MODELING QUALITY OF NORTHERN RED OAK (*Quercus rubra* L.) WOOD USING FRACTOMETRIC MEASUREMENTS

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ABSTRACT

Core samples taken from a northern red oak tree from three different locations in Serbia were tested using Fractometer 2 and the results were compared to the results obtained with the standard destructive method on the samples of the same trees. The study aimed to determine the connection between semi-destructive measurements conducted using a fractometer and the values of standard measurements of wood properties of this non-native tree species that adapted very well to Serbian climatic conditions. The results show that the values of the investigated properties are in the interval of literature data for this tree species. Statistical analysis showed that radial bending strength cannot be used as a reliable parameter in assessing wood quality, while the relationship between compressive strength and fracture angle and properties of northern red oak wood obtained multiple regression dependence with a coefficient of determination that was in the interval from 0.936 to 0.975. The primary advantage of the obtained models is the ability to predict the quality of wood before cutting trees, which could positively affect the optimal and further exploitation of wood.

KEYWORDS:
Northern Red Oak, Fractometer, Mechanical Properties of Wood, Modeling, Prediction

INTRODUCTION

The northern red oak (*Quercus rubra* L., Fagaceae) grows naturally in the eastern and central parts of the United States of America [1]. It was introduced to Switzerland in 1691 and to Germany in 1740, mainly planted as a park tree [2]. Northern red oak is widespread all over western, central, southern and south-eastern Europe, with the largest concentrations in Germany, France, Belgium and the Netherlands [3]. There are only small areas under this tree species in Serbia, mostly in the vicinity of the city of Belgrade [4]. Excluding our previously published preliminary results [5], the nature of the wood of northern red oak has not been examined in Serbia, so it would be of scientific and practical significance to concentrate on the properties of wood of this incredibly resistant and fast-growing oak species, which is an excellent material for handling in the wood industry [6].

Tree growth location, silvicultural treatments, genetics, weather, and soil conditions – all influence growth characteristics and properties within and between species [7]. Several elements influence mechanical properties; some of these include knots, species, the slope of grain, density, the ratio of earlywood to latewood, fungal rot and other damage, processing, or loading history. Because wood is a natural material exposed to different conditions and locations, it is impossible to replicate a sample or results exactly as in previous studies [8].

The mechanical properties can be obtained by destructive and nondestructive methods. These properties are necessary to evaluate the quality of wood and further compare it with various other tree species. The destructive mechanical tests are typically performed according to the SRPS ISO 13061 standard test to evaluate the strength and stiffness. When performed, destructive tests increase the cost for companies, since after these tests the samples cannot be used. Consequently, the investigation of nondestructive test (NDT) strategies to survey the nature of wood has been expanding [9-16]. Nondestructive tests imitate a dependable and somewhat fast outcome without influencing the wood properties, tree, log, or separated stumble item, and subsequently, the wood can be utilized from that point [17-21].

The fractometer is a tool for estimating the wood fracture and bending strength or compression on a core sample taken with an increment borer from a specific piece of the tree or branch being inspected [22]. The compressive strength of wood is a decent sign of value and beginning deterioration [22-23]. Various *in situ* examinations recommend that radial strength diminishes similarly to longitudinal strength in light of rot activity [24-26]. For instance, some authors [27] found a significant positive correlation between compression strength obtained with fractometer and static test. Others [26] achieved significant and positive relationships between radial bending strength and longitudinal compressive strength, showing a solid association between radial and longitudinal mechanical qualities. Moreover, a group of authors [28] presumed that fractometer could be applied for live tree properties in light of the great coefficient of assurance between the compressive strength and thickness. In three studies [29-31], authors inspected more than several articles distributed from 1995 to 2010 on utilizing a fractometer for dissecting wood properties, and the result of these reviews accentuated that mechanical properties of wood could be anticipated with this instrument. However, besides our study [5], there is only one accessible investigation of northern red oak using fractometer.

The authors [32] evaluated the fracture moment and fracture angle of core samples from the lower trunk of this tree species and 24 other species using fractometer. They determined that the results varied by core segment, and position of the tree. Also, there was a major variation in the results due to location, so they suggested that habitat factors could be the reasons for such differences. Factors such as climate, soil, available moisture, exposure to wind, past loading by snow and ice, and growth rate could be the source(s) of such variation [32]. It was concluded that in evaluating the strength loss associated with decay, fractometer results should be compared to the values obtained from clear samples of the same tree [32, 33].

Some studies have already found relationships between the results of fractometry analysis and mechanical characteristics of wood, strength and density lost using the correlation test [34], radial and longitudinal mechanical strength using the correlation test [26] and the compression strength obtained with the fractometer and the static test, also using a coefficient of correlation [27]. Scientists reported a wide variety of wood species, namely *Fagus sylvatica* L., *Populus* spp., *Picea abies* (L.) H. Karst., *Pseudotsuga menziesii* (Mirb.) Franco [35], *Taiwania cryptomerioides* Hay. [36], *Cryptomeria japonica* (L.f.) D. Don and *Pinus densiflora* Siebold & Zucc [27]. A few studies involved the prediction of wood mechanical properties from the values obtained in fractometry analysis, through the use of regression equation models, and some among them were highly efficient and precise. The resultant equations had medium to strong coefficients of determination (R^2). Such conditions are demonstrative of how values acquired utilizing fractometer are associated with the wood properties, which are communicated by regression coefficient (i.e., value for the regression equation for predicting the dependant variable from independent variable), while the efficiency and precision of the predictability of the given relationships are expressed by R^2. Given the previously mentioned writing, it is obvious that the flow comprehension of the connection between values got with fractometry examination and mechanical parts of wood has been very much contemplated; still, an examination into such a relationship for wood of northern red oak has not endeavoured previously.

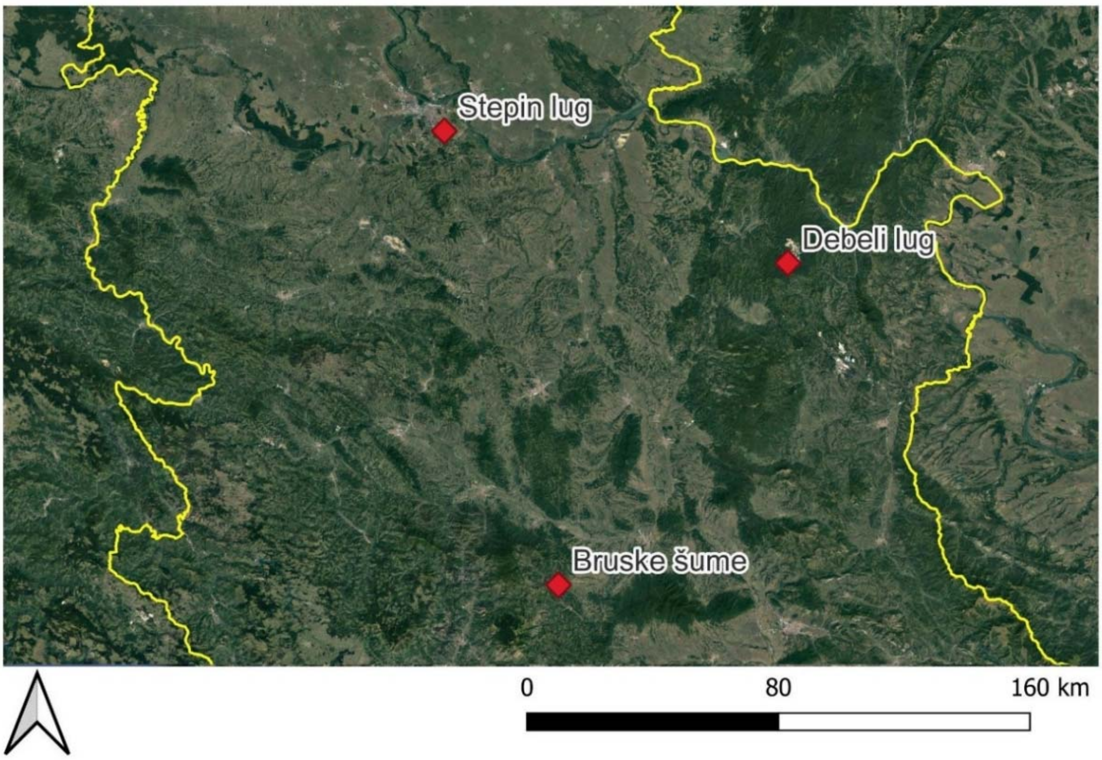

FIGURE 1
Locations of northern red oak forests in Serbia where samples were taken.

Therefore, this analysis tried to answer the following questions: (1) which fractometry parameters are correlated to which wood mechanical properties of northern red oak; (2) how high are these correlations; and (3) how efficiently and precisely the resulting equations predict the studied variables. Given these exploration interests, this study explores the connection between the fractometry estimations and the mechanical properties of wood, and all the more explicitly, which of these qualities are related to which wood properties, and how emphatically, as communicated through numerical conditions

In the present paper, core samples taken from a northern red oak tree from three different locations in Serbia were tested using Fractometer 2 and the results were compared to the results obtained with the standard destructive method on the samples of the same trees. The study aimed to determine the connection between semi-destructive measurements conducted using a fractometer and the values of standard measurements of wood properties of this non-native tree species that adapted very well to Serbian climatic conditions. Excluding our previously communicated preliminary results [5], the possibility of applying fractometer for assessing the properties of wood was examined in the country for the first time.

MATERIALS AND METHODS

Study area. The examined northern red oak trees were located in three different forests in Serbia (Figure 1). The first group of three trees was located in Debeli Lug in the vicinity of Majdanpek (44.367889°N, 21.905041°E), the second group of trees was sampled in Brus on Mt. Kopaonik (43.448750°N, 20.989536°E) and the third one is from Stepin Lug in the vicinity of Belgrade (44.748287°N, 20.530206°E). A visual tree inspection was conducted before core sampling.

Specimen preparation and testing methods. After visual inspection, core samples were extracted from nine trees at two heights above ground (1.4 m and 4.4 m) and in all four cardinal directions. Seventy-two pith-to-bark core samples (5 mm in diameter) were obtained from the trees with a core borer and used for determining the fractometar properties: compressive strength parallel to the grain, axial bending strength, and breaking angle.

The trees were cut down and two small logs, 400 mm in length, from the core sampled area were taken from each tree to the laboratory of the Faculty of Forestry, University of Belgrade, Serbia. Logs were cut, and two radial planks per direction from each tree were obtained. Samples with dimensions 20x20x320 mm were cut and grouped according to the tree height and cardinal direction. They were tested for modulus of rupture (MOR) and modulus of elasticity (MOE) by the three-point bending test (280 mm between supports, SRPS ISO 13061). After breakage, the rest of the samples were cut on 20x20x40 mm and tested for compressive strength parallel to the grain according to standard SRPS ISO 13061. Tests of wood density, static bending, and compression parallel to grain were conducted according to SRPS ISO 13061 standard. Before testing, all samples were conditioned at 21±2°C and a relative humidity of 65±5% for three weeks. Moisture content and wood density were determined by the oven-dry method.

The core samples were first tested for axial bending strength and breaking angle from pith to bark using a core sample testing device (Fractometer 2, IML), and then cut into small segments at 5 mm intervals. The values of compressive strength in each specimen were measured with the same tool.

Statistical analyses. To compare the properties of wood determined with the standard destructive method and those determined using a fractometer, the obtained numerical data were processed employing descriptive and multivariate statistical methods. Raw data were used to calculate the average values ($\bar{X}$) of all variables and to determine the average standard deviation (±SD) and coefficient of variation (CV) for every average value. The observed variables were also studied by comparing their minimum (MIN) and maximum (MAX) values with literature data. Before performing a multiple regression analysis, the variables were tested for normality and collinearity. The relationship between the properties of wood obtained with the standard destructive method and the properties determined with fractometer was identified using Pearson's linear correlation test. This relationship was also analyzed via a stepwise multiple regression method (with constant excluded) to generate the equation models that described the interactions. The statistical models were established based on measured data obtained from 137 samples taken from 9 trees, two heights and all four cardinal directions. All statistical analyses were performed using Statgraphics XVI.I (2009; Statpoint Technologies, Inc., Warrenton, Virginia, US).

RESULTS AND DISCUSSION

This paper examines the basic properties of the northern red oak wood (wood density, compressive strength in parallel to grain and bending properties), as well as the relationship between fractometric measurements obtained on the core sample (compressive strength in parallel to the grain, axial bending strength and fracture angle) and physical and mechanical properties of wood.

Descriptive statistics. Table 1 presents descriptive statistics for compressive strength parallel to the grain (σp F), axial bending strength (δs F) and breaking angle (Ba F) determined using fractometer, as well as wood density (WD), compressive strength parallel to the grain (Hp), modulus of elasticity (MOE) and modulus of rupture (MOR) obtained with standard, destructive method. The average moisture content during the examination was 12%.

Based on the presented data, the average value for compression parallel to grain measured with fractometer was 35.42 MPa with a coefficient of variation of 15.50%. Bending strength perpendicular to grain measured with fractometer was on average 9.26, with the highest coefficient of variation of 46.36%. The only available data for these properties is our previous research where the compression strength was 57.47 MPa, with a coefficient of variation of 10.99% and bending strength perpendicular to grain was on average of 19,32, with a coefficient of variation of 16.61% [5]. For breaking angles, apart from our previous research [5], there is only one research available. In this research [32], the mean value for the breaking angle was 16.70°, which is slightly lower than the value obtained in the present paper (17.39°). In our previous examination breaking angle was 21.46° [5]. In comparison to the other analyzed wood properties, wood density had the lowest coefficient of variation (7.71%), and a mean value of 0.71 g/cm^3. These values are within the range of the measurements given in the literature [e.g., 1, 6, 36, 37].

The values of compression parallel to grain ranged from 40.12 to 72.05 MPa, with a mean value of 60.35 MPa and a coefficient of variation of 11.60%. These values are very close to those obtained by the authors that studied the northern red oak in the eastern part of the USA [1]. Among the other analyzed wood properties, MOE had the highest coefficient of variation (24.50%). Still, the mean value (10074.94 MPa) was much higher compared to previous research. On the other hand, MOR showed a higher mean value (119.63 MPa) than those given in the same literature. For example, some authors [6] obtained 12,500 MPa for MOE and 99 MPa for MOR. An author [17] obtained 9,810 MPa for MOE and 62.1 MPa for MOR. The authors in the USA [1] obtained 12,211 MPa for MOE and 120 MPa for MOR. Since wood properties depend on many factors, such as climate, soil, elevation, exposition etc., and the results originate from different parts of the world, such variations are expected.

If we compare the obtained data with the values for the most important industrial domestic species of *Quercus* L. (i.e., sessile oak and pedunculate oak), we can conclude that the strength values are close to those shown by Šoškić [39], whereas the density and MOE of northern red oak deviate slightly. The same author stated that the properties of certain species of trees within the same genus depend on many factors, so variations are expected.

The results obtained in our investigation are the most similar to those presented by the authors in the eastern USA [1]. It can be assumed that the reason for this is similar climate conditions due to the similar geographical position of the trees examined and the use of similar testing machines and sample dimensions.

Regression analysis. Table 2 shows linear models which describe the relationship between wood properties tested with standard methods and values measured with fractometer.

According to the obtained results, the coefficient of correlation was within the range of 0.0026 to 0.2554, which shows that there is a great influence of different anatomical directions on wood properties. Namely, due to its heterogeneous structure and anisotropy, the wood's compressive and bending strengths differ between different anatomical directions even within a single species. In the present study, the strongest correlation occurred between MOR and compression parallel to grain (0.2554), while the weakest occurred between wood density and compression strength measured with a fractometer (0.0026). A low statistical significance was noticed between MOR and compression parallel to grain (0.2554) and all the other Pearson's coefficients are not showing a significant correlation.

TABLE 1
Descriptive statistics for wood properties of the northern red oak in Serbia determined with the standard destructive (SD) method and by using fractometer (F).

Method	Wood property	Count	$\bar{X}$	SD	CV (%)	MIN	MAX	Range
F	σp F (MPa)	137	35.42	5.49	15.50	17.00	46.60	29.60
F	δs F (Mpa)	137	9.26	4.29	46.36	2.00	23.00	21.00
F	Ba F(o)	137	17.39	4.21	24.25	8.00	32.00	16.00
SD	WD (g/cm^3)	137	0.71	0.05	7.71	544.94	892.62	347.22
SD	Hp (N/mm^3)	137	60.35	7.00	11.60	40.12	72.05	26.56
SD	MOR (MPa)	137	119.63	21.77	18.19	45.49	170.75	125.26
SD	MOR (MPa)	137	10074.94	2467.87	24.50	4687.17	17283.40	12596.23

TABLE 2
Coefficients of Pearson's correlations for wood properties tested with the standard destructive method and fractometer.

Wood properties – standard destructive method	Wood properties – fractometer	Coefficients of Pearson's correlations
WD	δpF	-0.0026
	δs F	-0.1131
	Ba F	0.0788
Hp	δpF	0.0561
	δs F	0.0405
	Ba F	0.0607
MOE	δpF	0.1578
	δs F	-0.0028
	Ba F	-0.0098
MOR	δpF	**0.2554**
	δs F	0.0788
	Ba F	0.0265

Note: Boldfaced numbers denote values that are statistically significant at the 95% confidence level.

TABLE 3
Multiple regression equation models and adjusted coefficient of determination for wood properties tested with the standard destructive method and fractometer.

Wood property	Multiple regression equation model (stepwise method; constant excluded)		Adjusted coefficient of determination (adjusted R^2)	Standard error of estimate
Density (WD)	yWD =	0,0148225 × σp F + 0,00957343 × Ba F	0.9753	0.11
Compression parallel to grain (Hp)	yHp =	1,20289 × σp F + 0,946356 × Ba F	0.9710	10.30
Modulus of rupture (MOR)	yMOR =	2,7065 × σp F + 1,26661 × Ba F	0.9620	23.80
Modulus of elasticity (MOE	yMOE =	229,951 × σp F + 102,138 × Ba F	0.9360	2650.05

There are only a few researches where fractometer measurements and standard wood property tests were compared. The results of our study are comparable to those obtained by Gruber and Hagermann [35]. The authors explored the bending solidity of 24 (1 m long) stem samples of *Fagus sylvatica*, *Populus* spp., *Picea abies*, and *Pseudotsuga menziesii*, using DIN 52186 and the fractometry method, and did not find any correlation between the DIN bending solidity and the fractometer measurements. The results of our review study [40] indicate that there is a significant positive correlation between the axial bending strength and the longitudinal compressive strength of wood. For instance, a group of authors [36] analyzed radial changes of living trees in *Taiwania cryptomerioides* and determined that the differences in crushing strength in the transverse direction increase from the pith to the bark. The analysis of variance and correlation showed that the value of the radial difference in crushing strength was lower than the tree-to-tree variation. Another group of authors [28] examined the wood properties of five Indonesian species and concluded that the compressive strength measured with fractometer could be applied to living tree properties based on a high coefficient of determination between this compressive strength and wood density. Since our research aimed to create a model for wood quality prediction using fractometer, it can be argued that further experiments must include a larger number of samples.

Multiple regression analysis. Multiple regression tests resulted in four successful models for each wood property studied, as shown in Table 3. In general, the obtained high values show that individual, as well as a combination of fractometric measurements, can be successfully used in the assessment of the investigated properties of wood. The highest value of the coefficient of determination was obtained when estimating the density of wood, and the lowest was when determining the MOE.

The compressive strength parallel to the grain and the fracture angle of the core samples were statistically determined as important variables that can influence the assessment of wood properties. Their influence is positive, while axial bending strength proved to be a parameter that is not statistically significant. These findings coincide with the results given by Matsumoto et al. [28]. On the other hand, Tang et al. [26] pointed out that the best indicators of tree strength are determined using a fractometer, compressive strength parallel to the grain and bending strength. The same authors pointed out the results which show that there is a dependence between these two properties and that their relationship depends on the tree species. The obtained values of R^2 in this paper indicate that the models are very successful in describing the data: however, it is still necessary to observe this in practice before reaching conclusions. Therefore, the results of future research should find an answer to the question of the efficiency and accuracy of the model predictability.

CONCLUSION

Based on the obtained results, it can be concluded that the values of the investigated properties are in the interval of literature data for the examined tree species. The determined strength values are similar to the data given for sessile and pedunculate oak, while the average values of density and modulus of elasticity deviate, but not significantly. Statistical analysis showed that axial bending strength cannot be used as a reliable parameter in assessing wood quality, while the relationship between compressive strength and fracture angle and properties of northern red oak wood obtained multiple regression dependence with a coefficient of determination that was in the interval from 0.936 to 0.975. The primary advantage of the obtained models is the ability to predict the quality of wood before cutting trees, which could positively affect the optimal and further exploitation of wood. The presented results indicate which parameters measured on the live tree give the best picture of the quality of wood.

Considering the very scarce literature in Serbia on the properties of the northern red oak wood, this research contributes to the knowledge of the variability of the physical and mechanical properties of wood of this introduced oak species, as well as the relationship between wood mechanical properties and fractometric measurements established on oak trees.

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