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Review paper

RADIAL VARIABILITY OF WOOD DENSITY AND FIBRE LENGTH IN THE RED OAK TREES (*Quercus rubra* L.)

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Abstract: *Wood density and fibre length are two wood properties that are important in determining the quality of wood for commercial use. The fibre length of red oak has not been studied to the same extent as in other oak species. The aim of this paper is to explore the anatomical variation and wood density of red oak wood, as valuable information for researchers in other fields. Samples were taken in a 60-year-old red oak stand in the south part of Belgrade on the site of Stepin Lug. Along the south radius, the disc samples of 20 x 20 mm were cut from the sapwood, mature and juvenile wood. Oven-dry density and fibre length were measured from the pith to the bark. According to the obtained data, the average oven-dry density of wood per radius is 0.694 g/cm^3. The lowest is in the juvenile wood and ranges from 0.628 to 0.681 g/cm^3, then in the part of sapwood - 0.662 g/cm^3, and the highest is in the mature wood where the density ranges from 0.707 to 0.740 g/cm^3. The presented values show certain differences, but also conform to literature data on the density of some industrial species from the genus Quercus L. The obtained results of the wood fibre length show that it varies from 0.99 to 1.33 mm which was measured in mature wood. The average length in a mature zone is 1.26 (1.16-1.33) mm, while in a juvenile area the average length is 1.02 (0.85-1.23) mm. Based on the known wood fibre length, it is possible to determine the density of red oak wood. In this research, a positive influence was determined in both parts of the tree, juvenile and mature, but a better mathematical dependence was obtained in the mature zone.*

Keywords: red oak, wood density, fibre length, juvenile wood

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RADIJALNA VARIJABILNOST GUSTINE DRVETA I DUŽINE VLAKANA U DRVETU CRVENOG HRASTA (*Quercus rubra* L.)

Izvod: *Gustina drveta i dužina vlakana su dva svojstva drveta koje su od značaja za određivanje kvaliteta drveta za komercijalnu upotrebu. Dužina vlakana crvenog hrasta nije proučavana u istoj meri kao kod drugih vrsta hrasta. Cilj ovog rada je istraživanje anatomske varijacije i gustine drveta crvenog hrasta, kao dragocene informacije za istraživače u drugim oblastima izučavanja nauke o drvetu drveta. Uzorci su uzeti u sastojini crvenog hrasta starog 60 godina u južnom delu Beograda na lokalitetu Stepin Lug. Po južnom poluprečniku diska sečeni su uzorci 20 x 20 mm od beljike, zrelog i juvenilnog drveta. Gustina drveta u apsolutno suvom stanju vlažnosti i dužina vlakana merene su od srži do kore. Prema dobijenim podacima, prosečna gustina drveta iznosi 0,694 g/cm3. Najniža je u juvenilnom drvetu i kreće se od 0,628 do 0,681 g/cm3, zatim u delu beljike - 0,662 g/cm3, a najveća je u zrelom drvetu gde se gustina kreće od 0,707 do 0,740 g/cm3. Prikazane vrednosti pokazuju određene razlike, ali su i u skladu sa literaturnim podacima o gustini pojedinih industrijskih vrsta iz roda Quercus L. Dobijeni rezultati dužine drvnog vlakna pokazuju da ona varira od 0,99 do 1,33 mm koliko je izmerena kod zrelog drveta. Prosečna dužina u zreloj zoni je 1,26 (1,16-1,33) mm, dok je u juvenilnom području prosečna dužina 1,02 (0,85-1,23) mm. Na osnovu poznate dužine drvenih vlakana moguće je odrediti gustinu drveta crvenog hrasta. U ovom istraživanju utvrđen je pozitivan uticaj u oba dela stabla, juvenilnom i zrelom, ali je bolja matematička zavisnost dobijena u zoni zrelog drveta.*

Ključne reči: crveni hrast, gustina drveta, dužina vlakana

1. INTRODUCTION

Oak (*Quercus* spp.) holds a high reputation as a strong, durable timber. It is traditionally used for high-grade construction work in much of Europe, and for boat and shipbuilding, fencing, interior woodwork, exterior joinery, flooring, coffins, beer casks and domestic furniture (Rendie, 1969). Oak wood anatomy is therefore of considerable interest with special attention to the strength properties, water relations and anatomical variation (Gasson, 1987). This paper aims to explore the anatomical variation in the wood of red oak(*Quercus rubra* L.), as valuable information for researchers in other fields.

Wood fibre length in red oak has not been studied to the same extent as in other oak species. As red oak is a ring-porous species, the growth ring properties have a great influence on the physical and mechanical wood properties. Gričar *et al*. (2013) point out that the change in the growth ring structure and its variability by radius is the most important indicator of oak wood quality. Tsoumis (1991) declares that this variability is more important than the structural and chemical changes during heartwood formation. Due to the above, in the literature, we can find different average values for the properties of species from the genus *Quercus* L.

Through earlier studies, it was determined that the wood density of European oaks is positively related to the ring width and negatively to the ring number from pith to bark. Ring-porous wood found in oak species is characterized by the division of each annual ring into low-density earlywood and high-density latewood zones. Latewood contains a lower number of tracheae and therefore a higher proportion of wood fibres than earlywood (Rao *et al.*, 1997). Within a tree, earlywood width and density are generally constant in pith to bark profiles, while latewood fiber width and wood density vary with ring number and ring width (Zhang *et al.*, 1993; Degron *et al.*, 1996).

In the literature, information on the density and properties of sessile oak (*Quercus petrea* L.) and pedunculate oak (*Quercus robur* L.) are more prominent through their presence in European forests (Zhang *et al.*, 1993; Degron, 1996). The density value for red oak was published by Alden (1995) and it amounts 0.660 g/cm^3 for specimens from North America. For samples grown in European conditions, Merele and Čufar (2013) showed that red oak species have a higher density than white oak species. Gohre and Wagenknecht (1955) found a very similar density to Alden, i.e., 0.666 g/cm3. Other authors mention values close to 0.660 g/cm3 (Wagenfuhr 2000), but even higher than the value determined in this work is shown by Genet *et al*. (2013) in the amount of 0.760 g/cm3 for wood from natural stands and 0.734 g/cm3 for wood that was produced in trees from plantations.

Anatomical wood properties significantly influence wood quality (Richter, 2015). The influence of anatomical parameters of red oak on the quality of its wood was investigated mainly by authors in North America (Guiher, 1965; Hamilton and Knaus, 1986; Tardif *et al*., 2006; Genet *et al*., 2013). The juvenile zone is a part of the tree that differs significantly from its anatomical characteristics and properties compared to the mature tree (Zobel and Buijtenen, 1989; Hernandez *et al*., 2006). The influence of location on the anatomical characteristics of red oak was investigated by Maeglin (1974), Tainter *et al.* (1990) and Tardif *et al*. (2006).

Wood fibres are involved in the structure of the red oak tree as mechanical elements. The domestic species of oaks (sessile oak, pedunculate oak and Turkey oak) also have fibrous tracheids as additional elements (Šoškić and Popović, 2002). The arrangement of wood fibres and their length from the pith to the bark, as well as their participation, are very important for knowing the quality of the wood. Fibres (40-60%) have the largest area in the structure of the oak wood. Accordingly, the vessel surface in early wood is 40%, and in latewood 8%, while the ray surface is 15-30% (Wagenfuhr and Scheiber, 2006).

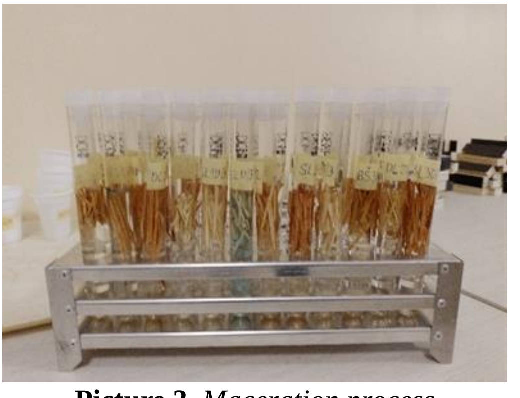
The aim of the work was to research the radial variability of wood density and fibre length in red oak trees. These properties were assessed for juvenile, mature and sapwood. Considering that anatomical elements affect the quality of wood, in this paper the dependence between fibres and wood density, from the pith to the bark, was investigated.

2. MATERIALS AND METHODS

Samples were taken in a 60-year-old red oak stand in the south part of Belgrade, the capitol of Serbia, Europe, on the site of Stepin Lug (Picture 1). After measuring the diameter, at tree breast height, a disc was taken.

Picture 1. *Site map*


Picture 2. *Cross section*

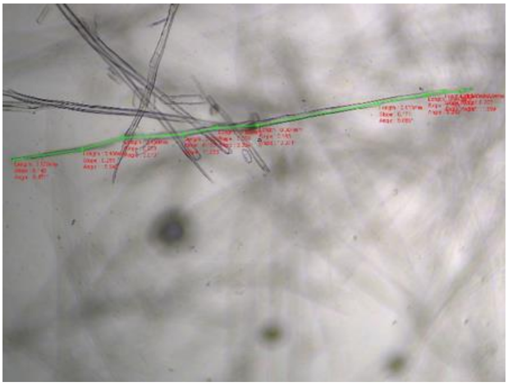

Picture 3. *Maceration process*

Along the south radius of the disc (Picture 2), samples of 20 x 20 mm were cut from the sapwood part, mature part and juvenile part of the tree cross-section. The radial length was divided into eight zones (1-6; 7-13; 14-20; 21-27; 28-34; 35-44; 45-52; 53-60) according to the growth rate and the number of tree-rings. From the whole width of each of the mentioned parts, the material was taken for maceration.

The length of the axial anatomical elements was measured on macerates obtained using a 1:1 ratio mixture of glacial acetic acid and 30% hydrogen peroxide solution (Picture 3). The maceration was performed at 60°C for 48 hours (Parharn and Grey, 1982). The macerated elements were washed several times with water, and then gently separated.

The length of the fibres was measured using a microscope Bio Blue with enlargement 40x (Picture 4), in each mentioned part of the wood cross-section 30 vessel elements were measured, including tails (Picture 5). The measurements were made with an accuracy of 0.001 mm.

Picture 4. *Wood fibres under microscope*



Picture 5. *Measured wood fibre*

In addition, the width of all the growth rings was measured. The ring width was measured with a microscope Bio Blue with enlargement 10x.

The wood density was expressed as oven-dry weight per unit green volume. The wood density was determined on samples having 20x20x40 mm. The wood density (ρ_0) at 0% moisture content was determined according to the following equation (SRPS ISO 13061-2):

$$\rho_0 = m_0/V_0 \text{ [g /cm}^3\text{]};$$

(1) where m_0 is the weight of the test specimen at 0% wood moisture content (kg) and
(2) V_0 is the volume of the test specimen at 0% wood moisture content (g/cm^3).

To obtain absolutely dry wood, the test specimens were dried in a laboratory kiln at 103 ± 2 °C until weight stabilization was reached.

A significance level of 95% was used for all statistical analyses. A t-test was used to evaluate the differences between the two tested samples. The ANOVA and Turkey's multiple-range tests were applied to evaluate the statistically significant differences among the other evaluated factors. The linear regression model was used to evaluate the dependence of fibre length density on the width of annual rings and proportion of latewood for both types of oaks.

3. RESULTS AND DISCUSSION

The variation of wood density and fibre length per radius is shown in Table 1.

Table 1. *The variation of oven-dry density and fibre length per radius of red oak wood*

Anatomical properties of wood	The number of tree-rings from the pith to the bark								
		Juvenile wood		Mature wood					Sapwood
	Statistical indicators	1-6	7-13	14-20	21-27	28-34	35-44	45-52	53-60
Fibre length (mm)	N_{mean} (mm)	0.99	1.04	1.16	1.21	1.26	1.33	1.33	1.27
	S_d (mm)	0.16	0.16	0.15	0.17	0.28	0.33	0.15	0.17
	C_v (%)	15.9	15.2	13.0	13.9	21.9	24.7	11.3	14.9
Wood density (g/cm^3)	N_{mean}	0.628	0.651	0.707	0.706	0.718	0.729	0.740	0.712
	S_d	0.07	0.03	0.05	0.05	0.04	0.08	0.09	0.05
	C_v	10.4	4.7	7.2	6.6	5.5	11.5	12.8	7.7

According to the results obtained in this research, the average wood density per radius is 0.694 g/cm^3. The lowest is in the juvenile wood and ranges from 0.628 to 0.681 g/cm^3, then in the part of sapwood - 0.662 g/cm^3, and the highest is in the mature zone where the density ranges from 0.707 to 0.740 g/cm^3. The presented values show certain differences, but also conform to the literature data for the density of some industrial species from the genus *Quercus*. Except for information that the 60 years old red oak tree located in Lipovačka Šuma stand had a wood density of about 0.724 g/cm^3 (Živanović *et al*., 2021), the red oak density values in the local literature are very scarce. Up to now, mainly the sessile oak wood density has been published, as the most important domestic industrial species from the oak genus. In comparison with the density of red oak from this work, Todorović (2006) obtained a similar density value (0.688 g/cm^3), while Šoškić *et al*. (2005) showed a significantly lower value of 0.651 g/cm^3 density for sessile oak from the area of Debeli Lug (Serbia). Examining the density of white oak from the forests of the apea Đerdap (Serbia), Popović *et al*. (2007) obtained data (0.720 g/cm^3) which shows a higher density compared to the red oak density from this study.

The obtained results of the length of the wood fibres show that it varies from 0.99 to 1.33 mm which was measured in mature wood. The average length in a mature tree is 1.26 (1.16-1.33) mm, while in a juvenile the average length is 1.02 (0.85-1.23) mm. On the basis of statistical analysis shown in Table 1, it was determined that zones 1 and 2 of the growth ring differ significantly in terms of fibre length and wood density from all zones that are further to the bark. Taylor (1976) showed that red oak wood fibres are longer in mature wood compared to juvenile wood. The same author studied the correlation between the position in the growth ring by radius and the wood fibre length and showed a functional quadratic dependence. In some studies (Mladenova *et al.*, 2017; Nazari *et al.*, 2020) fibre characteristics have been investigated, mainly fibre length in the wood of different oak species. The results showed a great dependence of its dimensions on location conditions.

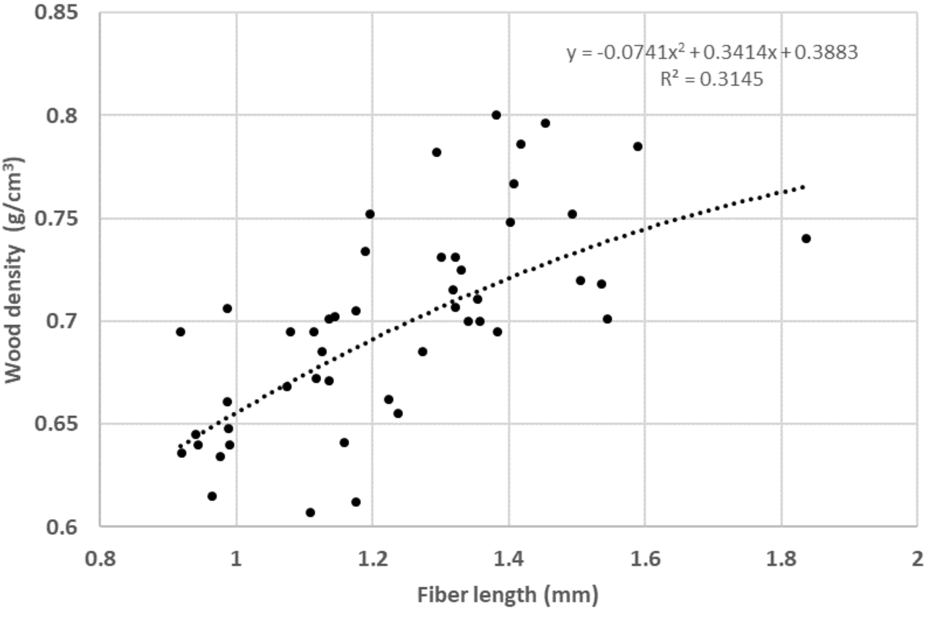
Raczkowska and Fabisika (1999) published that the fibre lengths increase from the pith to the bark and it is 0.99 mm in juvenile wood and 1.13 mm in the mature zone. The same authors pointed out that there is a negative correlation between the anatomical elements, length and the growth ring width for species from the genus *Quercus*. Mladenova *et al.* (2017) stated that the fibre length of 1,306 mm was measured for different oaks, while for red oak Wagenfuhr and

Scheiber (1985) stated a length of 1,300 mm, and for white oak, the same authors published a value of 1,360 mm. Nazari *et al*. (2020) reported that the fibre length in the wood of Persian oak (*Quercus macranthera* Fisch. et Mey.) was less than 1 mm while the average value was 0.87 mm. The differences shown are a consequence of genetic influences and the fact that the anatomical characteristics of wood can vary even within the same forest stand and are largely dependent on the microenvironment and hydrological conditions (Gričar *et al.*, 2013; Jokanović *et al.*, 2022), as well as variations in the structure of the growth ring by radius (Genet *et al.*, 2013).

Table 2. *Statistically significant differences in wood density and fibre length between zones by tree radius (+ fibre length;* * wood *density) (p≤0,05)*

Rings by tree radius	1-6	7-13	14-20	21-27	28-34	35-44	45-52	52-60
1-6			+*	+*	+*	+*	+*	+*
7-13			+*	+*	+*	+*	+*	+*
14-20	+*	+*						
21-27	+*	+*						
28-34	+*	+*						*
35-44	+*	+*						*
45-52	+*	+*						*
53-60	+*	+*			*	*	*	

The dependence between fibres and wood density in the juvenile part (not shown) of the tree was weaker compared to the mature wood zone (Graph 1). In the interval of fibres length from 0.96 to 1.8 mm, the wood density changes positively and according to the following equation form: $y=0,074x^2+0,3414x+0,3883$ ($R^2=0,3145$). This positive trend of wood density change with fibre length is in agreement with the previous results (Stringer and Olson, 1985; Yanchuk and Micko, 1990; Zobel and Sprague, 1998; De Bell *et al.*, 2004). Also, it should be pointed out that this trend cannot be observed separately from changes in the structure of the radial growth. Namely, in the juvenile wood, a larger ring growth was noted and with a greater share of latewood; however, the wood density is the lowest there. This indicates that in the late part of the growth ring in juvenile wood fibres are shorter with thinner walls compared to fibres in mature wood. Longer fibre dimensions with less participation of latewood indicate higher wood density. Therefore, the length of the fibres, latewood proportion and the double thickness of the fibre walls (Gričar *et al.*, 2013; Genet *et al.*, 2013) are the most important parameters that affect the density of the wood and its strength.



Graph 1. *Effect of fibre length on the density of red oak wood*

It should be noted that in the sapwood zone, a lower density was confirmed compared to mature wood, but higher compared to the area around the heartwood. This result largely coincides with that published by Todorović (2006) but contradicts the claims made by Merela and Čufar (2013). The authors showed that there is no significant difference between the sapwood and the heartwood properties for the sessile oak, pedunculate oak, and turkey oak, but statistically significant differences were found between, on one hand, the properties of the white oaks – sessile oak and pedunculate oak, and red oak and turkey oak, on the other hand. These differences may be a consequence of the positions of early and late wood zones and their anatomical elements ratio, as a result of climatic and locational conditions (Carlquist, 1988; Gričar *et al.*, 2013).

4. CONCLUSION

In this research, the average density of wood per radius of 0.694 g/cm3 was obtained. In the juvenile zone, a part of the tree with large variations in anatomical characteristics and properties, the dependence between fibre length and wood density was weaker than in the mature wood zone. The radial variation of fibre length and wood density in red oak was investigated, and the following results were obtained:

- The age of a tree and the variation of the growth ring structure by radius affect the change in the wood fibre length and the wood density;
- The wood fibre length increases from the pith to the bark, and it is lower in juvenile wood (1.02 mm), whereas it is higher in the mature zone (1.26

mm.) There is no difference between the heartwood and sapwood wood fibre lengths;

– Wood density decreases from pith to bark in the heartwood zone but, unlike wood fibres, density decreases again in the sapwood zone. The average density in juvenile wood is 0.654 (0.519-0.741) g/cm^3, in mature wood is 0.712 (0.595-0.865) g/cm^3, and in sapwood is 0.662 (0.514-0.832) g/cm^3.
– Based on the known length of wood fibres, it is possible to determine the density of red oak wood. In this paper, a positive influence was determined in both parts of the tree, juvenile and mature, but a better mathematical dependence was obtained in the mature zone.

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RADIAL VARIABILITY OF WOOD DENSITY AND FIBRE LENGTH IN THE RED OAK TREES (*Quercus rubra* L.)

Nebojša TODOROVIĆ, Ivana ŽIVANOVIĆ, Dragica VILOTIĆ, Goran MILIĆ

Summary

As a strong, durable timber, traditionally used for different household products, oak is one of the most favourable materials for the wood processing industry. The anatomy of wood has a great influence on its mechanical properties, so it is important to analyze the basic physical and anatomical wood properties, wood density and fibre length as valuable information for mechanical properties prediction.

The red oak wooden disk was taken from the tree that was located in the south part of Belgrade, Stepin Lug stand. Oven-dry density was measured on oven-dried 20x20x40 mm samples from pith to bark. Fibres were separated in the chemical process of maceration and measured with a microscope. The results are statistically analyzed.

The average density of wood per radius obtained in this research is 0.694 g/cm^3. The lowest is in the juvenile wood and ranges from 0.628 to 0.681 g/cm^3, then in the sapwood area - 0.662 g/cm^3, and the highest is in the mature wood where the density ranges from 0.707 to 0.740 g/cm^3. The presented values show certain differences, but also conform to literature data on the density of some industrial species from the genus *Quercus*. The results of wood fibre length show that it varies from 0.99 to 1.33 mm in mature wood. The average length in a mature zone is 1.26 (1.16-1.33) mm, while in a juvenile the average length is 1.02 (0.85-1.23) mm. There is no difference between the heartwood and sapwood wood fibre length.

Summarising all results obtained and available literature data, it can be concluded that based on the length of wood fibers it is possible to determine the density of red oak wood. In this research, a positive influence was determined in both parts of the tree, juvenile and mature, but a better mathematical dependence, square-shaped, was obtained in the mature zone.

RADIJALNA VARIJABILNOST GUSTINE DRVETA I DUŽINE VLAKANA U DRVETU CRVENOG HRASTA (*Quercus rubra* L.)

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Rezime

Kao tvrdo, trajno drvo, tradicionalno korišćeno za različite proizvode za domaćinstvo, hrast je jedan od najtraženijih materijala za drvnu industriju. Anatomija drveta ima veliki uticaj na mehanička svojstva tako da je za svako drvo, kao budući materijal za proizvodnju, značajno istražiti osnovna fizička i antomska svojstva drveta, gustinu drveta i dužinu vlakana kao značajnu informaciju za procenu drugih mehaničkih svojstava.

Kotur drveta crvenog hrasta uzet je sa stabla koje se nalazilo u južnom delu Beograda, sastojina Stepin lug. Gustina u apsolutno suvom stabnju vlažnosti merena je od srži do kore na uzorcima 20x20x40 mm. Drvna vlakna su odvojena u hemijskom procesu maceracije i merena mikroskopom. Rezultati su statistički analizirani.

Prosečna gustina drveta po radijusu dobijena u ovom istraživanju iznosi 0,694 g/cm^3. Najniža je u juvenilnom delu i kreće se od 0,628 do 0,681 g/cm^3, zatim u delu beljike - 0,662 g/cm^3, a najveća je u zrelom drvetu gde se gustina kreće od 0,707 do 0,740 g/cm^3. Prikazane vrednosti pokazuju određene razlike, ali i slaganje sa literaturnim podacima o gustini pojedinih industrijskih vrsta iz roda *Quercus*. Rezultati dužine drvnih vlakana pokazuju kod zrelog drveta varijaciju od 0,99 do 1,33 mm. Prosečna dužina u zreloj zoni je 1,26 (1,16-1,33) mm, dok je kod juvenilnog drveta prosečna dužina 1,02 (0,85-1,23) mm. Ne postoji razlika između dužine drvnih vlakana srži i beljike.

Sumirajući sve rezultate i literaturne podatke, zaključuje se da je na osnovu dužine drvnih vlakana moguće odrediti gustinu drveta crvenog hrasta. U ovom istraživanju utvrđen je pozitivan uticaj u oba dela stabla, juvenilnom i zrelom, ali je bolja matematička zavisnost, kvadratnog oblika, dobijena u zoni zrelosti.