For. Stud. China, 2011, 13(4): 276–284
DOI 10.1007/s11632-013-0405-5

RESEARCH ARTICLE

Effect of moisture on physical parameters of timber from Turkey oak (*Quercus cerris* L.) coppice in Central Italy

Angela LO MONACO[1*], Luigi TODARO[2], Mara SARLATTO[3], Raffaello SPINA[1], Luca CALIENNO[1], Rodolfo PICCHIO[1]

[1] Department of Science and Technology for Agriculture, Forests, Nature and Energy, University of Tuscia, Viterbo 01100, Italy
[2] Department of Crop Systems, Forestry and Environmental Sciences, University of Basilicata, Potenza 85100, Italy
[3] Agricultural Research Council, Rome 00184, Italy

Abstract This study aims to investigate wood density at different levels of moisture, basic density and shrinkage of timber from Turkey oak (*Quercus cerris* L.) coppice forests growing in Central Italy. We also studied the variability in density in the trees within and among sites. Density shows no significant statistical differences in the tested population. A higher variability in the shrinkage than in the density was found. Wood moisture is referred to as dry mass and fresh mass, which is related to many performance characteristics of wood, i.e., energy production. Trends in moisture and water content were studied because these physical parameters play an important role in the specific area of firewood which requires an accurate estimation of mass, volume and energy content. This work is a contribution to improve xylo-energy estimates of small and medium forestry issues.

Key words wood density, coppice, moisture content, *Quercus cerris* L., shrinkage

1 Introduction

Coppice, in particular of oak species, has supplied timber for consumption both as firewood and charcoal production for centuries. Coppice is a traditional method of regeneration to produce woody biomass rapidly. The biomass derived from Turkey oak (*Quercus cerris* L.) coppice, therefore, constitutes an opportunity as a renewable source of energy, even in the context of limited forestry extension. A recent study on timber trade in the world, based on FAO statistics (FAO, 2008), revealed a rising trend in the use of the wood for various markets, especially in response to energy demand.

Understanding the relationship between water and timber derived from the shoots is not only a prerequisite for an optimal use of energy, but also an essential factor in the selection for sustainable management and evaluation of land resources. In fact, a responsible management should take into account the energy efficiency of the transformation process: from the utilization of the forest to the energy use of wood (Picchio et al., 2009). An understanding of parameters, such as wood density, moisture content and dimensional shrinkage, is crucial to define the potential of a species to be used for energy purposes.

The Turkey oak is found mainly in Eastern Europe with restrictions to both north and south. The Balkans is the center of its range. In Turkey, the vicarious species, *Q. pseudocerris* Boiss., is found, while it is rare in Greece. Oak coppice forests are widespread especially in countries bordering the Mediterranean. It is rare in Italy north of the Po River, while it forms forests from the "Appennino Tosco-Emiliano" region down to Calabria. In Southern Italy, it is rare in Sicily and all together absent in Sardinia (Bernetti, 1995). The current distribution of this *Quercus* genus is correlated to human activity that has always favored oak forests, to the detriment of other tree species (Timbal and Aussenac, 1996). In Italy Turkey oak forests extend for over 1000000 ha, representing 11.5% of the national woodland, 9.7% of national forest area and 3.4% of national land surface (IFNC, 2007). In Central Italy, in particular, the surface area of mainly Turkey oak forests is approximately 710000 ha and 75.5% of this is coppice (IFNC, 2007).

Turkey oak wood is considered difficult to treat (Uzielli, 1989) and it is less appreciated compared with other deciduous oaks for furniture, floors and veneer. The timber splits and warps during seasoning, but the

*Author for correspondence. E-mail: lomonaco@unitus.it

major characteristic limiting its larger use is its high wood density and consequently, its shrinkage (Berti and Corona, 1983). The durability is low for both sapwood and heartwood (Giordano, 1990). Its wood has a higher percentage of bark compared to the other oak species and contains specific types of tannins that make it difficult to glue (Zanuttini, 1992). These tannins represent an important tool to distinguish Turkey oak wood from sessile oak (*Quercus petraea* (Matt.) Liebl.) and pedunculate oak (*Q. robur* L.). An aqueous extract stained with ferric chloride ($FeCl_3$) assumes a green coloration in the case of Turkey oak heartwood and blue in the other oaks (Giordano, 1981).

Uzielli (1989) and Guilley et al. (2004) considered that there are no substantial differences in the technological characteristics of oak wood from coppice compared to timber from a high forest when trees with diameters greater than 40 cm are considered. Local consumers appreciate the firewood from coppice oak, while forest owners mainly prefer fast growing ones (Bernetti, 1995).

Wood contains air and water as well as wood tissue. Wood, when oven-dried, contains only air and wood tissue. The oven-dry density of any species is a direct reflection of the amount of space occupied by wood tissue (Walker, 2006). Wood moisture is expressed in percentage in comparison with wood dry mass, but in the paper and cellulose industry it is referred to as wood green weight (Giordano, 1981; Walker, 2006).

This study aims to investigate wood density at different levels of moisture, basic density and shrinkage of timber from Turkey oak coppice forests growing in Central Italy. We then studied how it is related to performance characteristics of wood, i.e., energy production. Particularly, we studied the variability of density in relation to moisture. We refer to wood moisture as dry mass and fresh mass, which is related to many performance characteristics of wood, such as mechanical strength and energy production. Moreover, we investigated the variability of density in these trees within and among sites.

2 Materials and methods

The samples came from 10 plots of Turkey oak coppice, located in Central Italy and all identified with a letter from A to L. Tables 1 and 2 present the main features of the area and the characteristics of the trees in the 10 experimental plots examined. Three circular sub-plots (60 m in diameter) were chosen from each plot and the main dendrometric characteristics were measured. In each plot, 10 shoots were selected applying the following methodology: we started from

Table 1 Major site characteristics of experimental plots

Plot No.	Average elevation (m a.s.l.)	Exposure	Average slope (%)	Soil	Phyto-climate (Pavari)	Coordinates
A	450	N	30	Middle clay soil; little deep soil with a lot of calcareous skeleton	Lauretum	12°61′17″N 42°52′53″E
B	600	S–SE	25	Middle clay soil; little deep soil with a lot of calcareous skeleton	Lauretum	12°13′10″N 42°49′30″E
C	460	N–NE	20	Middle clay soil; deep soil with little calcareous skeleton	Lauretum	12°58′36″N 42°47′31″E
D	440	E	20	Middle clay soil; deep soil with little calcareous skeleton	Lauretum	11°58′41″N 42°47′15″E
E	240	N	25	Middle clay soil; deep soil with little calcareous skeleton	Lauretum	12°12′06″N 42°39′35″E
F	270	N	25	Middle clay soil; deep soil with little calcareous skeleton	Lauretum	12°11′50″N 43°39′42″E
G	700	S–SW	42	Calcareous conglomerate; little deep soil with skeleton	Castanetum	12°48′03″N 42°21′44″E
H	720	S–SW	42	Calcareous conglomerate; little deep soil with skeleton	Castanetum	12°48′01″N 42°21′47″E
I	450	N	15	Clay and sand soil; deep soil without skeleton	Lauretum	11°35′28″N 43°21′10″E
L	350	N	30	Clay and sand soil; deep soil without skeleton	Lauretum	11°36′25″N 43°19′01″E

the southern border of the sub-plot, moved with a linear transect in a northerly direction, and harvested a tree every 20 m. If the northern border was reached without harvesting 10 shoots, we repeated the operation, but started at 30 m in an easterly direction from the precedent starting point and moved always from south to north. For each shoot a disk was cut at breast height.

For each disk (a total of 100 disks were taken from 100 shoots), a section was removed corresponding to the largest diameter for the next specimen preparation according to the standards UNI 3252 and ISO 3129.

For each disk a further section, 30 mm thick and 20 mm wide, was cut in order to obtain samples with final dimensions of 20 mm × 20 mm × 30 mm (radial, tangential, longitudinal, respectively) with an error less than 1%. Each sample, taken according to the described methodology, was marked by a code that uniquely identified it during testing. The number of specimens obtained in each plot varied due to different diameters of the disks taken at 1.3-m height.

To define and refine the sampling procedures, a preliminary investigation was carried out in three randomly selected plots identified by the letters A, D and H, respectively. In order to test density at different shoot heights, five disks from each tree were removed at the following heights above ground level, i.e., at 1.3 m, 2.3 m, half length, 2 m above half length and at the tip diameter of 10 cm over bark. Data of dry density (Table 3) were analyzed by statistical analysis using the nonparametric Kruskal-Wallis test (Sprent and Smeeton, 2001). There were no significant differences between the values of density of samples taken at different heights (data not shown), therefore, a single disk at 1.3-m height per tree was collected in the other plots. No significant changes were reported in relation to the sampling height for other deciduous oaks (Zhang et al., 1993; Degron and Nepveu, 1996). This allowed us to maximize the performance and extend the sampling to other wooded areas, considering only the 1.3-m sampling height.

Table 2 Main characteristics of trees in the experimental plots

Plot No.	Coppice age (years)	Average DBH (cm)	Average height (m)	Number of coppice shoots ($n \cdot ha^{-1}$)	Average tree ring width (mm)
A	26	17 ± 0.3	14 ± 2.1	820	3.62 ± 0.2
B	18	16 ± 1.8	16 ± 2.2	790	4.02 ± 1.2
C	25	17 ± 1.3	13 ± 3.1	810	3.38 ± 0.3
D	23	15 ± 0.8	15 ± 1.2	830	3.11 ± 0.6
E	17	12 ± 2.7	9 ± 1.3	920	3.96 ± 1.1
F	17	12 ± 1.4	11 ± 2.8	940	4.01 ± 0.9
G	47	19 ± 2.3	15 ± 4.2	640	2.29 ± 0.2
H	47	15 ± 1.8	12 ± 3.1	790	1.89 ± 0.8
I	25	15 ± 1.2	14 ± 2.2	810	2.65 ± 0.5
L	24	14 ± 1.1	15 ± 3.4	850	2.78 ± 0.1

Note: ± means S.D.

Table 3 Dry wood densities for the plots A, D and H

Plot No.	Number of samples	Average ($g \cdot cm^{-3}$)	Confid. −95% ($g \cdot cm^{-3}$)	Confid. +95% ($g \cdot cm^{-3}$)	Min ($g \cdot cm^{-3}$)	Max ($g \cdot cm^{-3}$)	S.D. ($g \cdot cm^{-3}$)
A	223	0.817	0.807	0.827	0.580	0.981	0.079
D	210	0.840	0.828	0.853	0.637	1.082	0.090
H	228	0.797	0.790	0.803	0.615	0.901	0.050

Note: Average dry density considers the five levels of sampling.

The samples collected in all plots were conditioned for 30 d in a conditioned room at 20°C and 65% relative humidity. During this period, at 10-d intervals the samples were measured for dimensions (mm) and mass (g). At the end of the 30 d the samples were placed in an oven at 103 ± 2°C until the mass became constant (dry condition). The other two measurements of mass and size were carried out at intervals of 8 h. According to the UNI ISO 3131, the volume, basic density and the density at different moisture levels were determined. According to the European Commission Glossary, basic density refers to the ratio of dry mass and fully swollen volume.

$$\rho = \frac{m_u}{v_u} \qquad 1)$$

$$D_b = \frac{m_d}{v_u} \qquad 2)$$

where ρ is density, m_u mass at moisture content u, v_u volume at moisture content u, D_b basic density and m_d dry mass.

Water content (w) and moisture content (u) were calculated according to the UNI ISO 3130 and UNI EN 13183-1 standards.

The tangential, radial and volumetric shrinkage of each sample was calculated according to the UNI ISO 4469 and UNI ISO 4858 standards, considering the total amount of dimensional variation from the fully swollen to the oven-dry condition. In addition, for each variable measured, the coefficient of shrinkage was calculated: it is the shrinkage value when moisture content decreases by 1%, below the fiber saturation point and under the assumption of a linear relationship.

The values obtained (dry density and shrinkage) were statistically analyzed using the nonparametric Kruskal-Wallis test (Sprent and Smeeton, 2001). The aim was to identify some differences within the same plot and among the 10 plots. The statistical test was nonparametric because the data were not normally distributed and showed a lack of homogeneity of variance, as shown by applying the Bartlett and Levene tests (Zar, 1999).

Using the data obtained from all plots a regression analysis was applied in order to calculate the equations which describe the relations between the physical parameters tested and the water content. A non-parametric correlation analysis (Spearman's rho, r_s, $p < 0.01$) was selected to investigate the relationship between the variables (Sheskin, 2000).

3 Results

3.1 Density

The average dry density was 0.805 ± 0.080 g·cm^{-3}, with a minimum value of 0.573 g·cm^{-3} and a maximum of 1.061 g·cm^{-3} (Table 4). The values of dry density showed no significant statistical differences among trees, either within the same plot (data not shown) or among different plots.

The trees examined are from coppice and its wood is principally destined for firewood. Logs are relatively young, aged between 17 and 47 years, with a high rate of radial growth. Owing to these reasons, high density can be found in the plots.

3.2 Shrinkage

A total of 2272 samples were tested. The average values for each plot and the average of the 10 plots of the tangential, radial and volumetric shrinkage are shown in Tables 5–7. The average values were (11.1 ± 3.2)% for tangential shrinkage, (6.6 ± 3.2)% for radial shrinkage and (18.5 ± 4.9)% for total volumetric shrinkage (Tables 5–7).

Table 8 shows the shrinkage coefficients from the 10 plots. These coefficients, underlined and in bold in

Table 4 Dry wood densities for 10 plots from samples collected at breast height (1.3 m)

Plot No.	Number of samples	Average (g·cm^{-3})	Confid. −95% (g·cm^{-3})	Confid. +95% (g·cm^{-3})	Min (g·cm^{-3})	Max (g·cm^{-3})	S.D. (g·cm^{-3})
A	64	0.801	0.776	0.825	0.580	0.981	0.099
B	55	0.812	0.797	0.826	0.661	0.931	0.052
C	58	0.819	0.801	0.837	0.619	0.955	0.070
D	62	0.821	0.798	0.845	0.637	1.061	0.093
E	61	0.795	0.781	0.809	0.672	0.923	0.055
F	62	0.806	0.788	0.825	0.696	1.016	0.073
G	59	0.791	0.771	0.812	0.629	0.987	0.077
H	67	0.798	0.783	0.813	0.615	0.901	0.062
I	55	0.812	0.784	0.839	0.644	0.990	0.102
L	70	0.795	0.772	0.817	0.573	0.957	0.095
Total	613	0.805	0.798	0.811	0.573	1.061	0.080

Table 5 Total tangential shrinkage obtained in 10 plots

Plot No.	Number of samples	Average (%)	Confid. −95% (%)	Confid. +95% (%)	Min (%)	Max (%)	S.D. (%)
A	323	11.0	10.6	11.4	0	17.7	3.6
B	157	12.0	11.6	12.3	1.4	17.2	2.4
C	167	11.1	10.8	11.5	1.3	18.1	2.3
D	290	10.7	10.3	11.0	0.1	17.5	3.1
E	158	9.9	9.6	10.2	0.2	16.7	2.2
F	155	10.1	9.7	10.5	0.3	16.5	2.4
G	168	9.8	9.4	10.1	0.2	16.6	2.3
H	333	12.7	12.3	13.0	0.1	18.1	3.4
I	164	9.4	9.1	9.7	5.1	13.3	1.8
L	357	11.7	11.3	12.1	0.1	18.1	3.8
Total	2272	11.1	10.9	11.2	0	18.1	3.2

Table 6 Total radial shrinkage obtained in 10 plots

Plot No.	Number of samples	Average (%)	Confid. −95% (%)	Confid. +95% (%)	Min (%)	Max (%)	S.D. (%)
A	323	7.5	7.1	7.9	3.0	20.1	3.6
B	157	6.5	6.3	6.8	3.8	15.2	1.4
C	167	6.5	6.2	6.8	3.0	15.3	1.9
D	290	7.2	6.8	7.7	3.2	19.6	3.5
E	158	4.4	4.2	4.6	0	12.0	1.5
F	155	4.3	4.0	4.6	0	11.2	1.9
G	168	5.6	5.3	6.0	0	16.4	2.3
H	333	7.1	6.8	7.4	2.1	18.4	3.1
I	164	6.0	5.4	6.6	0	17.2	3.8
L	357	7.6	7.3	8.0	2.0	18.8	3.5
Total	2272	6.6	6.5	6.7	0	20.1	3.2

Table 7 Total volumetric shrinkage obtained in 10 plots

Plot No.	Number of samples	Average (%)	Confid. −95% (%)	Confid. +95% (%)	Min (%)	Max (%)	S.D. (%)
A	323	19.5	18.9	20.1	8.2	35.1	5.6
B	157	19.4	19.0	19.8	12.7	26.4	2.6
C	167	18.9	18.4	19.3	12.4	29.8	2.9
D	290	18.9	18.3	19.5	8.2	34.9	4.9
E	158	14.6	14.2	15.0	5.9	22.2	2.4
F	155	15.3	14.8	15.7	9.4	23.3	2.6
G	168	16.0	15.5	16.5	8.1	29.6	3.2
H	333	20.2	19.7	20.8	8.3	34.9	5.1
I	164	15.8	15.2	16.3	9.0	24.9	3.6
L	357	20.3	19.7	21.0	8.3	35.4	5.9
Total	2272	18.5	18.3	18.7	5.9	35.4	4.9

Table 8 Average values of the shrinkage coefficients obtained in 10 plots

	Total	A	B	C	D	E	F	G	H	I	L
Tangential shrinkage coefficient	0.210	0.203	0.229	0.221	0.205	0.204	0.206	0.187	0.234	0.179	0.212
Radial shrinkage coefficient	0.123	**0.136**	0.125	**0.128**	0.137	0.091	**0.087**	**0.109**	**0.128**	**0.120**	**0.131**
Volumetric shrinkage coefficient	0.348	**0.357**	0.371	**0.373**	0.361	0.302	0.312	**0.310**	**0.371**	**0.306**	**0.360**

Note: The Kruskal-Wallis test was applied to analyze the data ($1-\alpha = 0.95$; gdl 9; $n = 2272$). Bold and underscored estimates reveal that the samples belong to the same statistical population.

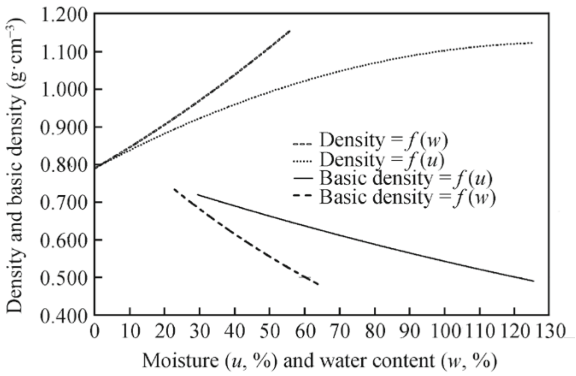

Fig. 1 Effect of moisture and water content on density and basic density

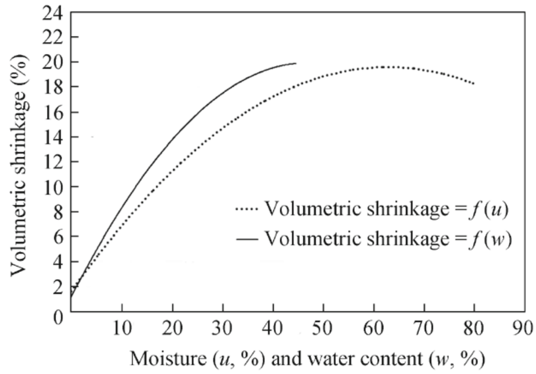

Fig. 2 Volumetric shrinkage as a function of moisture and water content

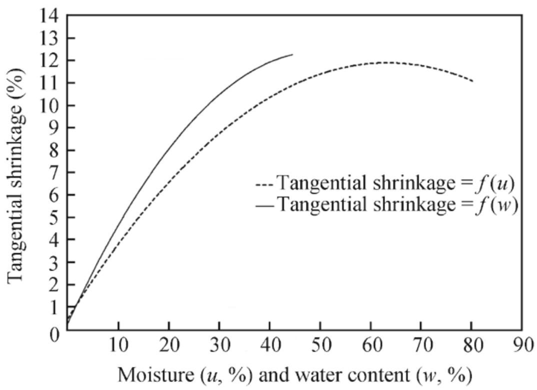

Fig. 3 Tangential shrinkage as a function of moisture and water content

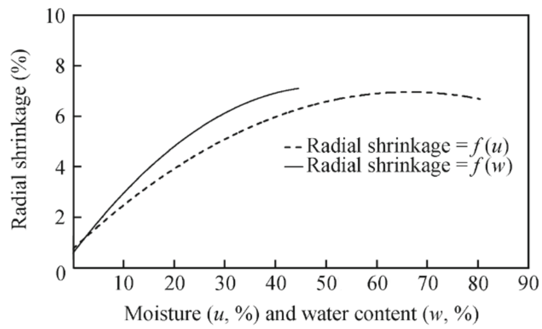

Fig. 4 Radial shrinkage as a function of moisture and water content

Table 8, indicate samples belonging to the same statistical population or without any statistically significant differences.

3.3 Water content

Figures 1–4 demonstrate the results of moisture and water content on density and shrinkage of wood. The equations that best approximate the trends of the values obtained with the corresponding value of R^2 are shown in Tables 9–12.

Analyzing the values of the coefficient of determination (R^2), the models show a good fit for the density (Table 10). The percentage change in volumetric, tangential and radial shrinkage (Table 12) was expressed as a function of both moisture and water content. In

Table 9 Regression and corresponding R^2 values refer to data shown in Fig. 1

	Regression	R^2
Density (u%)	$y = -0.184x^2 + 0.495x + 0.790$	0.663
Density (w%)	$y = 0.207x^2 + 0.537x + 0.790$	0.654
Basic density (u%)	$y = 0.810e^{-0.4x}$	0.470
Basic density (w%)	$y = 0.927e^{-1.02x}$	0.438

Table 10 Spearman's rank correlation coefficients refer to data shown in Fig. 1

	Number of samples	Spearman's r_s	t (N−2)	p-level
Density (u%)	4555	0.80	89.03	0.00
Density (w%)	4555	0.79	88.27	0.00
Basic density (u%)	2276	−0.64	−40.20	0.00
Basic density (w%)	2276	−0.64	−40.18	0.00

Table 11 Regression and corresponding R^2 values refer to data shown in Figs. 2–4

	Regression	R^2
Tangential shrinkage (u%)	$y = -0.3123x^2 + 0.3857x$	0.763
Tangential shrinkage (w%)	$y = -0.5303x^2 + 0.5095x$	0.765
Radial shrinkage (u%)	$y = -0.1835x^2 + 0.2258x$	0.511
Radial shrinkage (w%)	$y = -0.3623x^2 + 0.5244x$	0.524
Volumetric shrinkage (u%)	$y = -0.5504x^2 + 0.6579x$	0.763
Volumetric shrinkage (w%)	$y = -1.0544x^2 + 0.9062x$	0.775

Table 12 Spearman's rank correlation coefficients refer to data shown in Figs. 2–4

	Number of samples	Spearman's r_s	t (N–2)	p-level
Tangential shrinkage (u%)	4554	0.83	98.80	0.00
Tangential shrinkage (w%)	4554	0.83	98.80	0.00
Radial shrinkage (u%)	4554	0.79	88.12	0.00
Radial shrinkage (w%)	4554	0.79	88.12	0.00
Volumetric shrinkage (u%)	4554	0.84	106.13	0.00
Volumetric shrinkage (w%)	4554	0.84	106.13	0.00

Table 13 Comparison between the average data collected in the present study and those found in scientific references

Variables	0	1	2	3	4	5	6	7	8	9	10	11
Density (g·cm^{-3})	0.805	0.800	0.820	0.870	0.790	0.930	0.860	0.870	0.840	0.870	0.830	0.865
(moisture) (%)	(0)	(17.3)	(15.2)	(21.0)	(15.9)	(16.7)	(17.1)	(12.6)	(–)	(12.0)	(12.0)	(12.0)
Basic density (g·cm^{-3})	0.650								0.680			0.655
Volumetric shrinkage coefficient	0.35	0.48	0.46	0.51	0.43	0.59	0.50	0.62	0.57	0.50		0.56
Tangential shrinkage (%)	11.1										13.0	13.4
Radial shrinkage (%)	6.6										5.3	7.4
Volumetric shrinkage (%)	18.5											20.1

Note: 0 = this work; 1, 2, 3, 4, 5, 6, 7 = Uzielli, 1989; 8 = Berti and Corona, 1983; 9 = Giordano, 1981; 10 = Nardi Berti, 1993; 11 = Berti et al., 1991.

contrast, the model regarding the basic density did not show a statistical good fit (Table 10).

4 Discussion

4.1 Density

In our study, high values of dry density for the wood of Turkey oak were found. Because of the economic value of sessile oak and pedunculate oak, the relationship between density, as an estimator of wood quality and the width of growth rings has been widely studied (Bergès et al., 2000). A positive relationship has been established between density and radial growth (Zhang et al., 1993; Guilley et al., 1999; Le Moguédec et al., 2002; Guilley and Nepveu, 2003; Bergès et al., 2008). In particular, at high latewood widths, higher densities were found in deciduous oaks (Degron and Nepveu, 1996). A similar relationship is expected to occur for the Turkey oak, which is a ring-porous oak. The trees examined are relatively young, ranging between 17 and 47 years and with a higher mean radial increment than the trees examined in detail in the literature cited. It can therefore be assumed that the high density observed may be attributed to the age of the shoots. Guilley and Nepveu (2003) found that younger trees (52 years) had a higher average density than older trees (98 years) due to anatomical differences between the two age groups, considering the same average ring width.

The total average values observed in the density of wood in its dry state is therefore comparable with the results from scientific literature (Table 13) and consistent with other studies on oak wood. The results confirm that there is no statistical effect on the variation in density related to silvicultural management or to plot characteristics. This is consistent with the data on sessile oak and pedunculate oak found by other authors (Becker et al., 1979; Ackermann, 1995; Bergès et al., 2000; Guilley et al., 2004), which reported only a weak effect of site conditions on density. Similar results have been obtained in coniferous woods (Acuna and Murphy, 2006), although some authors found negative effects of forestry practices, mainly thinning, on the density of wood (Kennedy, 1995; Macdonald and Hubert, 2002).

Another hypothesis is that the geographical location of the experimental plots does not allow sufficient variation in ecological conditions to guarantee a significant effect on wood density.

4.2 Shrinkage

The average values of shrinkage for all the samples and for different plots are within the range of variation of this species with the same silvicultural management (Berti et al., 1991). Furthermore, the shrinkage in each plot shows a similar behavior.

The results of the statistical Kruskal-Wallis test (data not shown) indicate a large variability in shrinkage. This result was also noted by other authors (Zhang et al., 1994a, 1994b, 1995; Badel et al., 2006). Radial (plots A, C, F, G, H, I, L) and volumetric (plots A, C, G, H, I, L) shrinkage are an exception, showing a lower variability among these plots (Table 8). Therefore, in these cases, the characteristics of the sites seem to affect the variability.

Considering the results of the nonparametric tests in detail, we can see that the coefficient of shrinkage has a similar behavior compared to total shrinkage. However, the different plots react towards the coefficient of shrinkage as if they belonged to different statistical populations, showing a significant variability especially among sites. Unlike the density that does not seem to be affected by plots, this is not so unambiguous regarding shrinkage. Comparing these results with climate, soil and dendrometric characteristics of the site discloses no factor that could explain such behavior.

Density has a fairly close relationship with the morphology and ring width. According to Badel and Perré (2007) the morphology of xylem tissue could explain a large part of the variability of shrinkage of deciduous oaks, because their anatomy is the result of "genetic fingerprinting" of both physiological conditions of trees and site conditions. But a poor correlation between density and shrinkage was noted in our study. In fact, Zhang et al. (1995) stated that although shrinkage is governed by the structure and chemical composition of wood, density is not always a good estimator of shrinkage.

4.3 Water content

As firewood, the moisture content of wood, a few days after cutting, is a key factor. We have noticed a change in moisture among the maximum values of the various sites up to 40% (maximum moisture content ranging from 76% to 125%, corresponding to water content of 43%–56%), because of different sampling periods (November–April). These variations can be attributed to the physiological state of the tree. The water content is an important parameter of quality in case of firewood, affecting the weight of the wood during logging operations. The water content also can affect the amount of heat to be supplied for ignition, the production in terms of energy and the preservation of material that can be bio-deteriorated. Parameters of moisture and density or basic density with the heating value and ash content are elements of the calculation of the fuel value index (FVI), useful to compare firewood species (Chettri and Sharma, 2009). According to Abbot and Lowore (1999), an even "more parsimonious" FVI can be described as the ratio between basic density and moisture content because of the small variation in heating value and ash content of the different species for firewood.

5 Conclusions

The study analyzed some physical characteristics of Turkey oak wood from different coppice forests in Central Italy. Particularly, we examined the density in order to study its variability both within the plots and the entire experimental sample population.

The correlation of density with moisture and water content was examined in order to understand the statistical behavior of the species. The same procedure was applied to basic density. The statistical density trends are confirmed by a good R^2 value, although not for the basic density. However, being a parameter for quick energy evaluation, it may also be a starting point for technical uses based on data validated by experimental tests.

Other physical parameters were analyzed, such as shrinkage (volumetric, tangential and radial) and the coefficient of shrinkage. Its variability within each plot and then in the entire sample population were also studied. In this case there is a higher variability in shrinkage than in density. By examining the statistical Kruskal-Wallis test in the plots (data not shown), it is clear that the characteristics of the plot can affect the shrinkage of wood, principally the tangential shrinkage. Variability in volumetric and radial shrinkage were much lower and the statistical test results reveal that the samples are of the same statistical population within the plots, while among different plots the variability is statistically significant. Similar results were also achieved by analyzing statistical shrinkage coefficients.

Variability in moisture and water content was studied with the aim of identifying trends that could summarize the behavior of the species.

These physical parameters investigated play an important role in firewood destinations. In this field accurate estimates of mass, volume, energy content and moisture are mostly required. For economic reasons or for a lack of accurate analysis, generic bibliographical data are often used for the estimation of xylo-energy content of wood from coppice. This work can supply some additional information to improve the xylo-energy estimates for small and medium forest populations, which Turkey oak coppices usually are.

References

Abbot P G, Lowore J D. 1999. Characteristics and management potential of some indigenous firewood species in Malawi. Forest Ecol Manage, 119: 111–121

Ackermann F. 1995. Relationship between forest site and intra-ring wood density components for the pedunculate oak (*Quercus robur* L.) of southwestern France. Ann Sci Forest, 52: 635–652 (in French with English abstract)

Acuna M A, Murphy G. 2006. Geospatial and within tree variation of wood density and spiral grain in Douglas-fir. Forest Prod J, 56(4): 81–85

Badel E, Bakour R, Perré P. 2006. Investigation of the relationships between anatomical pattern, density and local swelling of oak wood. IAWA J, 27(1): 55–71

Badel E, Perré P. 2007. The shrinkage of oak predicted from its anatomical pattern: validation of a cognitive model. Trees, 21: 111–120. DOI 10.1007/s00468-006-0105-z

Becker M, Claude R F, Schipfer R. 1979. Une étude phyto-écologique sur les plateaux calcaires du Nord-Est (Massif de Haye-54). Utilisation de l'analyse des correspondances dans la typologie des stations. Relations avec la productivité et la qualité du hêtre et du chêne [A phyto-ecological study in the calcareous regions of N.-E. France (Forest of Haye-54). Use of factorial analysis of correspondences for site typology. Relationship with productivity and wood quality of beech and oak]. Ann Sci Forest, 36(2): 93–124 (in French with English abstract)

Bergès L, Dupouey J-L, Franc A. 2000. Long-term changes in wood density and radial growth of *Quercus petraea* Liebl. in northern France since the middle of the nineteenth century. Trees, 14: 398–408. DOI 10.1007/s004680000055

Bergès L, Nepveu G, Franc A. 2008. Effects of ecological factors on radial growth and wood density components of sessile oak (*Quercus petraea* Liebl.) in Northern France. Forest Ecol Manage, 255: 567–579

Bernetti G. 1995. Selvicoltura Speciale. Torino, Italy: UTET, 415 (in Italian)

Berti S, Corona P. 1983. Possibilità di impiego del legname di cerro in Italia: principali caratteristiche fisco meccaniche del cerro del Gargano [Potential for utilisation of Turkey oak (*Quercus cerris* L.) wood in Italy: physical and mechanical properties of timber from south-eastern Italy]. Annali Accademia Italiana di Scienze Forestali, vol. XXXVII, 149–165 (in Italian with English abstract)

Berti S, De Luca L, Edlmann Abbate M L, Gambetta A, Orlandi E. 1991. Per una migliore utilizzazione del legno ritraibile dal bosco ceduo [For a better utilization of timber from coppie stands]. Contributi scientifico pratici, vol. XXXV (86), CNR IRL, Firenze, Italy (in Italian with English abstract)

Chettri N, Sharma E. 2009. A scientific assessment of traditional knowledge on firewood and fodder values in Sikkim, India. Forest Ecol Manage, 257: 2073–2078. DOI 10.1016/j.foreco.2009.02.002

Degron R, Nepveu G. 1996. Predicting intra- and intertree variability of wood density in sessile oak (*Quercus petraea* Liebl) through modelling earlywood and latewood width and density from cambial age, ring width and height in the tree. Ann Sci Forest, 53(5): 1019–1030 (in French with English abstract)

FAO. 2008. Statistical Yearbook 2007–2008. http://www.fao.org/economic/ess/ess-publications/ess-yearbook/fao-statistical-yearbook-2007-2008/en/. Accessed 10 Jan 2011

Giordano G. 1981. Tecnologia del Legno (Wood Technology). vol. I. Torino, Italy: UTET (in Italian)

Giordano G. 1990. Classificazione delle Specie Legnose per Destinazione d'Impiego (Classification of Wood Species for Destination of Use). Firenze, Italy: Tipografia Giuntina (in Italian)

Guilley É, Hervé J-C, Huber F, Nepveu G. 1999. 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 Sci Forest, 56: 449–458

Guilley É, Hervé J-C, Nepveu G. 2004. The influence of site quality, silviculture and region on wood density mixed model in *Quercus petraea* Liebl. Forest Ecol Manage, 189: 111–121

Guilley E, Nepveu G. 2003. Anatomical interpretation of the components of a wood density mixed model in sessile oak (*Quercus petraea* Liebl.): ring number from the pith, ring width, tree, interannual variation, heartwood formation. Ann Sci Forest, 60(4): 331–346 (in French with English abstract)

IFNC. 2007. Inventario Nazionale delle Foreste e dei serbatoi forestali di Carbonio (anno di riferimento 2005) [National Inventory of Forests and Forest Carbon stock (reference year 2005)]. Ministero delle Politiche Agricole, Alimentari e Forestali, Rome, Italy (in Italian)

ISO 3129. 1975. Wood. Sampling methods and general requirements for physical and mechanical tests

Kennedy R W. 1995. Coniferous wood quality in the future: concerns and strategies. Wood Sci Technol, 29: 321–338

Macdonald E, Hubert J. 2002. A review of the effects of silviculture on timber quality of Sitka spruce. Forestry, 75(2): 107–138

Le Moguédec G, Dhôte J-F, Nepveu G. 2002. Choosing simplified mixed models for simulations when data have a complex hierarchical organization. An example with some basic properties in Sessile oak wood (*Quercus petraea* Liebl.). Ann Sci Forest, 59: 847–855

Nardi Berti R. 1993. La struttura anatomica del legno ed il riconoscimento dei legnami italiani di più corrente impiego (The anatomical structure of wood and the identification of Italian timber of more diffuse use). Contributi Scientifico Pratici., vol. XXIV. Consiglio Nazionale delle Ricerche, Istituto del Legno, Firenze, Italy (in Italian)

Picchio R, Maesano M, Savelli S, Marchi E. 2009. Productivity and energy balance in conversion of a *Quercus cerris* L. coppice stand into high forest in Central Italy. Croat J Forest Eng, 30(1): 15–26

Sheskin D J. 2000. Handbook of Parametric and Nonparametric Statistical Procedures. 2nd edn. London: Chapman & Hall/CRC, 982

Sprent P, Smeeton N C. 2001. Applied Nonparametric Statistical Methods. 3rd edn. London: Chapman & Hall/CRC, 461

Timbal J, Aussenac G. 1996. An overview of ecology and silviculture of indigenous oaks in France. Ann Sci Forest, 53: 649–661

UNI 3252. 1987. Wood. General requirements for physical and mechanical tests

UNI EN 13183-1. 2003. Moisture content of a piece of sawn timber. Determination by oven dry method

UNI ISO 3130. 1985. Wood. Determination of moisture content for physical and mechanical tests

UNI ISO 3131. 1985. Wood. Determination of density for physical and mechanical tests

UNI ISO 4469. 1985. Wood. Determination of radial and tangential shrinkage

UNI ISO 4858. 1988. Wood. Determination of volumetric shrinkage

Uzielli L. 1989. Valorizzazione tecnologica del legno di cerro (Technological valorization of Turkey oak wood). L'Italia Forestale e Montana, 46(3): 222–237 (in Italian)

Walker J C F. 2006. Primary Wood Processing. Principles and Practice. 2nd edn. Dordrecht, Netherlands: Springer

Zanuttini R. 1992. Valorizzazione del legname di cerro: risultati relativi ad alcuni aspetti tecnologici (Valorisation of Turkey oak timber: results for some technological aspects). Cellulosa Carta, 43(2): 39–43 (in Italian)

Zar J H. 1999. Biostatistical Analysis. 4th edn. New Jersey: Prentice Hall, Upper Saddler River

Zhang S Y, Nepveu G, Mothe F. 1994a. Modeling intratree wood shrinkage in European oak by measuring wood density. Forest Prod J, 44: 42–46

Zhang S Y, Nepveu G, Owoundi R E. 1994b. Intratree and intertree variation in selected wood quality characteristics of European oak (*Quercus petraea* and *Quercus robur*). Can J Forest Res, 24: 1818–1823

Zhang S Y, Owoundi R E, Nepveu G, Mothe F. 1995. Modelling wood shrinkage and simulating the silvicultural influence in European oak (*Quercus petraea* and *Quercus robur*). Holzforschung, 49: 35–44

Zhang S Y, Owoundi R E, Nepveu G, Mothe F, Dhôte J F. 1993. Modelling wood density in European oak (*Quercus petraea* and *Quercus robur*) and simulating the silvicultural influence. Can J Forest Res, 23: 2587–2593

(Received February 23, 2011 Accepted April 6, 2011)