Effect of ring shakes on mechanical properties of chestnut wood from a Greek coppice forest

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ABSTRACT

Measurements of several mechanical and physical properties were carried out to detect possible variations between ring shaken and non-ring shaken logs or between different areas of wood from the same log (i.e., ring shaken log). Mature wood from the ring shake area had lower axial compression and hardness strength compared to mature wood away from ring shakes. Wood from ring shakes area had lower tangential swelling and precisely at the position of the shakes, the wood had a higher coefficient of anisotropy than the surrounding wood. The juvenile wood's density from the ring shaken logs was higher compared to that of mature wood, as well as proportional limit and hardness strength. From comparisons between ring shaken and non-ring shaken log properties, the following results were determined: mature wood from any area (independent of the presence of shakes) of ring shaken logs had lower Modulus of Rupture, proportional limits, modulus of elasticity under static bending, axial compression, toughness, and hardness strength compared to mature wood from non-ring shaken logs. Moreover, lower radial swelling was found for ring shaken logs. The juvenile wood's density from ring shaken logs was higher compared either to mature or to juvenile wood from non-ring shaken logs.

Keywords: ring shake, chestnut, wood defects, wood strength, mechanical/physical properties

RÉSUMÉ

On a effectué différentes mesures des propriétés mécaniques et physiques afin de tenter de trouver des différences entre les billes avec des roulures et celles qui n'en avaient pas de même qu'entre le bois pris à différents endroits sur la même bille (sur une bille avec des roulures). Le bois mature d'une partie affectée par la roulure montrait un niveau résistance axiale à la compression et une dureté inférieures à ceux du bois mature loin des zones de roulure. Le bois des zones roulées présentait un moins grand gonflement tangentiel et, au site de la roulure, le bois avait un plus fort coefficient d'anisotropie que le bois environnant. La densité du bois juvénile des billes roulées avait une densité supérieure à celle du bois mûr et une résistance à la rupture et une dureté proportionnelle. La comparaison des bois provenant de billes roulées et non roulées nous permet d'en arriver aux conclusions suivantes : le bois mûr, peu importe d'où il venait (indépendamment de la présence de roulures) sur les billes roulées, avait un module de rupture, des limites proportionnelles d'élasticité, un module d'élasticité en flexion statique, une résistance axiale, une résistance et une dureté inférieures à ceux du bois mûr provenant de billes non roulées. De plus, on a observé un gonflement radial moins important chez les bois avec roulures. La densité du bois juvénile des billes avec roulures était plus élevée comparativement à celle du bois mûr ou juvénile venant de billes non roulées.

Mots-clés : roulure, châtaigner, défauts du bois, résistance du bois, propriétés mécaniques et physiques.

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Introduction

Chestnut (*Castanea sativa* Mill.) is a forest species widespread in the Mediterranean area. Chestnut wood is a valuable raw material in wood manufacturing due to its good mechanical properties, natural durability and attractive appearance. A disadvantage that negatively affects the utilisation of chestnut wood and decreases the timber value is the appearance of ring shakes in logs, a defect occurring as a detachment of wood between growth rings. In certain cases, the appearance of this defect is extensive, causing significant qualitative drop in timber produced (Fonti *et al.* 2002).

Chestnut trees prone to developing ring shakes after felling may include wood with differentiating mechanical or other properties (Leban 1985; Frascaria *et al.* 1992; Macchioni 1995; Fonti and Sell 2003; Fonti *et al.* 2003). These reports contain observations on the basis of which such variations have been identified between ring shaken and non-ring shaken wood. However, it is not clear that this is totally valid, because only some properties, mainly in a radial direction, have been determined and there is not enough evidence for this to be universally accepted. Furthermore, it has not been clarified whether these variations derive from the production of such wood by the tree or are subsequently created due to the existence of ring shake.

Comparing trees of the same age, Spina and Romagnoli (2010) noted that the diameter was not strongly related to the magnitude of defect, but had the effect of moving the ring shake location outwards. Wood defects (star shake, injuries, double core and eccentricity of the core) and stem defects (cortical cancer, epicormic branches, dead branches and bark cracking) were not significantly correlated with shake – indeed, only bark cracking and injuries seem to have a slight influence on ring shake risk. Macchioni and Pividori (1996) also found that ring shake is strongly related to genetic aspects – in the same coppice stand they found stumps completely ring shaken and others without any stem affected by the defect.

Romagnoli and Spina (2013) determined that shaken trees had lower mechanical strength and shrinkages than healthy ones, and that the physio-mechanical parameters might be used to predict ring shake occurrence in a specific geographic area. Geographical location strongly affects physio-mechanical properties of chestnut wood, and this factor influences ring shake occurrence. Modulus of Rupture (MOR) values were assumed to be the parameter that could be applied to almost all study sites to distinguish between shaken and healthy trees. There was no difference between the shaken and healthy portions of the disk inside the same tree.

Relationships between ring width, age of wood, physical and mechanical properties, which sometimes may affect ring shake occurrence, have been highlighted by Fioravanti (1995); Adamopoulos *et al.* (2010); Adamopoulos *et al.* (2011) and Romagnoli *et al.* (2014).

In this paper, measurements of several mechanical and physical properties of wood were determined to detect possible variations between ring shaken and non-ring shaken logs and between different areas on cross sections of ring shaken logs. Up to now, only variations between ring shaken and non-ring shaken wood, mainly in a radial direction, have been examined. By grading the samples not only by different

Table 1. Sample positions on ring-shaken logs

Code	Sample position according to the distance from ring shake
0	Sample precisely on ring shake area
1	Sample next to ring shake
2	Sample at 5 mm distance from ring shake
3	Sample at more than 5 mm distance from ring shake

trees but also at different distances from the ring shaken area, and by examining a greater variety of mechanical properties, more complete information of ring shake defect behavior on mechanical properties may be obtained.

Chestnut juvenile wood was the area of the first 10 rings around the pith based on previous studies (Fioravanti 1995; Militz *et al.* 2003; Chavenetidou 2009; Adamopoulos *et al.* 2010; Adamopoulos *et al.* 2011), from which we quote: “In chestnut wood, the increase in fibre length is greater up to the age of 10-12 years and then is gradually reduced. This area of change of growth coincides with the transition age from ‘immature’ (juvenile) to ‘typical’ wood” (Chavenetidou 2009). With chestnut coppice wood from central Italy, lateral dimensions (radial, tangential) of the vessels at the base and at a height of 5 m from the trunk increased from the pith to the outer wood (Fioravanti 1995). The increase is greatest initially up to 8-10 years of vessel age. The mean dimensions were larger at the base compared to the corresponding dimensions at a height of 5 m. The ratio of the radial to the tangential dimension decreased from the pith to outer wood at both heights. The decrease was initially also higher up to the age of 8-10 years.

Materials and Methods

Nine logs (2 m long) were selected from a coppice forest in Halkidiki, Greece, five without ring shakes and four with ring shakes. Logs were sawn to produce 2.5 cm thick boards and 50 x 2 x 2 cm (axial x radial x tangential) samples were cut. The samples from ring-shaken logs were classified according to their distance from ring shakes as described in Table 1 and shown in Fig. 1 and 2.

Mechanical properties were determined according to established international standards using the standardized methods described in detail and contained in those standards (Table 2). The length, width, height, and mass of each specimen were recorded to determine air-dry densities. All specimens were conditioned at 20 °C and 65 % relative humidity before testing. The mechanical properties of bending and compression were determined on a Shimadzu strength machine while an Amsler strength machine was used for hardness and toughness.

For MOR (Modulus of Rupture) and MOE (Modulus of Elasticity) measurements, a static bending test was performed using a Shimadzu testing machine by centre point loading over a 30-cm span. Half of the specimens with narrow or wide growth rings were loaded in the radial direction while the other half in the tangential direction. The load applied was about half of the estimated proportional load limit for each specimen and was based on previous tests. The crosshead

Fig. 1. Sample positions on ring shaken logs. From each sample test specimens were cut to determine mechanical properties.

Fig. 3. Sample for radial and tangential swelling measurements

speed (6 mm/min) was according to DIN 52186:1978 (Deutsche Industrie Normen 1988). From the stress strain diagram taken for each specimen, the fracture load (maximum load), the load at the elastic limit as well as the corresponding bending arrow were determined.

This methodology determines the 'experimental modulus of elasticity'. However, a methodology developed and used by Preston (1954), Wangaard (1964), Biblis (1965) and Chow (1972) was used to determine the real modulus of elasticity. With this methodology, it is possible to determine the actual

shear modulus or modulus of rigidity at the same time, and is based on the relationship between the previously mentioned properties and the flexural elastic modulus.

From the load deflection curve, the modulus of elasticity (MoE) in radial and tangential planes were obtained as follows:

$$\text{MoE} = \frac{PL^3}{4bd^3y}$$

Where:

MoE: modulus of elasticity, N/mm²

P: load in the region of proportionality, N

L: length between specimen supports, mm

b: width of specimen, mm

d: height of specimen, mm

y: mid span deflection of specimen at load P, mm

From the samples with code 0, (precisely on the area of ring shakes), the specimens were cut in a way that ring shake was not present in the final specimen (Fig. 2), following the length of the original bar up to the disappearing ring crack (Fig. 1 and 2).

It should be noted that toughness tests were conducted on an Amsler Universal wood testing machine at 24-cm span with centre loading. For each specimen, the impact of the falling pendulum occurred in the respective plane (radial or tangential) of the static bending test. The impact bending strength was determined according to DIN 52189:1981. It was tested according to the hammer method on specimens with a cross section of 20 x 20 mm. The energy (Newton) required to break the sample by the swing of the hammer was recorded. The impact bending strength is expressed as kJ/m². The work produced from fracturing the specimen was noted and toughness strength was calculated according to DIN 52189:1981 as follows:

Table 2. Description of mechanical properties test specimens

Test	Type of wood	Non-ring shaken logs	Ring shaken logs	Dimensions (rad. x tang. x ax.) cm	Standard
Static bending	Mature	125	106	2 x 2 x 34	DIN 52186: 1978
	Juvenile	18	11		
Axial compression	Mature	75	129	2 x 2 x 6	DIN 52185: 1976
	Juvenile	25	17		
Toughness	Mature	75	61	2 x 2 x 28	DIN 52189: 1981
	Juvenile	20	9		
Hardness	Mature	75	61	2 x 2 x 6	BS 373:1957
	Juvenile	20	9		

Table 3. Number of specimens from each position of ring-shaken logs

Code (position)	Static bending	Axial compression	Toughness / Hardness
0	12	32	15
1	14	32	11
2	21	17	5
3	59	48	30
Total	106	129	61

Fig. 2. Final specimens from ring shake area (code 0)

$$W = 1000w/bd$$

Where:

W: toughness, kJ/m²

w: work to total fracture, J

b: width of specimen, mm

d: height of specimen, mm

The determination of hardness was conducted by the Janka method and carried out on the tangential and radial surfaces with a corresponding (tangential and radial) direction of application of the load at a constant speed of 6 mm/min (British Standards Institution 1957).

Table 2 shows the number and the dimensions of test specimens used for the determination of mechanical properties. The number of specimens for each class of ring shaken logs according to their distance from ring shakes is shown in Table 3.

Test specimens (2 x 2 x 5 cm; rad. x tang. x ax.) were also cut from the chestnut samples (mature wood) to measure radial and tangential swelling (Fig. 3) and

coefficient of anisotropy, but not axial swelling. These specimens were used for measurements of oven-dry density. Thirty-two specimens were cut from ring shaken logs and 20 cut from non-ring shaken logs. They were dried to 0% moisture content and then immersed in water up to > 30 % moisture content. For the calculation of maximum swelling, the samples were placed in an oven at 103 ± 2 °C for 24 hours, and then their weight and dimensions (in dry state) were measured. They were placed fully covered in water for 72 hours until their dimensions were stabilized, and then re-measured at the level of maximum swelling.

Results and Discussion

The mean values of mechanical properties and air-dry densities are shown in Table 4. Table 5 shows the statistically significant differences ($p < 0.05$ for confidence limit 95 %) between the areas that were revealed from ANOVA (Analysis of Variance).

From the test on static bending, the Modulus of Rupture (MoR), proportional limit (PL) and modulus of elasticity (MoE) were determined according to DIN 52186:1978. All values were higher (statistically significant, $p < 0.05$ for confidence limit 95 %) for the non-ring-shaken logs. In ring shaken logs, wood from the shaken area (code 0) had a lower proportional limit compared to wood from other positions (code 1, 2, 3) of the same ring shaken log. Juvenile wood from ring shaken logs had higher proportional limits compared to mature wood from the same logs (Tables 4 and 5).

The test on axial compression (DIN 52185:1976; Deutsche Industrie Normen 1988) revealed higher strengths for non-ring shaken logs compared to ring shaken logs, and lower strength of areas close to the ring shake (code 0, 1) compared to areas at a distance from the ring shake (code 2, 3) from the same ring shaken log (Tables 4 and 5).

From the test on toughness (DIN 52189:1981; Deutsche Industrie Normen 1988), the non-ring shaken logs had greater strength compared to ring shaken logs (Tables 4 and 5).

The test on hardness (British Standards Institute 1957) revealed greater strength for non-ring shaken logs compared to ring shaken logs, and lower strength of areas close to the ring shake (code 0, 1) compared to areas at a distance from ring shake (code 2, 3). Juvenile wood from ring shaken logs had higher hardness compared to mature wood from the same logs (Tables 4 and 5).

Table 4. Mean values of mechanical properties and air-dry density

Property*	Logs with ring shakes					Logs without ring shakes	
	Juvenile	Mature (code as defined in table 1 and figure 1)				Juvenile	Mature
		0	1	2	3		
Static bending							
MoR (N/mm ²)	101.47	97.84	93.86	97.56	96.79	108.40	107.71
Proportional limit (N/mm ²)	48.70	42.82	44.66	44.00	43.88	47.76	46.20
MoE, Tangential (kN/mm ²)	16.99	14.67	15.42	16.52	15.95	18.96	19.00
MoE, Radial (kN/mm ²)	16.05	14.37	14.12	15.59	15.14	18.00	17.01
Axial compression (N/mm²)	58.59	53.31	51.54	57.66	58.15	60.81	60.32
Toughness (Joule/cm²)	3.95	3.96	3.65	4.72	4.26	4.59	5.18
Hardness (N/mm²)							
tangential	42.85	36.64	33.54	39.20	40.28	43.07	41.07
radial	43.77	33.08	32.30	36.95	37.65	42.45	40.29
Air-dry density (g/cm³)	0.655	0.616	0.599	0.626	0.624	0.615	0.629

*Radial or tangential according to the load direction.

Table 5. p-values from mechanical property comparisons with statistically significant differences

			Wood areas far from ring shakes (code 2, 3)	Wood areas close to ring shakes (code 0, 1)
Mechanical properties	Logs with ring shakes	Logs without ring shakes		
MOR	2x10 ⁻¹³		10 ⁻¹⁰	
MOR				
MOE (tang)	10 ⁻⁹			
Axial compression	10 ⁻⁷			
MOE (rad)	10 ⁻⁷		10 ⁻⁷	
MOE (tang)				
Toughness	2x10 ⁻⁶			
Hardness (rad)	6x10 ⁻⁶			
MOE (rad)		0.00002	0.00008	
Axial compression				
PL	0.001		0.002	
Toughness				
PL		0.004	0.01	
Hardness (rad)				
Hardness (tang)	0.013		0.014	0.022
Hardness (rad)				
Hardness (tang)			0.039	
Axial compression				

Air-dry density of the juvenile wood specimens from ring shaken logs was higher compared to other types of wood (mature from ring shaken logs, juvenile and mature from non-ring shaken logs; Table 4). Juvenile wood in chestnut has usually higher property values than mature wood (Fioravanti 1995; Adamopoulos *et al.* 2010; Adamopoulos *et al.* 2011). Due

to the distribution of stress inside the tree, ring shake is rarely present in juvenile wood (Fonti *et al.* 2003; Romagnoli and Spina 2013; Romagnoli *et al.* 2014).

Mature wood from any area (independent of the presence of shake) of ring shaken logs had lower mechanical strength compared to mature wood from non-ring shaken logs (Table

Table 6. Mean values of the swelling properties and oven-dry density

Code (for ring shaken logs)	n	Radial swelling	Tangential swelling	Coefficient of anisotropy	Oven-dry density g/cm ³
0	8	3.55%	7.36%	2.09	0.555
1	8	3.34%	8.08%	2.43	0.538
2	8	4.32%	8.80%	2.16	0.600
3	8	4.00%	9.24%	2.37	0.585
Ring shaken logs	32	3.80%	8.37%	2.26	0.570
Non-ring shaken logs	20	4.69%	8.90%	1.95	0.573

5). The wood areas at a distance (code 2, 3) from ring shake but belonging to ring shaken logs had lower values compared to wood from non-ring shaken logs.

Table 6 shows the mean values of the swelling properties and oven-dry density from mature wood. Statistically significant differences ($p < 0.05$ for confidence limit 95 %) were determined for the following:

Wood from ring shaken area (code 0, 1) had lower tangential swelling compared to wood further from ring shakes (code 2, 3) and, precisely at the shakes' position (code 0), wood had higher coefficients of anisotropy (the property of being directionally dependent) than the surrounding wood (code 1).

Ring shaken logs had lower radial swelling compared to non-ring shaken logs.

From the proceeding, some obvious trends may be observed. For example, some lower mechanical properties and shrinkage almost differentiate ring shaken wood, and are noted in the literature (Leban 1985; Frascaria *et al.* 1992; Macchioni 1995; Fonti and Sell 2003; Fonti *et al.* 2003; Romagnoli and Spina 2013). The MoR value, considered a critical parameter, was assumed to be the parameter that could be applied at almost all study sites to distinguish between shaken and healthy trees (Romagnoli and Spina 2013). It is also remarkable that in this research the greatest differences were not between the shaken and healthy portions within the same tree, similar to the findings of Romagnoli and Spina (2013). Some remarkable differences were also found between the shaken and healthy portions within the same tree, and this was due to sampling. Ring shake may run along the log for some centimeters to several metres, and therefore a lower value compared to specimens further from ring shakes (2-3) may be expected.

Reduced mechanical radial resistance of ring shaken wood is reported by other researchers who measured mechanical resistance to static bending and tensile strength in radially oriented specimens from ring shaken and non-ring shaken logs (Leban 1985; Frascaria *et al.*; 1992; Macchioni 1995). This reduced mechanical strength was associated with structural variations and the development of mechanical stresses that affect the properties of ring-shaken wood (Fonti 2001; Fonti and Frey 2002; Fonti 2003; Fonti *et al.* 2003).

Combining all the previous results with the results of this research, the hypothesis formulated by Fonti *et al.* (2003) that wood formation with different characteristics and properties may occur in ring shaken logs is strengthened. This hypothesis was based on results of previous work (Leban 1985; Frascaria *et al.*; 1992; Macchioni 1995; Fonti 2001; Fonti and Frey 2002) which concerned differences in two mechanical properties (bending and tensile strength in radial strips of chestnut

wood) and variations to the extent that vessel members and rays occupy in transverse sections of mature chestnut wood. In agreement with Fonti *et al.* (2003) and other research, we suggest an expanded hypothesis be investigated, i.e., that in chestnut trees, wood characteristics will likely differentiate (as a form of reaction, similar to reaction wood) when these trees receive excessive stress, either from internal (growth stresses) or external factors that cause ring shake.

Conclusions

Mature wood from the ring shake areas had lower axial compression and hardness strength compared with mature wood further away from ring shakes. Wood from ring shake areas had lower tangential swelling and, precisely at the position closest to the ring shake, had a higher coefficient of anisotropy than the surrounding wood. Juvenile wood density from ring shaken logs was higher compared to mature wood, as well as proportional limit and hardness strength. Comparisons between ring shaken and non-ring shaken logs indicate that mature wood from any area (independently of the presence of shakes) of ring shaken logs had lower Modulus of Rupture, proportional limit, modulus of elasticity under static bending, axial compression, toughness, and hardness strength compared with similar wood from non-ring shaken logs. Lower radial swelling was also found with ring shaken logs. Juvenile wood density from ring shaken logs was higher compared to either mature or juvenile wood from non-ring shaken logs. It also had higher modulus of elasticity under shearing compared to juvenile wood from non-ring shaken logs.

References:

- Adamopoulos, S., M. Chavenetidou, C. Passialis and E. Voulgaridis 2010. Effect of cambium age and ring width on density and fiber length of black locust and chestnut wood. *Wood Res.* 55: 25–36.
- Adamopoulos, S., A. Karageorgos, C. Passialis and M. Chavenetidou 2011. Mathematical approach for defining juvenile–mature wood transition zone in black locust and chestnut. *Wood Fiber Sci.* 43(3): 336–342.
- Biblis, E.J. 1965. Analysis of wood-fiberglass composite beams within and beyond the elastic region. *Forest Prod. J.* 15(2): 81–88.
- British Standards Institution 1957. *Methods of Testing Small Clear Specimens of Timber*. B.S. 373:1957.
- Chavenetidou, M. 2009. Anatomical characteristics and technical properties in relation to utilization of chestnut wood (*Castanea sativa* Mill.) from coppice forests. PhD Thesis, Thessaloniki, AUTH.
- Chow, P. 1972. Modulus of elasticity and shear deflection of walnut-veneered particleboard composite beams in flexure. *Forest Prod. J.* 22(11): 33–38.
- Deutsche Industrie Normen 1988. Prüfung von Holz, Bestimmung der Druckfestigkeit parallel zur Faser, DIN 52185:1976.
- Deutsche Industrie Normen 1988. Prüfung von Holz, Biegeversuch, DIN 52186:1978.
- Deutsche Industrie Normen 1988. Prüfung von Holz, Schlagbiegeversuch, DIN 52189:1981.
- Fioravanti, M. 1995. Nature and occurrence of juvenile wood in chestnut (*Castanea sativa* Mill.) stems from Coppice Forest. *Forêt Méditerranéenne* 16: 58–66.
- Fonti, P. 2001. Do ring-shaken chestnut trees display larger early-wood vessels and/or less radial rays than unshaken ones? Poster 217 in Conference “Tree Rings and People”, September 22–26 2001, Davos, Switzerland.

- Fonti, P. 2003.** Growth strain and ring shake in chestnut coppices trees. *Forêt méditerranéenne* 24(2):141–147.
- Fonti, P. and B. Frey 2002.** Is ray volume a possible factor influencing ring shake occurrence in chestnut wood? *Trees: Structure and Function* 16(8): 519–522.
- Fonti, P. and J. Sell 2003.** Radial split resistance of chestnut early-wood and its relation to ring width. *Wood Fiber Sci.* 35(2): 201–208.
- Fonti, P., N. Macchioni and B. Thibaut 2002.** Ring shake in chestnut (*Castanea sativa* Mill.): State of the art. *Ann. For. Sci.* Vol. 59 (2) 129–140.
- Fonti, P., N. Macchioni, B. Thibaut and J. Sell 2003.** Biomechanical adaptation of the wood structure of European chestnut to growth stresses. In: F. Telewski & F. Ewers (eds.), *Proceedings of the 4th International Plant Biomechanics Conference*, East Lansing, USA 20 - 25 July 2003.
- Frascaria, N., B. Chanson, B. Thibaut and M. Lefranc 1992.** Génotypes et résistance mécanique radiale du bois de châtaignier (*Castanea sativa* Mill.): Analyse d'un des facteurs explicatifs de la roulure, *Ann. Sci. For.* 49: 49–62.
- Leban, J.M. 1985.** Contribution à l'étude de la roulure de châtaignier. Thèse de doctorat, I.N.P.L., Nancy, 164 p.
- Macchioni, N. 1995.** Mechanical strength and ring shake in chestnut (*Castanea sativa* Mill.). *Forêt Méditerranéenne* 16: 67–73.
- Macchioni, N. and M. Pividori 1996.** Ring shake and structural characteristics of a chestnut (*Castanea sativa* Mill.) coppice stand in northern Piedmont (northwest Italy). *Annales des Sciences Forestières* 53: 31–50.
- Militz, H., Busetto, D. and F. Hapla 2003.** Investigation on natural durability and sorption properties of Italian Chestnut (*Castanea sativa* Mill.) from coppice stands. *Holz Roh-Werkstoff* 61:133–141.
- Preston, S.B. 1954.** The effect of synthetic resin adhesives on the strength and physical properties of wood veneer laminates. Yale University, School of Forestry Bul. No. 60. New Haven, Connecticut.
- Romagnoli, M. and S. Spina 2013.** Physical and mechanical wood properties of ring-shaken chestnut (*Castanea sativa*) trees. *Can. J. Forest Res.* 43(2): 200–207.
- Romagnoli, M., D. Cavalli and S. Spina 2014.** Wood Quality of Chestnut: Relationship between Ring Width, Specific Gravity, and Physical and Mechanical Properties. *Bioresources* 9(1): 1132–1147.
- Spina, S. and M. Romagnoli 2010.** Characterization of ring shake defect in chestnut wood in the Lazio Region (Italy). *Forestry* 83: 315–327.
- Wangaard, F.F. 1964.** Elastic Deflection of wood-fiberglass composite beams. *Forest Prod. J.* 14(6): 256–260.