1996; Bergès *et al.*, 2000; Guilley, 2000). The majority of the studies dealing with the within-tree and between-tree variation of wood density have used X-ray microdensitometric techniques as developed by Polge (1966, 1978).

The cork oak *(Quercus suber* L.*)* is an oak species that occupies a total area over 2 million ha, mainly in Portugal (725 000 ha) and Spain (475 000 ha), with its area extending towards the western Mediterranean basin in southern Europe and North Africa. Most of the *Q. suber* forests integrate an agro-forest system ('montado' in Portugal and 'dehesa' in Spain) that combines forest, agriculture and animal production (Pereira and Tomé, 2004).

The cork oak forests have been directed during the last century towards the production of cork with a silviculture and management oriented to the sustainable removal of the tree outer bark. As a consequence, research has been concentrated on cork (Fortes *et al.*, 2004) and cork production related issues, i.e. production modelling (Tomé *et al.*, 1998; Vasquez and Pereira, 2005), as summarized in a recent review book (Pereira, 2007). Little work was developed regarding the cork oak wood characterization.

With the present forest management, the rotation is long and when the trees are harvested no effort is done to value the wood component, which is used only as an energy biomass. However, cork oak wood is a strong and aesthetic wood, and in former times, it was highly prized for demanding uses such as shipbuilding.

The possibility of changing the silviculture of cork oaks and the management of oak forests towards more integrated tree utilization has been advised as a strategic approach to guarantee the sustainability of these systems (www.suberwood.com). The increase and diversification of the economic returns from the cork oak stands would contribute to improve their conservation and renovation.

The potential of cork oaks for the production of high-value wood products and the future availability of considerable amounts of thinning material from areas planted during the last two decades led us to research cork oak wood growth and properties. The objective of this paper is to study the within-tree and between-tree variation of wood density components in cork oak trees, through the analysis of X-ray microdensitometric data. For that purpose, a total of 11 cork oak trees were harvested from two sites in southern Portugal, including mature (under cork production) and juvenile trees before the first cork extraction and were studied at different stem height levels.

Material and methods

The samples for this study were collected in two sites within the natural range of cork oak in the southern part of Portugal, in the Alentejo region: Contenda and Albardeiros (Table 1).

Sampling was carried out in 2002 by taking advantage of authorized fellings, since law forbids cork oak harvesting. A total of 11 trees were harvested, six from Contenda and five from Albardeiros. In Contenda, the stand was even aged with 40 years of age and the trees had never been

Table 1: Characterization of the sampled sites of Contenda and Albardeiros in the Alentejo region (Portugal)

	Site 1 – Contenda	Site 2 – Albardeiros
Designation	Perímetro Florestal da Contenda	Herdade dos Albardeiros
Localization	Beja, Beja district	Alvito, Beja district
Coordinates	38° 06′–38° 00′ N and 6° 59′–7° 06′ W	38° 15′ N and 7° 59′ W
Soil	Grauwacke or schist lithosoils; the soils are very poor and belong to class E (Ee, Es and Ee + S)	Luvisols derived from diorite and granite; with some granite outcrops, and also cambisols; belong to class C (Cs and Ce)
Climate	Mediterranean with great deficiency of water in summer (July to October), mesothermic (C2, B′ 2, S2).	Subdry mesothermic
Average annual temperature	15.9°C	16.2°C
Average annual precipitation	550 mm	583 mm

debarked, with diameter at breast height (d.b.h.) ranging from 29 to 38 cm and a total height ranging from 7.0 to 11.0 m; in Albardeiros, the stand was uneven aged and the trees were under cork production, last debarked in 1997. The trees had an average d.b.h. of 55 cm, ranging from 38 to 68 cm, with ages estimated to be between 70 and 110 years and a total height ranging from 11.2 to 13.6 m.

From each tree, 4-cm-thick disks were taken at the base level, at breast height (1.3 m) and before stem bifurcation (2–3 m of height). From each disk, three directions were randomly selected and a 2-mm-thick radial strip segment was sawn from the pith to the bark using especially designed equipment consisting of a carriage driven feed to a high-speed (10 000 rpm) twin-blade cutting system. The strips were conditioned at 12 per cent moisture content. These radial samples were X-rayed perpendicularly to the transverse section and their image scanned by microdensitometric analysis as described by Polge (1966, 1978). The time of exposure to radiation was 350 s, at an intensity of 18 mA and an accelerating tension of 12 kV, with a 2.5-m distance between X-ray source and film. The data composing the radial density profiles were recorded every 100 μm with a slit height (tangential direction) of 455 μm. Density calibration was made using control strips of acetate cellulose, which is simultaneously radiographed with the wood samples, and of which we know whether the optic whether the real density.

Due to extreme difficulty in ring boundary identification, the density components were not calculated ring by ring, but in sequential radial segments. Each radial sample was divided in 10 equal segments, and for each segment average density (D), earlywood density (EWD), latewood density (LWD) and latewood percentage (LWP) were determined. Each sample contained areas where the rings were visible and others where they were not (Figure 1). The distinction between earlywood and latewood was made based on the density values, respectively, below and above the average of the minimum and maximum density values found within each segment (Degron and Nepveu, 1996; Mothe *et al.*, 1998; Rozenberg *et al.*, 2001).

Analyses of variance for all density components were performed according to the mixed model where the sources of variation site, level and position were considered as fixed effects and

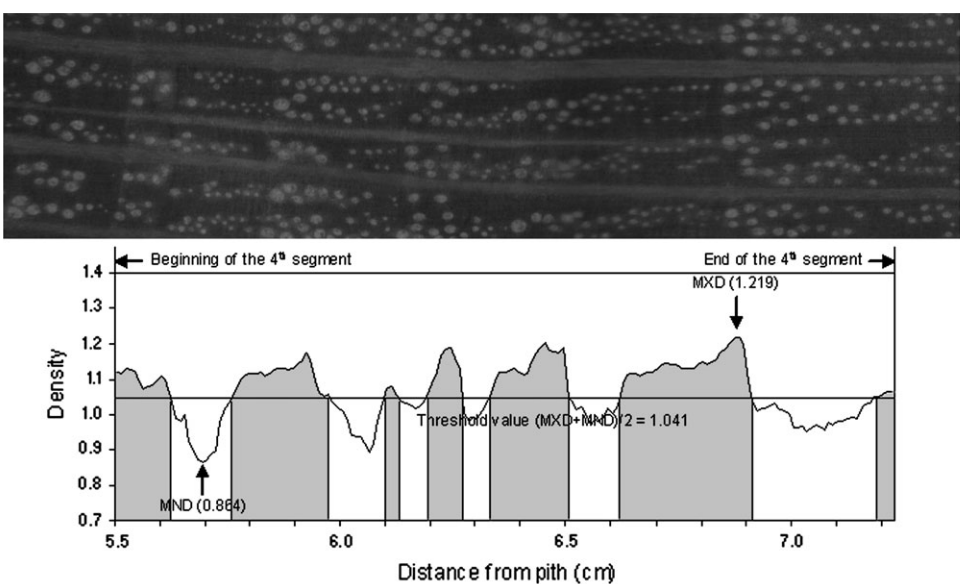

Figure 1. An example of the application of the criterion based on the average of minimum and maximum density for determining the limit between earlywood (□) and latewood (■).

tree and radial sample as random effects. Variance components for the sources of variation were estimated.

All statistical analyses were performed using the IMP statistical software (SAS Institute Inc. Cary, North Carolina, USA).

Results

The microdensitometric profiles obtained for the cork oak wood are exemplified in Figure 2 for the breast height level of one tree from each site. The profiles were similar among trees, with a large variation between contiguous measurements, showing an up-and-down pattern with peak maximal values at ~1.171 and 1.714 g cm^{-3} and minima at 0.723 and 0.340 g cm^{-3} for site 1 and 2, respectively. The variation of density values indicative of annual rings could be observed in some regions of the density profiles, with a sharp decrease of density corresponding to the transition between the vessel-free latewood and the large vessels occurring in the beginning of the earlywood of the next ring. However, in most cases, the density variation had not this clear pattern (Figure 3).

Table 2 shows the mean density components for each tree. The cork oak wood revealed a very high mean density that ranged between 0.884 and 1.068 g cm^{-3}, with an average EWD of 0.866 g cm^{-3} and LWD of 1.061 g cm^{-3}. The latewood corresponded on average to 61 per cent of the total growth.

Table 3 shows the results obtained for the analysis of variance made for each density component, regarding the statistical significance and proportion of explained variation for the different sources of variation. The residual effect was responsible for 39.7–44.5 per cent of the total variation, i.e., the variation of these components of density is due to other factors that were not taken into account in this experimental design.

The site effect was not statistically relevant and did not contribute to the total variation of the density components. The average values for each site showed no differences: 0.997 g cm^{-3} in Contenda and 0.968 g cm^{-3} in Albardeiros.

The density variation between trees was statistically highly significant and explained 6.1 per cent of the total variation. This between-tree variation was more important in latewood than in earlywood (8.2 and 4.2 per cent of the total variation, respectively).

Along the tree, the density remained practically constant and the differences between average densities at base, breast height and near crown levels were not statistically significant. The lack of axial variation of density components was quite clear in any of the sites (L × S) and of the trees (L × T/S).

The effect of direction within the cross-section (radial samples) revealed to be highly significant and one of the main origins of variation of the density components, explaining ~19 per cent of the variation.

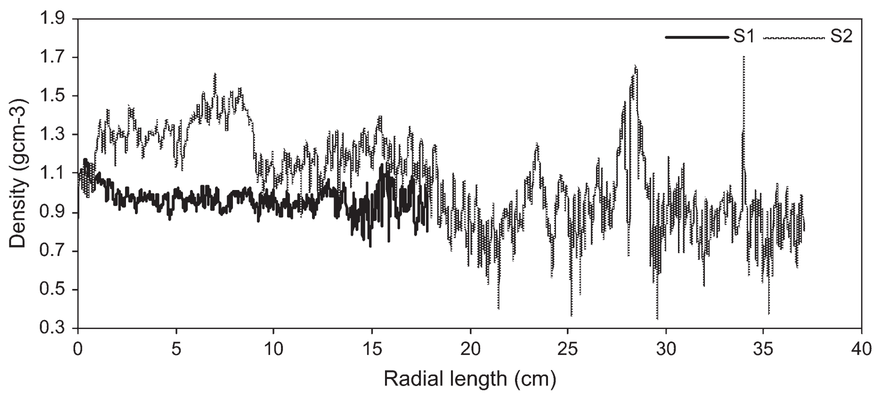

Figure 2. Microdensitometric profiles obtained for the cork oak wood at breast height level of one tree from each site (S1 – Contenda, S2 – Albardeiros).

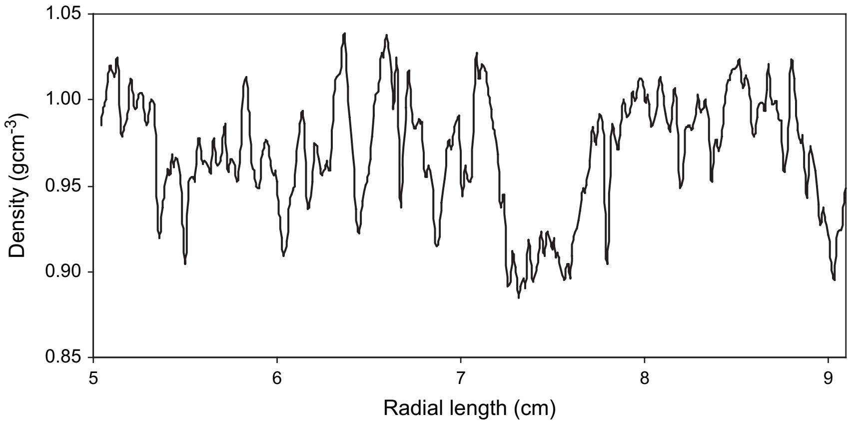

Figure 3. Microdensitometric profiles obtained for the cork oak wood at breast height level of one tree from site 1, in the region of 5–9 cm of radial distance from pith.

Table 2: Mean values of wood density components for the studied cork oak trees (site 1 – Contenda; Site 2 – Albardeiros)

Site	Tree	Mean density (g cm^{-3})	EWD (g cm^{-3})	LWD (g cm^{-3})	Latewood (%)
1	1	0.964	0.861	1.006	69.2
	2	0.991	0.890	1.054	60.9
	3	0.974	0.864	1.041	60.6
	4	0.992	0.900	1.044	61.5
	5	1.056	0.930	1.117	65.2
	6	1.002	0.883	1.054	68.1
Mean		0.997	0.888	1.053	64.3
2	1	0.956	0.830	1.028	63.6
	2	1.014	0.839	1.139	63.0
	3	0.884	0.799	0.980	51.3
	4	1.068	0.953	1.199	51.5
	5	0.920	0.775	1.011	61.3
Mean		0.968	0.839	1.071	58.1
Total mean		0.984	0.866	1.061	61.5

The effect of the radial variation from pith to cambium of the components of density was highly significant, contributing with 18.8–23.6 per cent of their total variation. This effect was shown by a tendency of decreasing values of density from pith to cambium. However, this pattern of radial variation of density differed from site to site (P × S: ***, representing 6.8–9.8 per cent of the total variation), while the decreasing trend of the density components from pith to the cambium was maintained at the different height levels of the tree (P × L: ns).

The radial variation of density in the cork oaks of the two sites can be observed in Figure 4 for two trees at the 1.3-m height level that exemplify the variation occurring in the other trees. Although the decreasing trend of density from pith to bark was present in all cases, there was a difference between trees under cork production in site 2 and the younger never debarked trees in site 1. In site 2, the trees had a higher density in the innermost region that was followed by a decrease at ~15 cm from the pith.

As regards the LWP, the residual variance absorbed 83 per cent of the total variation, i.e. the

Table 3: Summary of the analysis of variance for each wood density component, showing the percentage of total variation due to each source of variation and their significance

Sources of variation	Degrees of freedom	Mean density (%)	EWD (%)	LWD (%)	Latewood (%)
Site (S)	1	0.0, ns	2.1, ns	0.0, ns	4.0, ns
Residual a (tree)	9	6.1**	4.2*	8.2***	6.5***
Level (L)	2	0.0, ns	0.0, ns	0.0, ns	1.1*
L × S	2	0.0, ns	0.0, ns	1.4, ns	0.2, ns
Residual b (disks)	18	0.6, ns	0.1, ns	0.0, ns	0.0, ns
Residual c (radial sample)	66	18.8***	18.8***	18.2***	0.7, ns
Position (P)	9	23.6***	19.3***	18.8***	0.0, ns
P × S	9	10.2***	9.8***	6.8**	0.6, ns
P × L	18	0.0, ns	0.0, ns	0.0, ns	0.0, ns
P × L × S	18	0.9, ns	1.2, ns	2.4*	3.8*
Residual d	837	39.7	44.5	44.1	83.1

*** P < 0.001, ** P < 0.01, * P < 0.05.

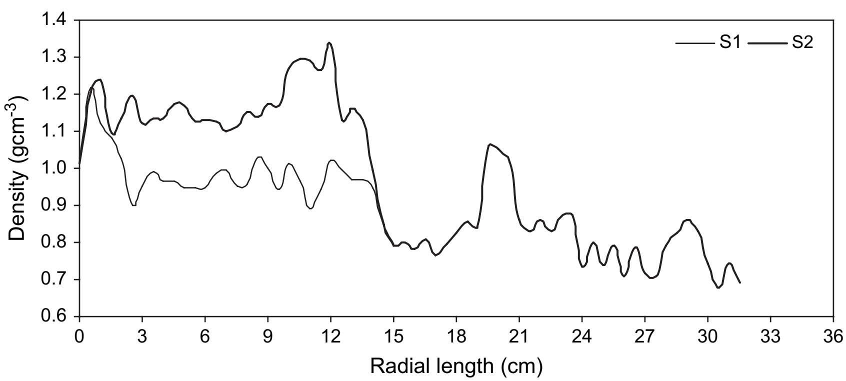

Figure 4. Radial variation of density at the 1.3 m height level of one cork oak at each site (S1 – Contenda, S2 – Albardeiros).

LWP was little affected by the studied factors. The only source of variation that revealed statistical relevance was the trees, although with a small contribution (6.5 per cent) to the total variation.

Discussion

The results obtained showed that the *Q. suber* wood is very dense, with a mean density of 0.984 g cm^{-3} (Table 2). This value is identical to some tropical species such as *Apidosperma*, *Bowdichia*, *Chlorofora* and *Dalbergia* (Hidayat and Simpson, 1994; Fearnside, 1997; Williams *et al.*, 2001; Parolin, 2002), and above the majority of European hardwoods, reaching identical values to the *Olea europea* L., one of the denser European species (Bonamini, 1996). In relation to other oaks, the cork oak showed values identical to *Quercus ilex* (0.96–1.00 g cm^{-3}), or higher than *Quercus penduculata* (0.82 g cm $^{-3}$), *Quercus cerris* (0.85 g cm^{-3}), *Q. petraea* (0.51–0.85 g cm^{-3}), *Quercus liaotungensis* Koidz (0.66 g cm^{-3}), *Q. robur* (0.50–0.66 g cm^{-3}) and *Q. rubra* (0.54–0.61 g cm^{-3}) (Deret-Varcin, 1983; Nepveu, 1984; Zhang and Zhong, 1991; Zhang *et al.*, 1993; Dilem, 1995; Degron and Nepveu, 1996; Zhang, 1997; Bergès *et al.*, 2000; Woodcock and Shier, 2002; Badel *et al.*, 2006).

Another important characteristic of the cork oak wood was its low variability with small differences between earlywood and latewood densities. On average latewood was only 22.5 per cent denser than the earlywood, and the distribution of latewood was rather uniform within the tree (radially and axially) accounting for over 60 per cent of the wood. It should be stressed that the concept of earlywood and latewood as defined here and by other authors (respectively under and above an average value) is not related to the physiologically based annual variation, as clearly seen on Figure 1.

There was no significant difference of wood density between the two sites. A study with *Q. petraea* in 10 locations in France (Degron and Nepveu, 1996) concluded also that the differences of earlywood and LWD among sites were not statistically relevant, as well as similar studies for *Q. petrae* in five locations in France (Guilley *et al.*, 2004). However, a site effect was reported responsible for 12.4, 6.5 and 9.9 per cent of the variation of mean, earlywood and latewood densities, respectively (Guilley *et al.*, 1999). Studies with *Q. borealis* revealed that there were no relevant differences between the D values of the trees from two regions, but that there were differences comparing with the trees from another region (Keller *et al.*, 1980).

The tree effect was statistically significant (Table 2) with a range of mean tree density values from 0.884 to 1.068 g cm^{-3}. The same was reported in *Q. petraea* where the 'tree' effect was one of the main causes of the variation of the density components (Zhang *et al.*, 1993; Ackermann, 1995; Degron and Nepveu, 1996; Guilley *et al.*, 1999). More recently, Guilley *et al.* (2004) estimated that the between-tree variation ranged from 29 to 31 per cent of the total variation. Lei *et al.* (1996) with *Quercus garryana* came to the conclusion that the effect of trees was not statistically relevant for density, although this conclusion might be blurred by the fact that the sampling was small (six trees).

The density variation with height in the cork oak stem was very small and without statistical significance (Table 3). Contrary results were obtained in studies with *Q. petraea* at three levels (0.4, 1.3 and 3.5 m), where the effect of "Levels" was highly or very highly significant for earlywood and latewood densities, respectively (Degron and Nepveu, 1996). The decrease of density components with height level in the tree was confirmed by Guilley *et al.* (1999) in *Q. petraea*, as well as by Lei *et al.* (1996) in *Q. garryana*.

The cork oak wood showed a significant variation of density in relation to the radial direction (Table 3). The direction effect is usually associated to reactions of the tree to external disturbances to its growth (Zobel and Buijtenen, 1989; Guilley *et al.*, 1999), such as dominant winds or unbalances of the crown that lead to formation of reaction wood or to traumatic reactions. Guilley *et al.* (1999) found highly significant differences between directions with *Q. petraea*. Although other authors have considered that the presence of tension wood could stand as an explanation to this phenomenon, it was concluded that in the specific case of their own sampling a direct relation between reaction wood and wood density variation could not be established. Comparatively Zhang (1997) in *Q. petraea* and *Q. robur* obtained only minor contributions of the direction effect, as well as Lei *et al.* (1996) in *Q. garryana*.

The heterogeneous distribution of wood density with radial direction that was found in the present cork oak trees should be the result of their growth conditions and silvicultural treatments. In fact, cork oaks are subjected to several cultural operations that may unbalance the crown, i.e. early pruning for tree formation and regular pruning for acorn production (Pereira and Tomé, 2004), and insect attacks, i.e. *Lymantria dispar* and *Coroebus scutellari*, that affect foliage unevenly, are also frequent. The extraction of cork may also result in wounds and specific tree response (Costa *et al.*, 2004). The irregular radial development of the cork oaks is shown by the differences in radii within a cross-section that were present in the studied trees (data not shown).

The cork oak showed a radial variation of density decreasing from pith to bark (Figure 3). The pattern of decreasing density components with age is relatively frequent in broadleaves (Zobel and Buijtenen, 1989; Fearnside, 1997), including some species of *Quercus*, as for instance *Q. garryana* (Lei *et al.*, 1996), *Q. petraea* (Deret-Varcin,1983; Zhang *et al.*, 1993; Degron and Nepveu, 1996; Zhang, 1997; Guilley *et al.*, 1999; Bergès *et al.*, 2000), *Q. robur* (Deret-Varcin, 1983; Zhang *et al.*, 1993) and *Q. rubra* (Woodcock and Shier, 2002). In this study, the age effect explained 23 per cent of density variation. Zhang (1997) found a somewhat higher value of 32 per cent in European oak.

The radial variation of cork density showed an interesting characteristic regarding the difference observed between the trees in site 2 in comparison with site 1 (Figure 3). The site 2 trees were mature trees (70–110 years of age) under periodic cork removal while the site 1 trees were younger (40 years old) and never debarked. The mature trees showed a somewhat higher density in the inner region, from pith to ~15 cm distance, after which a decrease of density occurred. The younger trees had radii corresponding approximately to this distance and did not show this inflexion in density. This difference is attributed to the formation of heartwood in the cork oak and to an accumulation of extractives in the inner region.

It is interesting to note that some of the density values of Figure 2 are higher than the density of the cell wall which can be explained by the accumulation of extractives within the cell wall and the presence of mineral inclusions in cell lumen. Anatomical features of cork oak wood, namely, the high amount of rays and their size may contribute to the high-density values found along a radial direction (Leal *et al*., 2006, 2007).

Conclusions

The cork oak (*Q. suber*) wood is very dense (mean density between 0.884 and 1.068 g cm^{-3}) and homogeneous with an average EWD of 0.866 g cm^{-3} and LWD of 1.061 g cm^{-3}. It presents a reduced variability of the density components between trees and within the tree along the stem. There was a radial variation with age from the pith to the exterior, although inferior to other similar woods.

The overall wood density characteristics of cork oak stems regarding their high values and low variation between and within the tree are advantageous factors for the utilization of cork oaks for quality wood products.

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Conflict of Interest Statement

None declared.

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