forests

MDPI

Article

Variation of Ring Width and Wood Density in Two Unmanaged Stands of the Mediterranean Oak *Quercus faginea*

Vicelina B. Sousa [1,*], José Luís Louzada [2] and Helena Pereira [1]

1 Centro de Estudos Florestais, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal; hpereira@isa.ulisboa.pt

2 Departamento Florestal/CITAB, Universidade de Trás-os-Montes e Alto Douro, Quinta de Prados Apartado 202, 5000-911 Vila Real, Portugal; jlousada@utad.pt

* Correspondence: vsousa@isa.ulisboa.pt; Tel.: +351-213653336; Fax: +351-213653338

Received: 27 November 2017; Accepted: 17 January 2018; Published: 20 January 2018

Abstract: Ring width and wood density variation were studied from pith-to-bark and along the stem in two naturally regenerated stands of *Quercus faginea* Lam. in Portugal. Ring width was significantly different between sites, in both heartwood and sapwood rings, ranging from 1.83 mm to 2.52 mm and from 0.77 mm to 2.11 mm, respectively. Wood density was significantly different between sites only in the heartwood, i.e., 914 kg m^{-3} and 1037 kg m^{-3}. Site effects were the main source of variation for ring width and wood density within the heartwood as well as for sapwood ring width, while the between-tree effects explained more the density variation within the sapwood. Wood density showed within-tree uniformity that was not affected by site. The stand characteristics such as basal area and tree age may override the environmental growth conditions. There was also a weak correlation between wood density and ring width components therefore suggesting the possibility of forestry management for both fast tree growth and high wood density.

Keywords: *Quercus* spp.; wood variability; wood characteristics; endemic species; sustainability

1. Introduction

Quercus faginea Lam. is naturally distributed in the Iberian Peninsula and Maghreb Africa, in the Mediterranean Basin. It is commonly known as the Portuguese or Lusitanian oak and belongs to the white oaks subgroup. In Portugal, its present area is very restricted because of the past intensive utilization [1]. The species shows favorable characteristics for wood processing and performance, and is considered a good potential timber species for structural and flooring components, and cooperage [2–5].

Forest management practices combining wood production and conservation are gaining more interest and application in forestry and within ecological contexts, e.g., attention is given to mixed stand dynamics, slow growth species and low management conditions. In the case of *Q. faginea*, wood production doubled in mixed forests compared to mono-specific stands [6]. Regeneration of species, typically including slow growing and late-successional species such as deciduous oaks, suggested good performances for mixed-forests with fast-growing species such as *Pinus* spp. [7]. Knowledge of growth features over the tree's life-time, especially for slow growing species, as is the case for *Q. faginea*, will be important for better designing a forest management (e.g., stand location and density, rotation age and tree selection) that will include a high-value product-oriented approach.

The wood structure of *Q. faginea* is heterogeneous, as in other oaks with expected tree variability, namely of fiber and ray cells [5]. Despite the large number of relevant wood properties, the most used indicators of wood stem quality are ring width and wood density [8,9]. The typical radial ring width pattern in *Q. faginea*, and in oaks in general, is characterized by a decrease with cambial age (i.e., age from the pith) followed by some stabilization [10–14]. A decreasing trend in wood density is also common in *Quercus* spp. [10,11,15–17]. Wood density is related to both cambial age and ring width including ring structure, e.g., the latewood proportion is often the main responsible for wood density in ring-porous species [12,13,18]. Overall, the radial, pith-to-bark, variation is associated with the cambium maturation or physiological age [19,20].

It is widely known that oaks are highly appreciated due to their heartwood and wood technological characteristics related to high extractives content ensuring higher durability and attractive colors, as well as to specific features such as tyloses that provide less permeability and also increase durability [21–23]. Sapwood in general is undesirable for most timber uses and usually eliminated during the primary conversion. In *Q. faginea*, a positive relationship between heartwood proportion and tree diameter was found, i.e., 60–70% of heartwood for 20–25 cm stem diameters, while the sapwood width was relatively constant, ranging from 23 mm to 38 mm in older and younger trees, respectively [14].

The present study adds information on radial growth and wood density of *Q. faginea* based on trees from two different sites within the natural distribution range of this species. The specific aims of this study were to identify the main effects of site, trees, cambial age and stem height levels on wood variability of *Q. faginea* that could support a sustainable management including wood production.

2. Material and Methods

2.1. Sites and Sampling

The study was carried out in two locations, near Macedo de Cavaleiros (MC, northeast of Portugal), and near Vimeiro (VI, center of Portugal), both within the *Q. faginea* geographical natural distribution [1]. The stands resulted from natural regeneration, were unmanaged, mixed and uneven-aged, and VI is kept for state conservational purposes. The vegetation at MC is mainly characterized by minor occurrence of *Q. suber* L., *Q. rotundifolia* Lam. and *Pinus pinaster* Aiton trees, and mainly *Cistus ladanifer* L., *Lavandula* spp., *Daphne gnidium* L., *Cytisus multiflorus* (L'Hér) Sweet shrubs; at VI there were sparse *Q. suber, Castanea sativa* Mill. and *P. pinaster* trees, shrubs such as *Arbutus unedo* L., *Ulex europeaus* L., and *Erica arborea* L. and the fern *Pteridium aquilinum* L. (Kuhn).

The climate is of Mediterranean type at both sites. However, at Site MC the weather is described as interior Mediterranean characterized by dry and hot summer, and rainy winters (Csa) while at Site VI the coastal Mediterranean designation is applied with climate being characterized by cool and dry summer, and rainy winters (Csb) according to the international Köppen-Geiger climate classification system.

Basal area of *Q. faginea* was 18 m^2/ha and 102 m^2/ha, and overall stand density was 327 trees/ha and 300 trees/ha at MC and VI, respectively. Trees were on average 40 and 125 years old at MC and VI, respectively. Due to the reduction of *Q. faginea* distribution area it was allowed to cut only a very limited number of specimens. Ten dominant or co-dominant healthy trees were randomly selected from each site. Tree and site characteristics are shown in Table 1. From each of the 20 trees harvested, a disc was taken at stem base, 1.3 m, 3.4 m, and every 2.1 m along the stem to the top level.

Table 1. Description of the sampled *Quercus faginea* trees by each site. Mean of ten trees and standard deviation.

	Macedo de Cavaleiros (MC)	Vimeiro (VI)
Latitude	41°31′ N	39°29′ N
Longitude	06°51′ W	09°01′ W
Altitude (m)	540	100
Soil	Orthic Dystric and Eutric Leptosols	Chromic Cambisols
Annual precipitation (mm)	700 ± 141	890 ± 249
Annual mean temperature (°C)	12 ± 1	15 ± 3
Q. faginea basal area (m^2/ha)	18	102
Stand density (trees/ha)	327	300
Tree height (m)	10.5 ± 0.7	14.8 ± 2.3
Diameter (cm) *	20.9 ± 4.2	36.7 ± 5.9
Crown height (m) **	8.3 ±1.3	8.5 ± 2.3
Radius crown (m)	2.4 ± 0.7	4.4 ± 1.1
Tree age ***	40 ± 8	125 ± 11

* Over bark diameter at 1.3 m of tree height; ** Crown height = Total tree height − branch-free stem height; *** Age based in ring counts at the stem base.

2.2. X-Ray Microdensitometry

A radial sample from pith to bark was cut from each disc avoiding tension wood and knots. The radial samples were trimmed down to strips with 5 mm width and 2 mm thickness (longitudinal) with a specially designed dual-saw equipment, and then conditioned at 20 °C, 65% RH to 12% moisture content.

The radial strips were X-rayed perpendicularly to the transverse section with an accelerating tension of 12 kV, an intensity of 18 mA and a time of exposure to radiation of 350 s, at 2.5 m distance between X-ray source and Kodak film. The images were scanned by microdensitometric analysis and density was recorded at every 100 µm with a slit height of 455 µm. Detailed descriptions of the method are given in [24].

The ring boundary was identified on the transverse section by focusing on anatomical parameters, namely the pore distribution that is characterized by an abrupt size transition; and by visual cross-examination locating the sharp density variations set by the earlywood and latewood on the radial X-ray profiles.

Per each growth ring the following wood density and ring width components were obtained: ring density (RD), earlywood density (EWD), latewood density (LWD), the heterogeneity index (HI), ring width (RW) and latewood percentage (LWP). The within-ring determination of early and latewood density was made using the average of the minimum and maximum density values per each ring [3,25]. The heterogeneity index was calculated as the standard deviation of all density values across each ring to quantify the intra ring density variation [26].

2.3. Data Analysis

Analyses of variance were performed for wood density and ring width components to assess the effects of site (S), trees per site (T/S), cambial age or rings (R), stem height levels (L) and their interactions, according to the model presented in Table 2. The number of rings included in the analyses was limited by the uppermost height level of the youngest tree at Site MC. Based on previous research [3], two approaches were followed: (i) a core analysis of the trees made up with the innermost 15 rings with the same cambial age (vertical series, the heartwood); and (ii) a sheath analysis made with a sequence of the 10 outermost rings with the same chronological age (oblique series, in the sapwood).

The analyses were performed with three levels (base, 1.3 m, and 3.4 m of stem height) or four levels (including 5.5 m of stem height). Despite the differences regarding tree characteristics between sites the obtained results were qualitatively the same and therefore the four levels analyses were chosen to be presented here.

Correlation analysis was also performed between the studied variables.

The statistical analyses were performed using the JMP Statistical Software (SAS Institute Inc., Cary, NC, USA).

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

Source of Variation	Degrees of Freedom	Expected Variance	Error Term
(1) Sites (S)	$s - 1$	$\sigma^2\varepsilon$ + rl σ^2T/S + rlt σ^2S	(2)
(2) Trees/Sites (T/S)	$(t - 1)s$	$\sigma^2\varepsilon$ + rl σ^2T/S	(11)
(3) Levels (L)	$l - 1$	$\sigma^2\varepsilon$ + rts σ^2L	(11)
(4) L × S	$(l - 1)(s - 1)$	$\sigma^2\varepsilon$ + r σ^2LT/S + rt σ^2LS	(5)
(5) L × T/S	$(l - 1)(t - 1)s$	$\sigma^2\varepsilon$ + r σ^2LT/S	(11)
(6) Rings (R)	$r - 1$	$\sigma^2\varepsilon$ + lts σ^2R	(11)
(7) R × S	$(r - 1)(s - 1)$	$\sigma^2\varepsilon$ + l σ^2RT/S + lt σ^2RS	(8)
(8) R × T/S	$(r - 1)(t - 1)s$	$\sigma^2\varepsilon$ + l σ^2RT/S	(11)
(9) R × L	$(r - 1)(l - 1)$	$\sigma^2\varepsilon$ + ts σ^2RL	(11)
(10) R × L × S	$(r - 1)(l - 1)(s - 1)$	$\sigma^2\varepsilon$ + t σ^2RLS	(11)
(11) Residual (R × L × T/S)	$(r - 1)(l - 1)(t - 1)s$	$\sigma^2\varepsilon$	

T = trees (10/Site); L = height levels (4/tree); R = rings (15 or 10); σ^2S, σ^2T/S, σ^2L, σ^2LS, σ^2LT/S, σ^2R, σ^2RS, σ^2RT/S, σ^2RL, σ^2RLS and $\sigma^2\varepsilon$ are variance components due to Sites, Trees/Sites, Levels, Levels × Sites, Levels × Trees/Sites, Rings, Rings × Sites, Rings × Trees/Sites, Rings × Levels, Rings × Levels × Sites and Residual.

3. Results

3.1. Variation of Ring Width Components

Q. faginea growth rings were wider and latewood percentage was higher at Site MC with statistically significant between-site differences (Table 3).

Site effects were statistically more significant but explained less of the total variation of ring width in the core analysis (14%, $P < 0.001$) in opposition to the sheath analysis (49%, $P < 0.01$) (Table 4). The between-tree variation (T/S) was highly significant in both analysis (7–16%, $P < 0.001$) (Table 4). Overall, the ring width decreased from the base to the top (Table 5). However, the height level effects accounted little for the total variation of ring width even if its interaction with trees/sites (L × T/S) was highly significant (7–9%, $P < 0.0001$) (Table 4). In the initial period of tree growth, the effect of cambial age (given by the rings) and its interactions were mostly non-significant (Table 4). Within the sheath analysis, the effect of cambial age was highly significant but only accounted for 3% ($P < 0.001$) of the total variation (Table 4).

Table 3. Mean values (±standard deviation) of the ring width and wood density components measured within the core and sheath analyses at both sites. Mean of 10 trees per site and four stem height levels per tree (RD, ring density; EWD, earlywood density; LWD, latewood density; HI, heterogeneity index; RW, ring width; and LWP, latewood percentage).

Analysis	Site	RD (g/cm^3)	EWD (g/cm^3)	LWD (g/cm^3)	HI (g/cm^3)	RW (mm)	LWP (%)
Core	MC	0.914 ± 0.114 ^{a}	0.790 ± 0.148 ^{a}	0.963 ± 0.103 ^{a}	0.057 ± 0.039 ^{a}	2.52 ± 1.27 ^{a}	68.54 ± 14.11 ^{a}
	VI	1.037 ± 0.117 ^{b}	0.965 ± 0.144 ^{b}	1.076 ± 0.108 ^{b}	0.085 ± 0.042 ^{b}	1.83 ± 0.92 ^{b}	60.25 ± 15.80 ^{b}
Sheath	MC	0.751 ± 0.132 ^{a}	0.611 ± 0.160 ^{a}	0.827 ± 0.129 ^{a}	0.114 ± 0.056 ^{a}	2.11 ± 1.15 ^{a}	63.01 ± 13.79 ^{a}
	VI	0.680 ± 0.131 ^{a}	0.623 ± 0.148 ^{a}	0.722 ± 0.130 ^{b}	0.055 ± 0.050 ^{b}	0.77 ± 0.47 ^{b}	54.88 ± 15.83 ^{b}

Different letters for each variable and type of analysis (core, sheath) correspond to significant ($P < 0.05$) differences between sites by Duncan multiple test.

Table 4. Results of the core and sheath analysis of variance for the wood density and ring width components, showing their significance (*P* values) and the expected variation (EV%, percentage of total variation due to each source of variation), at both sites (RD, ring density; EWD, earlywood density; LWD, latewood density; HI, heterogeneity index; RW, ring width; and LWP, latewood percentage).

Analysis	**Source of Variation**	**RD**		**EWD**		**LWD**		**HI**		**RW**		**LWP**	
		P	**EV%**	***P***	**EV%**	***P***	**EV%**	***P***	**EV%**	***P***	**EV%**	***P***	**EV%**
Core	S	0.0009	29.7	0.0002	34.5	0.001	30.8	0.0017	13.8	0.0005	13.6	0.0008	11.4
	T/S	0.0001	19.6	0.0001	16.1	0.0001	20.8	0.0001	10.2	0.0001	7.1	0.0001	6.4
	L	0.0001	4.7	0.0001	4.4	0.0001	2.9	0.0001	4.8	0.0001	3.1	0.0121	0.6
	L × S	0.0156	4.2	0.0288	3.0	0.0093	4.8	0.1506	1.1	0.0015	6.2	0.2877	0.3
	L × T/S	0.0001	13.5	0.0001	11.8	0.0001	13.4	0.0001	10.6	0.0001	9.2	0.0001	5.9
	R	0.0001	2.3	0.0001	4.2	0.0001	1.9	0.0001	7.4	0.0424	0.5	0.0001	4.2
	R × S	0.0003	1.1	0.0001	1.6	0.0584	0.4	0.0001	3.4	0.0163	1.7	0.3907	0.1
	R × T/S	0.1774	0.5	0.1518	0.6	0.1437	0.6	0.1683	1.1	0.0151	3.2	0.5134	0
	R × L	0.0001	3.0	0.0001	2.2	0.0001	3.2	0.1648	0.5	0.0046	1.8	0.783	0
	R × L × S	0.4006	0.1	0.3661	0.1	0.3865	0.1	0.0987	1.4	0.2017	1.0	0.735	0
	R × L × T/S		21.2		21.4		21.0		45.7		52.7		71.1
Sheath	S	0.0834	8.1	0.7508	0.0	0.0142	19.7	0.0001	34.8	0.0001	49.3	0.0010	11.9
	T/S	0.0001	33.5	0.0001	24.5	0.0001	30.2	0.0001	8.0	0.0001	16.2	0.0001	6.5
	L	0.0199	0.4	0.0641	0.3	0.0104	0.4	0.0054	0.6	0.0212	0.1	0.1428	0.3
	L × S	0.2046	1.5	0.6622	0.0	0.0849	2.6	0.7768	0.0	0.7583	0.0	0.4874	0.0
	L × T/S	0.0001	23.6	0.0001	31.8	0.0001	17.1	0.0001	17.7	0.0001	7.2	0.0015	5.3
	R	0.1279	0.2	0.1193	0.3	0.5498	0.0	0.0807	0.3	0.0001	2.5	0.3660	0.1
	R × S	0.5109	0.0	0.5135	0.0	0.7115	0.0	0.2645	0.3	0.0097	2.1	0.1030	1.3
	R × T/S	0.2312	0.7	0.6063	0.0	0.1754	0.9	0.3528	0.4	0.0001	10.8	0.1821	2.2
	R × L	0.7859	0.0	0.9702	0.0	0.1462	0.4	0.4881	0.0	0.2901	0.1	0.5253	0.0
	R × L × S	0.1578	0.9	0.1273	1.4	0.2448	0.5	0.1898	0.9	0.4690	0.0	0.4859	0.0
	R × L × T/S		31.2		41.7		28.2		37.0		11.6		72.5

Sites (S), Trees/Sites (T/S), Levels (L), Levels × Sites (L × S), Levels × Trees/Sites (L × T/S), Rings (R), Rings × Sites (R × S), Rings × Trees/Sites (R × T/S), Rings × Levels (R × L), Rings × Levels × Sites (R × L × S) and Residual (R × L × T/S).

Table 5. Mean values (±standard deviation) for the wood density components and ring width within the core and sheath analyses by tree height levels at both sites (RD, ring density; EWD, earlywood density; LWD, latewood density; HI, heterogeneity index; RW, ring width; and LWP, latewood percentage).

Analysis	Height (m)	RD (g/cm^3)	EWD (g/cm^3)	LWD (g/cm^3)	HI (g/cm^3)	RW (mm)	LWP (%)
Core	5.5	0.943 ± 0.102^{a}	0.842 ± 0.134^{a}	0.998 ± 0.097^{a}	0.080 ± 0.047^{c}	1.9 ± 1.4^{a}	62.1 ± 16.8^{a}
	3.4	0.958 ± 0.124^{b}	0.849 ± 0.165^{a}	1.006 ± 0.116^{a}	0.078 ± 0.046^{c}	2.1 ± 1.1^{b}	65.2 ± 14.6^{b}
	1.3	0.980 ± 0.144^{c}	0.881 ± 0.187^{b}	1.022 ± 0.130^{b}	0.070 ± 0.040^{b}	2.3 ± 1.0^{b}	65.3 ± 15.6^{b}
	0.5	1.021 ± 0.137^{d}	0.938 ± 0.177^{c}	1.053 ± 0.125^{c}	0.056 ± 0.034^{a}	2.4 ± 1.0^{c}	65.0 ± 14.7^{b}
Sheath	5.5	0.717 ± 0.120^{ab}	0.618 ± 0.146^{ab}	0.782 ± 0.120^{bc}	0.089 ± 0.059^{b}	1.41 ± 1.0^{a}	58.2 ± 13.8^{a}
	3.4	0.703 ± 0.134^{a}	0.600 ± 0.135^{a}	0.763 ± 0.147^{a}	0.087 ± 0.062^{b}	1.44 ± 1.1^{b}	59.5 ± 14.7^{a}
	1.3	0.728 ± 0.144^{b}	0.624 ± 0.173^{b}	0.786 ± 0.145^{c}	0.085 ± 0.068^{b}	1.39 ± 1.1^{b}	60.5 ± 15.7^{a}
	0.5	0.713 ± 0.144^{ab}	0.626 ± 0.160^{b}	0.767 ± 0.146^{ab}	0.075 ± 0.055^{a}	1.52 ± 1.1^{c}	57.6 ± 17.1^{a}

Different letters for each variable and type of analysis (core, sheath) correspond to significant ($P < 0.05$) differences between height levels by Duncan multiple test.

Latewood proportion variation was also mainly explained by site effects accounting for 11% ($P < 0.001$) and 12% ($P < 0.001$) of the total variation followed by trees/sites (T/S) accounting for 6% and 7% ($P < 0.0001$) within the core and sheath analysis, respectively (Table 4). Within the tree, the latewood proportion was quite constant axially at both sites (Table 5), e.g., the cambial age explained only 4% ($P < 0.0001$) of the total variation near the pith and the height level was non-significant in both analyses (Table 4).

Ring width and latewood proportion correlations were positive but only slightly significant at both sites (Table 6).

Table 6. Correlation matrix (Pearson bivariate) for ring width and density components within the heartwood (lower triangle, n = 1200) and sapwood rings (upper triangle, n = 800) (RD, ring density; EWD, earlywood density; LWD, latewood density; RW, ring width; and LWP, latewood percentage).

		Sapwood				
		RD	EWD	LWD	RW	LWP
Heartwood	RD	1	**0.893**	**0.948**	0.061	**0.099**
	EWD	**0.904**	1	**0.772**	**−0.128**	**−0.163**
	LWD	**0.969**	**0.842**	1	**0.087**	0.027
	RW	−0.037	**−0.186**	−0.044	1	**0.385**
	LWP	−0.013	**−0.287**	**−0.072**	**0.371**	1

Values statistically significant ($P < 0.05$) in bold.

3.2. Variation of Wood Density Components

In the heartwood rings, the wood density was higher at Site VI but no differences were found in the sapwood rings (Table 3).

Site was the main source of variation for wood density components (RD, EWD and LWD) within the heartwood rings (30–35%, $P < 0.001$) but was non-significant within the sapwood rings (Table 4). The between-tree variability per site (T/S) was highly significant for both analyses accounting more for the total variation of wood density components in the sapwood (25–34%, $P < 0.0001$) than in the heartwood (16–21%, $P < 0.0001$). The interaction of height levels and trees/site (L × T/S) also showed similar results but explaining more the wood density variation in the sapwood rings (17–32%, $P < 0.0001$) than in the heartwood (12–14%, $P < 0.0001$) (Table 4).

The cambial age effects were non-significant in the sheath analysis; in the core analysis, cambial age was a highly significant effect ($P < 0.001$) but only accounted for 2–4% of the total variation (Table 4). There was a general axial decrease of wood density from the base to the top; in the core analysis, the differences were statistically significant although the height level effects only accounted for 3–5% of the total variation of the wood density components while in the sheath analysis they were non-significant (Tables 4 and 5).

The wood produced at Site MC was more homogenous i.e., the heterogeneity index was lower than at Site VI, and site effects accounted for the major differences specially in the sapwood rings (35%, $P < 0.001$) (Tables 3 and 4).

There were no negative correlations between wood density components and ring width or latewood proportion (Table 6).

4. Discussion

Environmental and stand conditions are main factors that account for ring width and wood density variability of *Quercus* spp. [9,12,13,19,27–29]. For example, in *Q. petraea* the water and nutrients soil availability and climate seem to have more effect in radial growth than in wood density [29,30].

In this study, however, as regards the soil conditions, higher growth rates would be expected at Site VI since *Q. faginea* prefers deeper soils with higher water availability [1,31], as is the case for Site VI (Tables 1 and 3). More results were found on ring width that showed different correlations with temperature and precipitation suggesting that *Q. faginea* achieves a relative independence from the regional rainfall regime under aridity conditions [31–33]. Thus, other environmental characteristics present at Site MC may have been important to increase growth rates, e.g., low temperature and soil silica availability, that are related to good growth conditions for this species or even the evaporation rates. Moreover, the stand characteristics were obviously more favorable at Site MC where trees are younger and there is lower between-tree competition essentially due to a smaller basal area (Table 1). The present findings call attention to the link of increased radial growth with forest management as it was already reported for commercial oaks such as *Q. petraea* and *Q. robur*, by preferring shorter rotations and faster growth [12,29].

The present study also suggests that wood density variation is mainly explained by the site effects although interpretations must be done carefully due to small number of sites tested and stand age and density differences as pointed above. For example, in the more studied species such as *Q. petraea*, controversial results were found on the site effects evidence including no geographical and site quality effects at all [28,34]. In other species, e.g., *Acacia melanoxylon*, no between-site differences were found [35].

In general, higher wood density values are found in the heartwood in relation with the accumulation of heartwood extractives and eventual tension wood formation or presence of knots [9,36]. As tension and knot wood were avoided in the present measurements, it is the extractives content that should explain the density variations in *Q. faginea* wood between sites and between trees per site. However, the total heartwood extractives were approximately the same at both sites (19%) [4], suggesting that it does not explain per se the wood density variability found between these sites. Within-tree extractives content might be important to explain heart- and sapwood differences in wood density. In general, it was possible to detect a clear decrease in wood density at the heartwood/sapwood transition by visual observation of the studied samples and each wood density profile. Even if this tendency was more evident in older trees at Site VI and at the lower stem height levels, it emphasizes the extractives accumulation importance to explain wood density variability within tree. As suggested for *Q. petraea* [37], the high wood density in heartwood might be also related with changes in anatomical features during its maturation, namely the presence of rays and tyloses. Regarding sapwood, it was observed that its width was rather constant along the stem showing significant differences between sites [14], although this study showed that its wood density was not affected by site.

Tissues composition namely the latewood proportion affects ring width and wood density in *Quercus* spp. The constant latewood proportion trend found in *Q. faginea* was also observed in *Q. petraea* that is the axial variation following the same cambial rings, showed weaker relationships than following identical calendar rings [38]. Site and trees seemed to contribute more for its variation in the young *Q. faginea* trees development than in older trees. In *Q. faginea*, the positive correlation of latewood proportion with ring width was stronger than with wood density. These correlations were similar to those obtained for the European oak [3,12,18,27,39]. It might be suggested that latewood percentage seems to be less correlated to radial growth increase when other ecological or environmental effects are more important for its development in *Q. faginea*.

The correlations between ring width and wood density components were weak, as was already seen in previous studies [3,39]. Similar results were also found in 110-year-old *Q. petraea* trees at plot scale, although a correlation was present at tree scale, thereby suggesting that a better radial growth due to better site conditions does not imply higher wood density [29]. In other ring-porous species as *Robinia pseudoacacia* L. from different origins, the growth rate accounted for only a proportion of the variation in wood density and latewood proportion showed also inconsistent influence in wood density [40].

The explanation for the wood density differences between sites could be also related to other anatomical features, e.g., to the extent and size of the large earlywood vessels [5,37]. However, a recent study [41] showed similar earlywood vessel area and radial patterns of all vessel features at both sites, which suggests that other cellular features such as wood rays or latewood vessels might be involved.

Despite the site effects that might be also related with the different tree physiological stages, it is important to note that between-tree effects were the second main factor to explain wood density and ring width variability in *Q. faginea*, which is in agreement with other wood quality studies of the most commercial oaks [12,28,29].

5. Conclusions

In *Q. faginea* stands, the site effects seem to contribute more for wood density than for radial growth variability. Wood density was high regardless of site, ranging from 914 kg m^{-3} to 1037 kg m^{-3}. Cambial age only accounted for 2–4% of the total variation of wood density components in the heartwood and it was not significant for ring width variability. The latewood proportion was constant within tree and not significantly correlated with wood density. The correlations between wood density and ring width, although positive at both sites, were weak.

This study suggests that *Q. faginea* stand conditions regarding basal area, density and tree age may override the site edaphic and climatic conditions stressing the importance of forest management for increased tree growth. However, further research on more sites with similar tree age is needed to clarify the effects of tree competition, environmental conditions, heartwood formation and anatomical features such as wood rays.

The results show the wood potential from the actual unmanaged stands of *Q. faginea* for high value wood components, thereby contributing to avoid the species decline through wood valorization and sustainable management.

Acknowledgments: CEF is a research unit funded by Fundação para a Ciência e a Tecnologia I.P. (FCT), Portugal (UID/AGR/00239/2013). The authors would like to thank S. Knapič for project management and S. Cardoso for logistic and fieldwork support and arrangements. Thanks are also due to A. Gonçalves for sample preparation and C. Fernandes for helping with density measurements. The first author acknowledges FCT for a fellowship (SFRH/BPD/97970/2013).

Author Contributions: V.B.S., J.L.L. and H.P. contributed to the general study conceptualization; J.L.L. and V.B.S. conducted and supervised the laboratory measurements and observations; J.L.L. performed the statistical analyses; and H.P. was responsible for funding acquisition and work supervision. All authors interpreted the data and contributed substantially to the manuscript preparation.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Capelo, J.; Catry, F. A distribuição do carvalho-português em Portugal. In *Os Carvalhais: Um Património a Conserver*; Silva, J.S., Ed.; Liga Para a Protecção da Natureza: Lisbon, Portugal, 2007; pp. 83–94. (In Portuguese)
2. Ramos, S.; Knapič, S.; Machado, J.S.; Nunes, L.; Pereira, H. Potencial tecnológico da madeira de *Quercus faginea* Lam. para revestimentos de superficies. In Proceedings of the 6th Congresso Florestal Nacional, Ponta Delgada, Portugal, 6–9 October 2009. (In Portuguese)
3. Knapič, S.; Louzada, J.L.; Pereira, H. Variation of wood density components within and between *Quercus faginea* trees. *Can. J. For. Res.* **2011**, *41*, 1212–1219. [CrossRef]
4. Miranda, I.; Sousa, V.; Ferreira, J.; Pereira, H. Chemical characterization and extractives composition of heartwood and sapwood from *Quercus faginea*. *PLoS ONE* **2017**, *12*, e0179268. [CrossRef] [PubMed]
5. Sousa, V.B.; Cardoso, S.; Pereira, H. Age trends in the wood anatomy of *Quercus faginea*. *IAWA J.* **2014**, *35*, 293–306. [CrossRef]
6. Vilà, M.; Vayreda, J.; Comas, L.; Ibáñez, J.J.; Mata, T.; Obón, B. Species richness and wood production: A positive association in Mediterranean forests. *Ecol. Lett.* **2007**, *10*, 241–250. [CrossRef] [PubMed]
7. Vayreda, J.; Gracia, M.; Martinez-Vilalta, J.; Retana, J. Patterns and drivers of regeneration of tree species in forests of peninsular Spain. *J. Biogeogr.* **2013**, *40*, 1252–1265. [CrossRef]
8. Saranpää, P. Wood density and growth. In *Wood Quality and Its Biological Basis*; Barnett, J., Jeronimidis, G., Eds.; Blackwell Publishing Ltd.: Victoria, TX, USA; CRC Press: Oxford, UK, 2003; pp. 87–113.
9. Zobel, B.J.; van Buijtenen, J.P. *Wood Variation, Its Causes and Control*; Springer: Berlin, Germany, 1989; p. XV-363.
10. Lei, H.; Milota, M.R.; Gärtner, B.L. Between-and within-tree variation in the anatomy and specific gravity of wood in Oregon white oak (*Quercus garryana* Dougl.). *IAWA J.* **1996**, *17*, 445–461. [CrossRef]
11. Paul, B.H. *The Application of Silviculture in Controlling the Specific Gravity of Wood*; Technical Bulletin No. 1288; USDA Forest Service: Washington, DC, USA, 1963.
12. Zhang, S.Y.; Owoundi, R.E.; Nepveu, G.; Mothe, F.; Dhôte, J.F. Modelling wood density in European oak (*Quercus petraea* and *Quercus robur*) and simulating the silvicultural influence. *Can. J. For. Res.* **1993**, *23*, 2587–2593. [CrossRef]
13. Lebourgeois, F.; Coussea, G.; Ducos, Y. Climate-tree-growth relationships of *Quercus petraea* Mill. stand in the Forest of Bercé ("Futaie des Clos", Sarthe, France). *Ann. For. Sci.* **2004**, *61*, 361–372. [CrossRef]
14. Sousa, V.B.; Cardoso, S.; Pereira, H. Ring width variation and heartwood development in *Quercus faginea*. *Wood Fiber Sci.* **2013**, *45*, 1–10.
15. Knapič, S.; Louzada, J.L.; Leal, S.; Pereira, H. Within-tree and between-tree variation of wood density components in cork oak trees in two sites in Portugal. *Forestry* **2008**, *81*, 465–473. [CrossRef]
16. Bergès, L.; Dupouey, J.-L.; Franc, A. Long-term changes in wood density and radial growth of *Quercus petraea* Liebl. in northern France since the middle of the nineteenth century. *Trees* **2000**, *14*, 398–408. [CrossRef]
17. Bakour, R. Infuence de L'espèce et de la Provenance des deux Principaux Chênes Français (*Quercus robur* L.). Ph.D. Thesis, ENGREF (AgroParisTech), Paris, France, 2003.
18. Polge, H.; Keller, R. Qualité du bois et largeur d'accroissements en foret de trançais. *Ann. Sci. For.* **1973**, *30*, 91–125. [CrossRef]
19. Burdon, R.; Walker, J.; Megraw, B.; Evans, R.; Cown, D. Juvenile wood (sensu novo) in pine, conflicts and possible opportunities for growing, processing and utilisation. *N. Z. J. For.* **2004**, *49*, 24–31.
20. Bamber, R.K. Heartwood, its function and formation. *Wood Sci. Technol.* **1976**, *10*, 1–8. [CrossRef]
21. Hillis, W.E. Heartwood formation and its influence on utilization. *Wood Sci. Technol.* **1968**, *2*, 260–267. [CrossRef]
22. Meyer, R.W. Tyloses development in white oak. *For. Prod. J.* **1967**, *17*, 50–56.
23. Bamber, R.K. *Sapwood and Heartwood*; Technical Submission nr 2; Wood Technology and Forest Research Division: New South Wales, Australia, 1961.
24. Gaspar, M.J.; Louzada, J.L.; Silva, M.E.; Aguiar, A.; Almeida, M.H. Age trends in genetic parameters of wood density components in 46 half-sibling families of *Pinus pinaster*. *Can. J. For. Res.* **2008**, *38*, 1470–1477. [CrossRef]

25. Rozenberg, P.; Franc, A.; Cahalan, C. Incorporating wood density in breeding programs for softwoods in Europe: A strategy and associated methods. *Silvae Genet.* **2001**, *50*, 1–7.
26. Ferrand, J.C. Réflexions sur la densité du bois. 2e partie: Calcul de la densité et de son hétérogénéité. *Holzforschung* **1982**, *36*, 153–157. [CrossRef]
27. Nepveau, G. Déterminisme génotypique de la structure anatomique du bois chez *Quercus robur*. *Silvae Genet.* **1984**, *33*, 91–95.
28. Ackermann, F. Influence du type de station forestière sur les composantes intracernes de la densité du bois du chêne pédonculé (*Quercus robur* L.) dans les chênaies de l'Adour et des coteaux basco-béarnais. *Ann. For. Sci.* **1995**, *52*, 635–652. [CrossRef]
29. Bergès, L.; Nepveau, G.; Franc, A. Effects of ecological factors on radial growth and wood density components of sessile oak (*Quercus petraea* Liebl.) in Northern France. *For. Ecol. Manag.* **2008**, *255*, 567–579. [CrossRef]
30. Guilley, E.; Hervé, J.-C.; Huber, F.; Nepveu, G. Modelling variability of within-ring density components in *Quercus petraea* Liebl. with mixed-effect models and simulating the influence of contrasting silvicultures on wood density. *Ann. For. Sci.* **1999**, *56*, 449–458. [CrossRef]
31. Villar-Salvador, P.; Castro-Díez, P.; Pérez-Rontomé, C.; Montserrat-Martí, G. Stem xylem features in three *Quercus* (*Fagaceae*) species along a climatic gradient in NE Spain. *Trees* **1997**, *12*, 90–96. [CrossRef]
32. Alla, A.Q.; Camarero, J.J. Contrasting responses of radial growth and wood anatomy to climate in a Mediterranean ring-porous oak: Implications for its future persistence or why the variance matters more than the mean. *Eur. J. For. Res.* **2012**, *131*, 1537–1550. [CrossRef]
33. Corcuera, L.; Camarero, J.J.; Gil-Pelegrin, E. Effects of a severe drought on growth and anatomical properties of *Quercus faginea*. *IAWA J.* **2004**, *25*, 185–204. [CrossRef]
34. Degron, R.; Nepveu, G. Prévision de la variabilité intra- et interarbre de la densité du bois de chêne rouvre (*Quercus petraea* Liebl) par modélisation des largeurs et des densités des bois initial et final en fonction de l'âge cambial, de la largeur de cerne et du niveau dans l'arbre. *Ann. Sci. For.* **1996**, *53*, 1019–1030.
35. Tavares, F.; Louzada, J.L.; Pereira, H. Variation in wood density and ring width in *Acacia melanoxylon* at four sites in Portugal. *Eur. J. For. Res.* **2014**, *133*, 31–39. [CrossRef]
36. Pereira, H.; Graça, J.; Rodrigues, J.C. Wood chemistry in relation to quality. In *Wood Quality and Its Biological Basis*; Barnett, J., Jeronimidis, G., Eds.; Blackwell Publishing Ltd.: Victoria, TX, USA, 2003; pp. 53–86.
37. Guilley, E.; Nepveu, G. Interprétation anatomique des composantes d'un modèle mixte de densité du bois chez le chêne sessile (*Quercus petraea* Liebl.): Âge du cerne compté depuis la moelle, largeur de cerne, arbre, variabilité interannuelle et duraminisation. *Ann. Sci. For.* **2003**, *60*, 331–346.
38. Weigl, M.; Grabner, M.; Helle, G.; Schleser, G.H.; Wimmer, R. Variability of latewood-widths and -stable isotope ratios in a sessile oak tree (*Quercus petraea* (Matt.) Liebl.). *Dendrochronologia* **2007**, *24*, 117–122. [CrossRef]
39. Sousa, V.B.; Louzada, J.L.; Pereira, H. Age trends and within-site effects in wood density and radial growth in *Quercus faginea* mature trees. *For. Syst.* **2016**, *25*, E053. [CrossRef]
40. Adamopoulos, S.; Passialiset, C.; Voulgaridis, E. Ring width, latewood proportion and density relationships in black locust wood of different origins and clones. *IAWA J.* **2010**, *31*, 169–178. [CrossRef]
41. Sousa, V.B.; Louzada, J.L.; Pereira, H. Earlywood vessel features in *Quercus faginea*: Relationship between ring width and wood density at two sites in Portugal. *iForest* **2015**, *8*, 866–873. [CrossRef]

© 2018 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).