Wood Quality of Chestnut: Relationship between Ring Width, Specific Gravity, and Physical and Mechanical Properties

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This article investigates the relationships between ring width (expressed as ring width class) and cambial age (expressed as chronological class) with specific gravity, modulus of rupture (MOR), compressive strength, and shrinkage. On those stands located on volcanic soils, it was found that when moving from the first ring width class (≤2 mm) to the seventh class (≥7 mm), a total decrease in specific gravity of 12.7% was observed, accompanied by a 19.5% decrease in compressive strength and a 22.8% decrease in MOR. With an increase in tree age, as expressed by the chronological class, there was a general decrease in the values of specific gravity, MOR, and compressive strength. It was therefore determined that chronological class is related to ring width, while specific gravity can predict MOR and compressive strength values for trees grown at volcanic sites. The results for a stand grown on calcareous soils showed a different trend. Furthermore, it was confirmed by cross-variance analysis that there was a correlation between ring width and chronological class.

Keywords: MOR; Shrinkages; Specific gravity; Compressive strength; Wood quality

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INTRODUCTION

Wood quality is a complex concept that incorporates various aspects related to wood defects, wood anatomy, and the physical and mechanical properties of wood. These aspects can be interrelated. For example, the physical and mechanical properties are often highly related to wood defects such as ring shake in chestnut (Spina and Romagnoli 2010; Romagnoli and Spina 2013). For a long time, foresters have attempted to identify easily measured parameters that could be good predictors of wood quality. Among these, wood density is considered a very important attribute because it is known to influence several physical and mechanical properties of the material (Genet *et al.* 2013). In particular, wood density affects the wood workability and mechanical strength (Giordano 1984; Tsoumis 1991), as well as other characteristics such as wood health and durability (Humar *et al.* 2008). Exploring the links between wood density and the growth rate of trees is therefore an important research topic.

The growth rate, which can be determined from an assessment of ring width in cores extracted by a Pressler increment borer, could prove to be an advantageous indicator of wood quality. Furthermore, it may be possible to use ring width to predict wood density and other parameters related to growth rate, such as the microfibril angle

(Auty *et al.* 2013), along with mechanical properties such as modulus of elasticity (MOE) and modulus of rupture (MOR) (Zhang 1995; Dunham *et al.* 1999; Lasserre *et al.* 2009; Schneider *et al.* 2008). Correlations between wood density and ring width are not readily predictable. Research on conifers suggests that there may be possible correlations between wood density and cambial age (Guller *et al.* 2011, 2012), and that these parameters are related to site conditions and climate (Drew *et al.* 2013; Ikvovic *et al.* 2013). Cambial age, therefore, may play a major role in the relationship between wood density and ring width. In much of the literature on conifers, wider growth rings are associated with lower wood densities because the percentage of earlywood was higher; hence, in forest plantations, the annual rings of logs should not be too widely spaced (Kubojima *et al.* 2008). In diffuse porous hardwoods, both positive and negative correlations were found between ring width and density; yet in some cases, no correlations were found (Zeidler 2012; Skarvelis and Mantanis 2013).

Many other studies have shown that density is related to additional variables associated with wood anatomy, which are not reflected in either ring widths (Wimmer 1995; Rathgeber *et al.* 2006) or the percentage of latewood (Adamopoulos *et al.* 2009). The growth rate of ring-porous hardwoods, which is expressed as ring width, has been positively correlated to wood density, *i.e.*, wider growth rings are associated with higher wood densities (Zobel and Van Bujten 1989; Dobrowolska *et al.* 2011). These findings were attributed to the fact that the earlywood zone was nearly constant from year to year and the wider rings contained higher contents of dense latewood with fewer vessels (Zobel and Sprague 1998; Zobel and Van Bujten 1989; Adamopoulos *et al.* 2010a). However, a few studies suggest that this relationship is sometimes neither significant (Adamopoulos *et al.* 2010b) nor predictable because of the influence of silvicultural management, variations due to the position inside the tree (Adamopoulos and Voulgaridis 2002), differences in cambial age, and other factors that can modify the expected correlation. Nevertheless some authors (Guilley *et al.* 2004, Bouriaud *et al.* 2004), were able to elaborate a model.

The object of the present investigation is chestnut, an economically important species in the Lazio region in Italy. The goal is to study the correlations of ring width (RW) and cambial age (expressed by chronological class) with specific gravity, shrinkages, and mechanical strength, and the correlations between density and shrinkages and mechanical properties. From this research, it may be possible to identify those parameters related to the growth rate of a tree that can be directly used in forests to predict wood quality. It is also possible that such research may be able to assess the effect of growth rate on more than just the microfibril angle (Auty *et al.* 2013) or the ratio of modulus of elasticity to modulus of rupture (MOE/MOR) (Dunham *et al.* 1999; Lasserre *et al.* 2009; Schneider *et al.* 2008, *etc.*).

Because chestnut is a ring-porous species, the results are subsequently compared with the few references available regarding either chestnut wood (Fioravanti 1999; Adamopoulos *et al.* 2010b), or similar hardwood species in comparable study situations.

EXPERIMENTAL

Materials and Methods

The study was carried out on chestnut trees collected from seven sites in Lazio, Italy. These sites belong to four different regions of high productivity: Cimini Mountains

(A), Sabatini Mountains (B), Castelli Romani (C), and Lepini Mountains (D). The site characteristics have been described in detail in previous reports (Spina and Romagnoli 2010; Romagnoli and Spina 2013). A notable difference in these sites is that the Cimini Mountains, Sabatini Mountains, and Castelli Romani are all located on volcanic soils, whereas the Lepini Mountains are located on a calcareous substrate.

After four months of seasoning, important physical and mechanical characteristics of the wood were measured in accordance with the UNI ISO 3130, 3131, 3133, 3787, and 4469 protocols (1985). Disks were prepared with strips along the length of the radius being marked in 2 cm increments. Specimens measuring 2 × 2 × 3 cm were used to measure shrinkage, specific gravity by the gravimetric method, and compressive strength in the axial direction. For measurement of the MOR (*i.e.*, bending strength), samples measuring 2 × 2 × 30 cm were used. Several physical and mechanical characteristics representative of each site and of the total region have been reported in a previous investigation (Romagnoli and Spina 2013); these characteristics were distinguished in both sound and shaken trees. For this investigation, only the wood specific gravity at a moisture content of 12% ($\rho 12$), tangential and radial shrinkages (βt, βr), axial compressive strength (σ12), and static MOR were determined.

For each of the specimens prepared for measuring physical and mechanical properties, the number of rings present was counted within a 2 × 2 cm surface area. The ring width was the estimated by the ratio between the radial size of the specimen (2 cm) and the number of rings visible on the cross-cut. Specimens were excluded from further analyses when the rings could no longer be regarded as almost complete, and thus the analysis was carried out only on those samples without defects. The specimens were next divided into seven classes according to their average ring width, and the cambial age of each specimen was then measured. Afterwards, the samples were divided according to their cambial age class, as reported in Table 1.

Table 1. RW Class Number and Corresponding Interval of Ring Width, along with the Chronological Class and Corresponding Interval of Tree Age

RW Class	Ring width Mm	Chronological class	Age Years
1	≤ 2	3	11-15
2	2-3	4	16-20
3	3-4	5	21-25
4	4-5	6	26-30
5	5-6	7	>31
6	6-7		
7	≥ 7		

The decision was made that rings below 10 years of cambial age would not be taken into account, in order to limit juvenile wood effects. Hence, the cambial age class begins with Class 3 rather than Class 1 in the following analysis. The ring width and chronology class were treated as independent variables in statistical analyses. Analysis of variance (ANOVA) was used to test whether or not the dependent variables of density ($\rho 12$), tangential and radial shrinkage (βt and βr), compressive strength (σ), and MOR were significantly related to ring width or chronology class. Fisher test values (F) and the corresponding values of $p<0.05$ (*), $p<0.01$ (**), and $p<0.001$ (***) were determined, and the Kolmogorov-Smirnov test was used to verify which ring width class was significantly different from the others.

Cross-variance testing, which takes into account the interactive effect of chronology class and ring width, was also performed using ANOVA analysis. This analysis also took into account whether the samples were nested within trees according to their ring width class within a given chronological class. However, these results proved to be insignificant, and thus this variable was not considered in further analysis. A general linear model was also performed in order to estimate each physical and mechanical parameter according to the ring width and chronological class.

To transpose the results obtained from these specimens to the typical parameters used by foresters in the field, trees of comparable ages (25 to 30 years) were considered, and their diameter at breast height was measured. This measurement, however, was not possible to perform at any site other than Site A. The trees were then divided into seven diameter classes: 0–20, 21–25, 26–30, 31–35, 36–40, and >40 cm. The average values of specific gravity, tangential and radial shrinkages, compressive strength, and MOR for each of the trees were compared. A variance analysis of the physical-mechanical characteristics of the wood was taken into account, using the diameter class as an independent variable. The results of this analysis may therefore be considered a further approach to estimate the growth rate of a tree.

RESULTS

Effect of Ring Width and Chronological Class on Physical and Mechanical Parameters

The values for the physical and mechanical properties within each region have been previously reported (Romagnoli and Spina 2013). These results show that the physical and mechanical properties vary according to the site of origin. In Table 2, the average specific gravity at 12% moisture, tangential and radial shrinkage, compressive strength, and MOR are reported, along with the number of specimens represented in each average ring width class and the chronological class for each site.

The highest density value of 666 kg/m^3 was found in the Lepini Mountains (Site D), while the lowest density value of 586 kg/m^3 was found in the Cimini Mountains (Site A). The highest MOR value of 117 MPa was found in the Sabatini Mountains (Site B), and the lowest MOR value of 76 MPa was found in the Castelli Romani (Site A). On average, the highest shrinkage was found in the Sabatini Mountains (Site C), and the lowest value was found in the Lepini Mountains (Site D). Although there are no average ring widths for these samples, the specimen data used to measure specific gravity by gravimetric methods were inserted in Table 1 so as to place each specimen in a chronological class.

As can be seen from Table 2, the fifth ring width class was lacking at all sites, while the most represented ring width classes were the third and fourth. The Castelli Romani site had the highest number of specimens located in the sixth class.

The results from the ANOVA analysis (Fig. 1) show the effect of ring width class on density values. A significant decrease in density can be observed with increasing ring widths at Sites A and C; however, a different behavior was observed at Site D, which is located on a calcareous substrate. At Site D, increases in density were associated with an increase in ring width up to a threshold of ring width class 6 (6 to 7 mm), but above class 6, a decrease in density is observed.

Table 2. Mean Values (mv) and Standard Deviations (sd) of Each Physical and Mechanical Property

SITE	ρ_{12} (kg/m^3) mv±sd	σ_{12} (N/mm^2) mv±sd	MOR (N/mm^2) mv±sd	β_R % mv±sd	β_T % mv±sd	RW class (n. specimen of each class)	Chronological class (n. specimen of each class)
A	586.39±48	45.58±6	85.05±15.48	2.87±0.62	6.80±0.86	1(13), 2(28), 3(36), 4(45), 6(17), 7(3)	3(46), 4(50), 5(30), 6(7), 7(9)
B	626±95	57.38±8	117.06±17.79	3.21±0.75	6.81±0.86	1(8), 2(29), 3(64), 4(24), 6(11)	3(67), 4(52), 5(16), 6(2)
C	612.90±62	49.31±8	72.55±15.38	3.79±0.82	6.55±0.97	1(10), 2(25), 3(37), 4(33), 6(18), 7(7)	3(45), 4(52), 5(20), 6(11), 7(2)
D	666.43±46	54.0±6	97.71±16.23	3.04±0.66	5.85±1.01	1(4), 2 (21), 3 (22), 4 (15), 6 (7), 7(9)	2(1),3(28),4(17), 5(16), 6(10), 7(6)

Numbers in brackets represent the number of investigated specimens for each RW class and each chronological class.

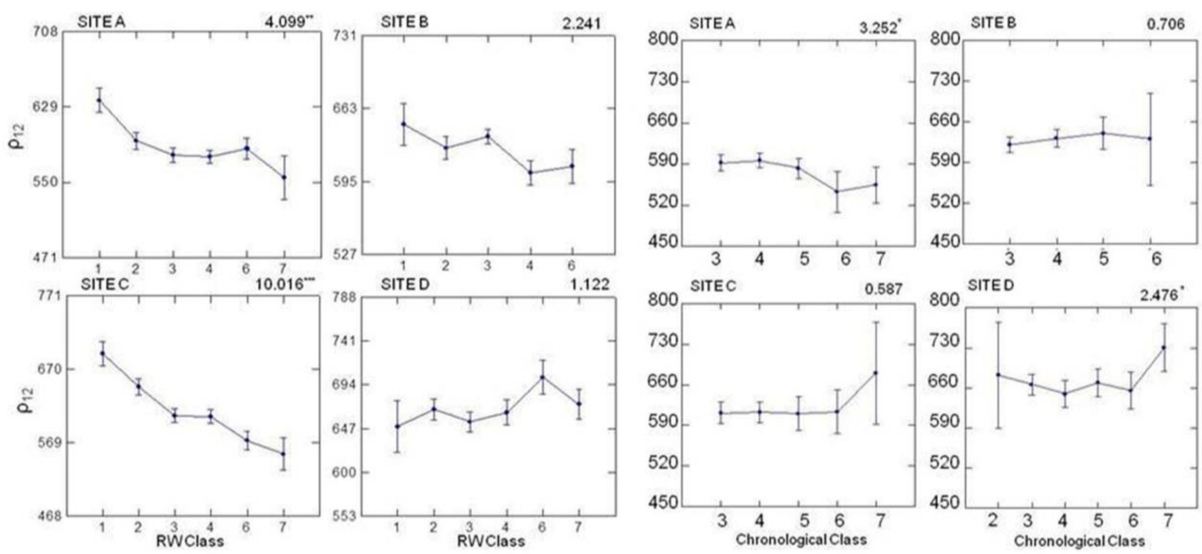

Fig. 1. ANOVA analysis of ring width (RW) class and chronological class showing the effect on specific gravity at Site A-Cimini Mountains, B-Sabatini Mountains, C-Castelli Romani, and D-Lepini Mountains. The numbers above the graphs are F values with significant probability: * p<0.05, ** p<0.01, *** p<0.001.

In this study, an increase in the ring width class is associated with a decrease in compressive strength and MOR at Sites A and C, while significant decreases were only observed in compressive strength at Site D (Fig. 2).

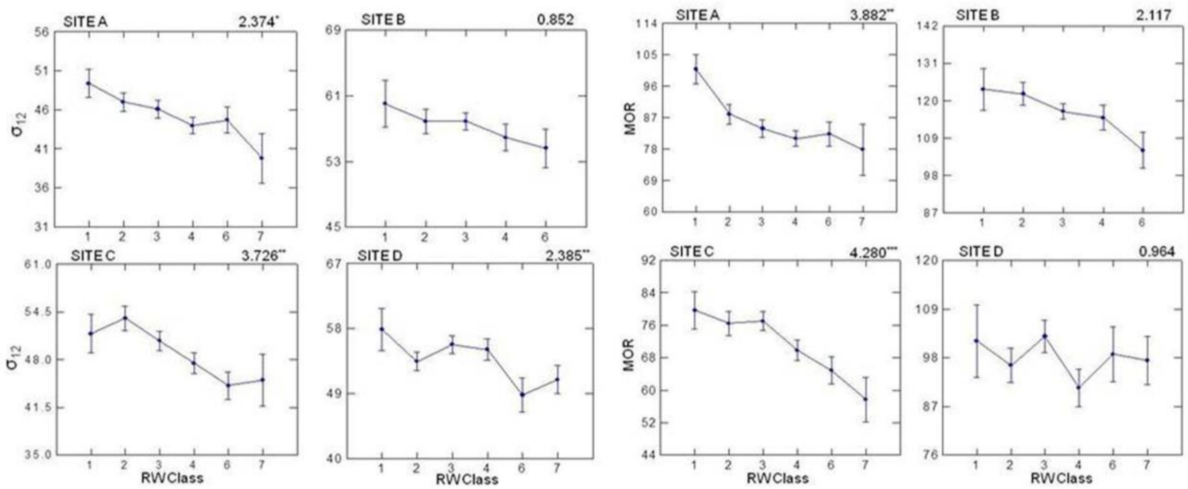

Fig. 2. ANOVA analysis of the effect of ring width (RW) class on compressive strength and MOR. The numbers above the graphs are F values with significant probability: * p<0.05, ** p<0.01, *** p<0.001.

Most studies of ring-porous hardwoods have shown frequent positive correlations between ring width and density (Zhang *et al.* 1993; Zobel and Van Bujten 1989; Guilley *et al.* 1999). Although divergences from this trend have been observed in the past (Zobel and Van Bujten 1989), further studies have shown that ring width relationships can depend on many other factors. Foremost among these is management, and both Sites A and C are characterized by high growth rates initiated via coppice management.

The results of this study are somewhat in agreement with data obtained on plantation-grown *Quercus rubra*; while in mature natural stands of the same species, some positive correlations were observed (Genet *et al.* 2013). In chestnut from sites in Greece (Adamopoulos *et al.* 2010a) and from other coppice stands in the Tuscany region in Italy (Fioravanti, 1999), the data shows a decreasing trend in density over a threshold of 6 mm in ring width. This is exactly the result that was obtained from Site C on volcanic soil, where the most evident decreasing trend in density, which is also significant from a statistical point of view, started from e ring width class of 6 mm. The effects of forest management practices were similarly not negligible in diffuse-porous hardwood. For example, studies of coppiced *Betula pubescens* trees revealed a higher growth rate than seed-originated birches, though the management technique only caused minor differences in density that were insignificant with regards to industrial use (Luostarinen *et al.* 2009). Similar results, though lacking in statistical significance, were also observed in hornbeam (Samariha 2011), cherry (Nocetti *et al.* 2010; Nocetti *et al.* 2012), and yellow poplar (Mettanurak *et al.* 2010).

Coppice management cannot be the only reason for this high growth rate, because the relationship between ring width and density shows little difference in behavior at Site

D that is also coppice managed, but stands on a calcareous substrate. The results therefore reveal a complexity in the relationship between ring-width and density in chestnut: the site characteristics, in this case related mainly to the soil and high growth rate of coppice management, play an important role in determining such correlation.

If one looks at the decreasing trend in density with increasing growth rate, one cannot exclude the possibility that it is influenced by the analytical methods used. In the literature, the relationship between density and ring width are typically investigated by means of X-ray densitometry, which allows detection of annual and inter-annual variability. Conversely, the methods used in this study were more focused on detecting large variations in wood quality that could affect its practical utilization, than on single ring widths or annual growths; therefore, it is expected that the information obtained differs from that obtained by X-ray densitometry.

The unexpected negative correlations between ring width and wood density observed at some sites of this investigation may possibly be explained by the effect of morphological anatomical parameters that can cause variations in wood density. Consequently, ring width may not be sufficient to explain variations in wood density, even when it is related to the width or percentage of earlywood and latewood (Wimmer 1995). That has been observed by Fioravanti (1999) to be the case in chestnut, in which decreasing density values explained anatomically by a lower cell wall thickness and the proportion of latewood alone could not explain the density variation.

The effect of chronological class on density was less pronounced than that due to ring width class, and general trends were difficult to detect. The most significant results were again seen at Site A, where decreases in density were associated with increases in the chronological class. A similar behavior was observed at Site D, but here additional increases in the higher chronological class were observed. Chronological class, *i.e.*, tree age, takes into account the process of wood maturation, which is crucial when evaluating juvenile and mature wood (Zobel and van Bujten 1989; Zhang and Zhang 1991; Adamopoulos *et al.* 2011). Many of the difficulties that can be associated with age variations due to juvenile wood were avoided in this study by excluding specimens with cambial ages of less than 10 years from analyses, and this explains why only a minimal influence of chronological class on density was observed. At Site D, however, an increase in the density of the highest chronological class was observed because of wood maturation.

The correlation between ring width and mechanical properties may be related by the effect of ring width on density, especially when we consider the agreement among the experimental results of ring width-density-mechanical properties for Sites A and C. In site D, the ring width seems to have had a more direct effect on mechanical properties than on the density values. This result can be compared with that obtained in poplar trees, where the effects of growth suppression and release can be seen more readily in the mechanical properties than in the specific gravity (Mettanurak *et al.* 2010).

The effects of ring width class on shrinkage were significant only with respect to the tangential direction at Site A. Compared to the results obtained by ANOVA for density and mechanical properties, the correlation between ring width and shrinkage was less significant, and no specific trends were readily apparent (data not shown). This can be compared with results obtained with *Carpinus betulus*, where it was shown that some environmental factors that can interact significantly with growth rate do not have any significant effect on the physical properties of wood, such as shrinkage (Samariha *et al.* 2011).

Chronological class was found to have a significant effect on compressive strength and MOR at Site A (Fig. 3). It also had a significant effect on MOR at Site D, whereby increases in the chronological class were associated with lower MOR values until class 7, after which the mechanical properties actually increased. These trends were particularly apparent in class 4 and above (≥4 mm).

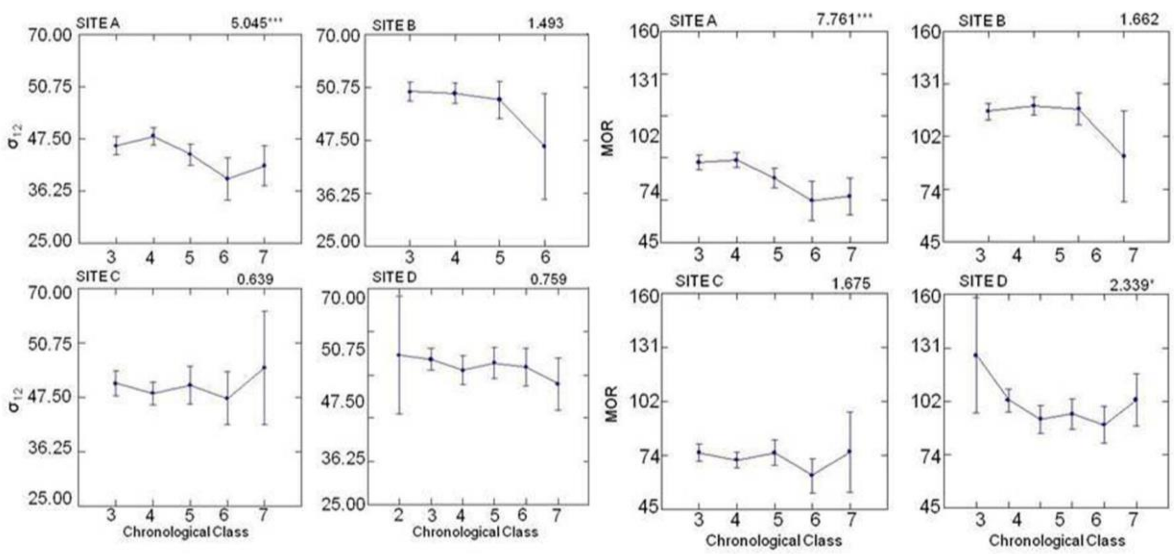

Fig. 3. ANOVA analysis of the effect of chronological class on compressive strength and MOR. The numbers above the graphs are F values with significant probability: * $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Overall, the trends of the compressive strength and MOR curves were more similar for all sites other than Site D, where the trend of both compressive strength and MOR was every different. No relationships were found between chronological class and shrinkage values. Fluctuations in density due to chronological class have also been shown to be related to whether the tree stands were natural or managed (Genet *et al.* 2013).

In Table 3, the results of the Kolmogorov-Smirnov test show that the physical and mechanical parameters of each ring width class differed significantly from each other. At Site A, the most remarkable difference was observed for parameters starting at Class 2 and above. At the second ring width class, the density decreased significantly; meanwhile, above the second ring width class, a significant decrease in compressive strength and MOR were also observed. At Site B, changes were apparent by Class 4 when the density is compared to Class 2. At Site C, a significant decrease in mechanical properties by Class 4 was observed with respect to Class 1 and 2, while density changes were significant for Class 3. Much greater variability was observed for the correlations with ring width at Site D, although increases in density with ring width were also observed.

The analyses carried out on the wood samples were comparable with experiments carried out through the measurement of a standing tree, where in the diameters were grouped by diameter class. In Fig. 4, decreases in density and other mechanical properties are apparent as the diameter of trees comparable in age (25 to 30 years) is increased (*i.e.*, a higher growth rate).

Table 3. Matrix of Significant Differences According to Kolmogorov Smirnov Test among each RW Class for Each Site

SITE A					
RWClass	1	2	3	4	6
2	ρ_{12}^{*}	X	X	X	X
3	ρ_{12}^{**} MOR^{*}		X	X	X
4	ρ_{12}^{***} σ_{12}^{*} MOR^{**} β_T^{*}			X	X
6	ρ_{12}^{**} MOR^{*}				X
7	σ_{12}^{*} MOR^{**}				

SITE B					
RWClass	1	2	3	4	6
2		X	X	X	X
3			X	X	X
4		ρ_{12}^{*}		X	X
6		β_R^{*}			X
7					

SITE C					
RWClass	1	2	3	4	6
2		X	X	X	X
3	ρ_{12}^{***}	ρ_{12}^{*}	X	X	X
4	ρ_{12}^{***}	σ_{12}^{*} MOR^{*}	σ_{12}^{*}	X	X
6	ρ_{12}^{***} σ_{12}^{**} MOR^{*}	ρ_{12}^{***} σ_{12}^{***} MOR^{***}	σ_{12}^{*}		X
7	ρ_{12}^{**} σ_{12}^{*} MOR^{***}	ρ_{12}^{**} σ_{12}^{*} MOR^{***}	ρ_{12}^{*} MOR^{*}	ρ_{12}^{*} MOR^{*}	MOR^{*}

SITE D					
RWClass	1	2	3	4	6
2		X	X	X	X
3	β_T^{*}		X	X	X
4	β_T^{*}			X	X
6	β_T^{*}		ρ_{12}^{*}	σ_{12}^{*}	X
7					

Parameters differing significantly at $p<0.05$ (*), $p<0.01$ (**), and $p<0.001$ (***) are reported for each RW class

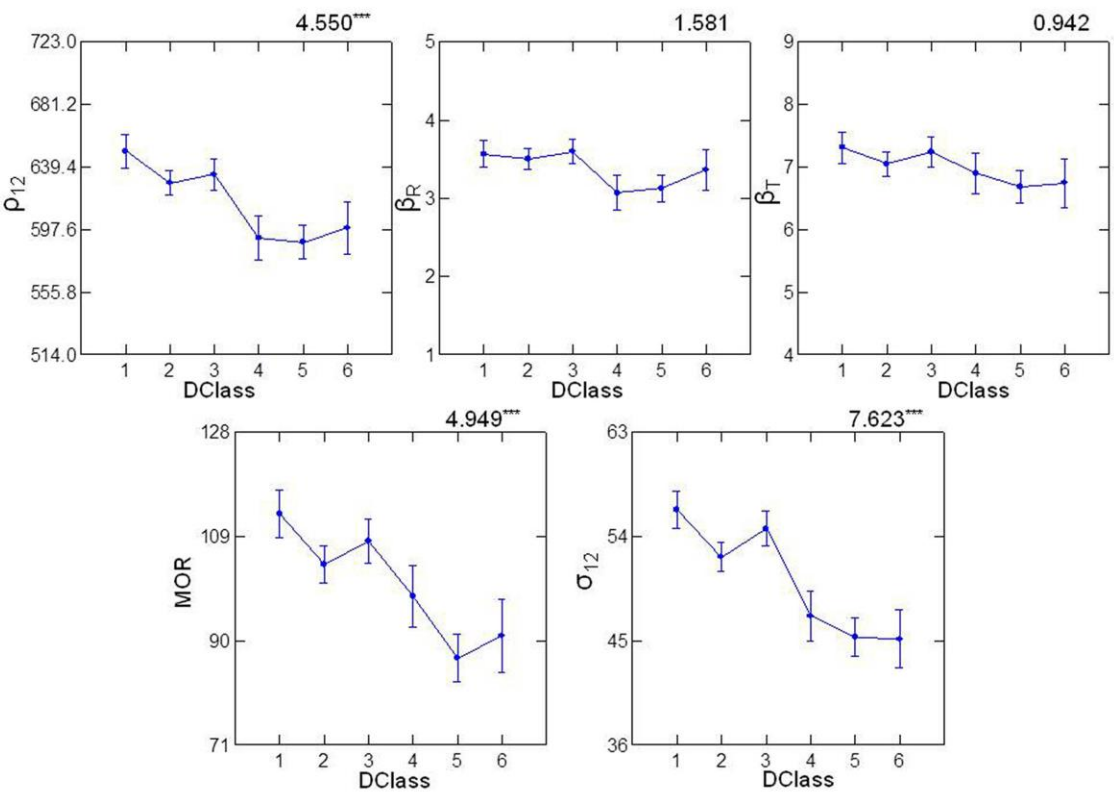

Fig. 4. ANOVA analysis of the effect of diameter class on physical and mechanical properties of whole trees aged 25–30 years at Site A

The obtained results are remarkable if one takes into account their effects on the decision of the stakeholders, who require quick and effective predictors for assessing wood quality. Ring width is a well-known parameter that may be useful for foresters because it is very easy to measure and it is sometimes already known for certain geographic locations. The results obtained in this investigation suggest that increases in diameter are associated with significant decreases in specific gravity, MOR, and compressive strength. The graphs also suggest that there is a threshold near the fourth diameter class (≥35 cm), where there is a change in the mechanical performance of trees with a comparable age of 25 to 30 years.

During the course of typical forestry operations for chestnut, trees are harvested at a specific age that is characterized site by site by a specific diameter. Therefore, the implications of wood quality (*i.e.*, density and mechanical properties) on this type of forest management system should be discussed in terms of stem diameter at harvest (Genet *et al.* 2013).

In order to provide an effective insight in this study, one should not neglect the fact that tree age is another parameter that can affect ring width variability and wood properties.

Ring width in forest trees usually decreases as the trees age, although deviations may occur because of soil and climatic conditions. Deviations may also have occurred in this study because of silviculture management practices, *e.g.*, after thinning there is a general increase in ring widths (Spina and Romagnoli 2010). For this reason, the correlations between RW and chronological class were taken into account by variance analysis, as shown in in Table 4.

Table 4. Cross Correlation by Anova Analysis of RW Class and Chronological Class

RW class x chronological class	β_R	β_T	ρ_{12}	σ_{12}	MOR
SITE A	1.66	1.534	3.953***	3.014***	4.068***
SITE B	3.016	0.798	1.037	4.909*	6.616**
SITE C	3.313	0.742	39.588***	20.766***	29.958***
SITE D	2.727	0.451	4.924*	11.123***	2,305

The F Value and the statistical probability at p<0.05 (*), p<0.01(**), p<0.001 (***) are reported for each physical and mechanical property

The cross-variance was significant at all of the investigated sites for compressive strength and density. Hence, chronological class and ring width act together to determine these properties. A significant cross-correlation between ring width and chronological class is expected, as it has been shown to be more prevalent in conifers (Park *et al.* 2009; Ivkovic *et al.* 2013); meanwhile, age has been used as a parameter to explain ring density variation in these species (Munoz and Anta 2010). Age also has also been shown to play an important role in ring-porous species such as chestnut and black locust, affecting the relationship between ring width and density (Adamopoulos *et al.* 2010b) in exactly the same manner as in this experiment.

Based on these results, a general linear model (GLM) was processed in order to estimate the physical and mechanical properties by the RW and chronological class. The results of the GLM are reported in Table 5.

Table 5. Coefficients of the GLM in Order to Estimate Each Parameter by RW, CC, and RW x CC

SITE A	β_R	β_T	ρ_{12}	σ_{12}	MOR	SITE C	β_R	β_T	ρ_{12}	σ_{12}	MOR
Constant	3.825***	7.595***	692.508***	64.691***	127.406***	Constant	4.305***	7.683***	655.192***	52.920***	112.017***
Chronological Class	-0.186	-0.098	-16.651	-3.279*	-6.881*	Chronological Class	-0.217	-0.329	7.303	0.864	-6.129*
Ring Width (RW)	-0.161	-0.241	-13.679	-2.982*	-4.214	Ring Width (RW)	-0.041	-0.201	-4.265	0.524	-6.907*
RW x Chronological class	0.034	0.031	0.718	0.343	0.055	RW x Chronological class	0.036	0.065	-4.116	-0.650	0.698
SITE B	β_R	β_T	ρ_{12}	σ_{12}	**MOR**	**SITE D**	β_R	β_T	ρ_{12}	σ_{12}	**MOR**
Constant	4.409***	7.634***	653.729***	73.466***	155.699***	Constant	3.370***	7.148***	630.278***	56.905***	96.755***
Chronological Class	-0.271	-0.176	-1.312	-3.465	-7.466	Chronological Class	-0.050	-0.319	3.801	0.194	0.850
Ring Width (RW)	-0.189	-0.222	-16.601	-3.233	-10.569	Ring Width (RW)	0.079	-0.074	0.175	0.570	3.811
RW x Chronological class	0.034	0.045	2.639	0.591	1.909	RW x Chronological class	-0.027	0.022	1.282	0.393	-1.089

The most significant results were obtained in the coefficients related to MOR and compressive strength for Site A, and MOR for Site C.

Correlations between Density-shrinkage and Density-mechanical Properties

Density was positively correlated with both mechanical properties and shrinkage. In Figs. 5 and 6, the scatter plots show an estimate of the physical and mechanical properties using the density values. These results suggest that at Sites A, B, and C, density can be used as a parameter to predict the MOR and compressive strength; the highest values were observed at Site A. A very different pattern was observed at Site D, where the estimates of physical and mechanical parameters were not significant.

Though density is the most widely used indicator for wood quality (Zobel and Van Bujten 1989), correlations between density and wood quality are not always obvious. In beech trees for example, density had a high correlation with static bending strength and hardness, while less correlation was found with compressive strength (Skarvelis and Mantanis 2013). In this investigation, density played an important role in influencing the mechanical properties, though the effects were found to be site-dependent because of a poor correlation with Site D.

From these results, one can infer that the ring width-density-mechanical properties correlation cannot always be used, as the mechanical properties of some sites are more directly related to ring width than to density. Zhang and Zhang (1991) speculated that the impact of growth rate on mechanical properties in a species could not be precisely estimated using the relationship between growth rate and specific gravity, as the growth rate may have an extra effect that is not delineated by specific gravity *per se*.

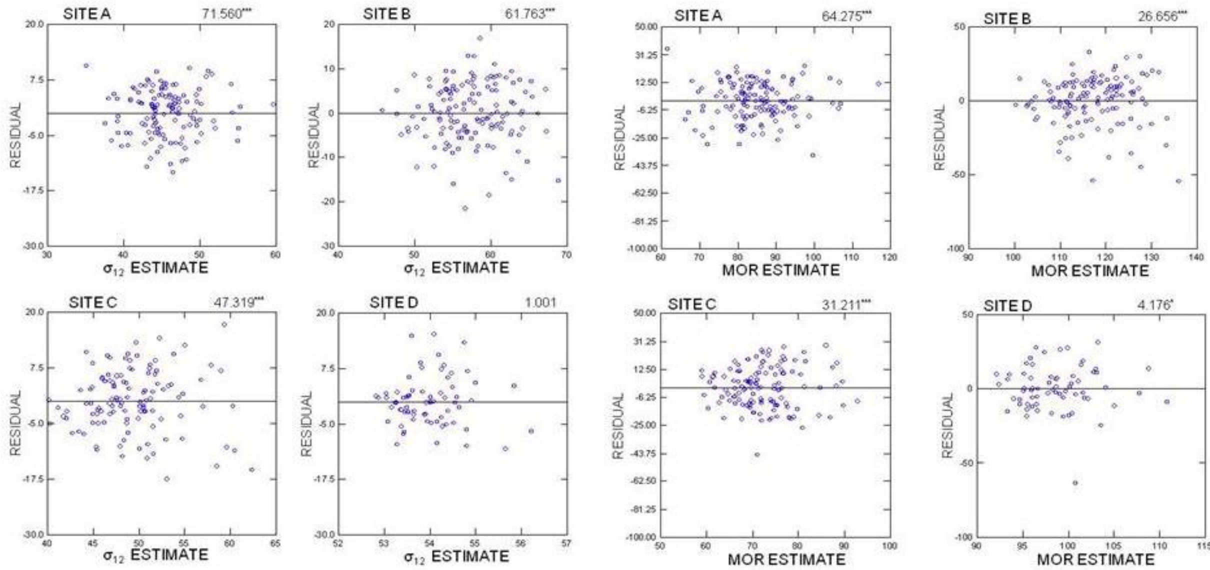

Fig. 5. Scatter diagrams showing the estimated effect of density on compressive strength (*σ*) and MOR

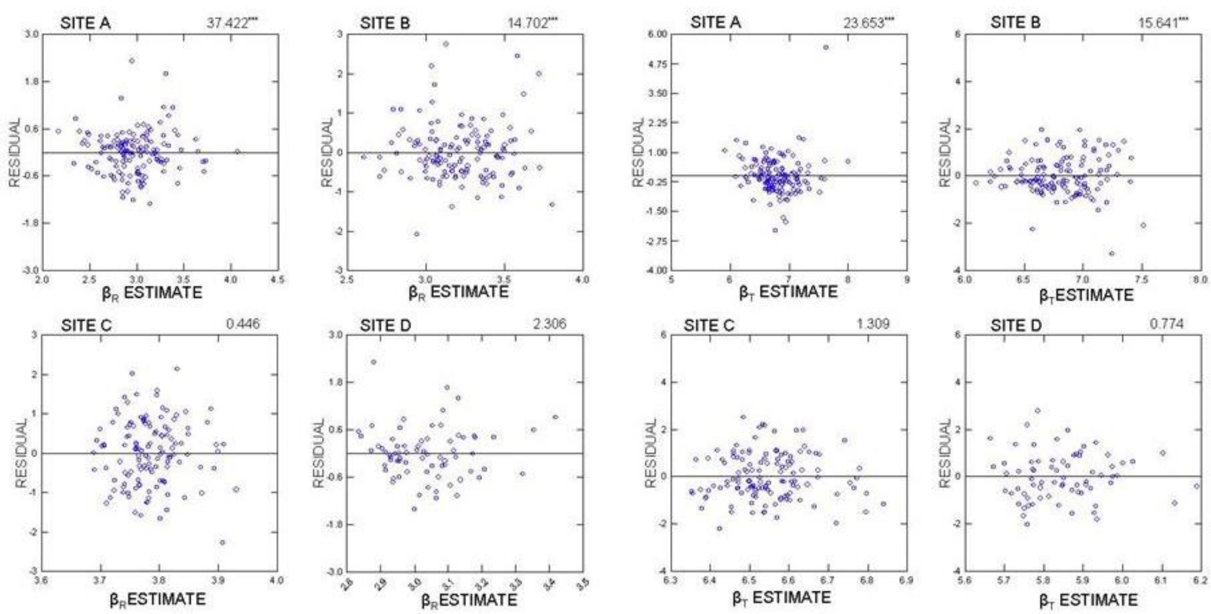

Fig. 6. Scatter diagram showing the estimated effect of density on radial (*βr*) and tangential shrinkages (*βt*)

Mettanurak *et al.* (2010) found that growth rate can have an additional effect on strength that is not entirely captured by specific gravity. A similar phenomenon was observed in this investigation, particularly in the case of Site D, and one can therefore assume that site conditions have an important effect, particularly with regards to the soil type. Site D (Lepini Mountains) was located on calcareous soil and the specific wood density was highest in this location.

Furthermore, even the chemical composition of the wood is different compared to the other sites (Vinciguerra *et al.* 2011). Trends in wood density were consequently different in this area, the density increasing with ring width up to Class 6 (7 mm), then decreasing in the larger class sizes. The result is comparable with that obtained in *Quercus petraea* by Berges *et al.* (2008), who demonstrated that the average density increased from acidic to less acidic sites. Hamilton *et al.* (1978) also found similar results for *Q. rubra* in that despite better radial growth on sandstone, oak wood density was higher in those trees sourced from calcareous soils.

Finally, it should be noted that this investigation indirectly provides further knowledge of ring-shake formation, as there is a relationship between ring shake and the parameters measured in this study. In previously published papers, it was shown that large growth ring values (Spina and Romagnoli 2010) and small MOR values (Romagnoli and Spina 2013) were associated with ring-shake formation and extent, although again, the site located on calcareous soil showed a different pattern of behavior than sites located on volcanic soils. This supports the necessity of developing specific gravity models that consider climatic variability and soil type (Drew *et al.* 2013).

CONCLUSIONS

1. As in chestnut coppice management, where ring width affects density and mechanical properties, it was verified that when moving from the first ring width class (≤2 mm) to the seventh (≥7 mm), a total decrease in specific gravity of up to 12.7 % was observed. Similarly, the decrease in compressive strength reached a maximum of 19.5 %, while the decrease in MOR was up to 22.8 %.

2. Specific gravity was found to have an important role in determining MOR and compressive strength, but a less important role in determining shrinkage values.

3. Ring width is sometimes more related to the mechanical properties than passing through specific gravity.

4. Site conditions were found to have a major influence on the relationships between the individual parameters. At Site D, which was located on calcareous soil, the effects of growth rate were non-linear and a threshold RW effect was present.

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