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Research Article

Physical properties and structural features of common walnut (*Juglans regia* L.) wood: A case-study

Physikalische Eigenschaften und strukturelle Charakteristika des Holzes der Walnuß (*Juglans regia* L.): Eine Fallstudie

Mihai-Florin Ostafi[1], Florin Dinulică[1], Valeriu-Norocel Nicolescu[1]*

[1] Faculty of Silviculture and Forest Engineering, University "Transylvania" of Brasov. Sirul Beethoven 1, 500123 Brasov, Romania
* Corresponding author: nvnicolescu@unitbv.ro

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Summary

We assessed wood quality in common walnut using a combination of physical properties and structural features. Five common walnut trees were selected and processed in order to produce wood samples for further analyses.
The results showed a wide spread of values of structural features and of wood water content. The color indices were strongly grouped around the averages. All experimental distributions were stratified following at least one of the analyzed factors (tree and its structural directions i.e. longitudinal, radial, and tangential). The radial anisotropy was the most pronounced. The longitudinal stability of density and water content, the inter-tree stability of color saturation as well as the homogeneity of all color indices on the girth were noticed. The heartwood covered up to 12.5% of transverse section and included 1–10 growth rings. The annual rate of bio-accumulation allowed the separation of stages of radial development of the structure using the width of growth rings: *juvenile wood*, composed of the first 8–9 rings from the pith; a *transition zone* to the mature wood (10 rings); and *mature wood* under way to be formed. Wood density was not a reliable criterion for differentiating the sapwood from heartwood but brightness, redness and hue's color could be used for this purpose.

Keywords: common walnut, wood quality, physical properties, structural features, heartwood, juvenile wood, mature wood

Zusammenfassung

Eine Kombination unterschiedlicher physikalischer und struktureller Holzkennwerte wurde eingesetzt, um Walnußholz zu untersuchen. Hierzu wurden fünf Probebäume ausgesucht, bearbeitet und definierte Holzproben hergestellt.
Die Ergebnis zeigten eine weite Streuung bei den Werten der strukturellen Kennwerte sowie des Wassergehaltes. Die Farbkennwerte waren streng um die Mittelwerte gruppiert. Alle experimentellen Verteilungen wurden an mindestens einem der analysierten Faktoren stratifiziert (der Baum und sein strukureller Aufbau, d.h. longitudinal, radial und tangential). Die radiale Anisotropie war dabei besonders ausgeprägt. Die Stabilität von Dichte und Wassergehalt in longitudinaler Richtung, eine Stabilität der Farbsättigung zwischen den Probebäumen sowie eine Homogenität aller Farbindices im Randbereich konne festgestellt werden. Das Kernholz deckte bis zu 12,5 % des transversalen Abschnittes ab und umfaßte 1–10 Ringe. Die jährliche Bioakkumulationsrate erlaubte eine Trennung von Stadien der radialen Strukturetwicklung auf Basis der Breite der Zuwachsringe: juveniles Holz, die ersten 8–9 Ringe um das Mark umfassend, eine Übergangszone zum reifen Holz (10 Jahrringe) und reifes Holz in Entstehung. Die Holzdichte war kein zuverlässiges Kriterium um Splintholz von Kernholz zu unterscheiden, jedoch konnten Helligkeit, Rötung und hue's Farbe zu diesem Zweck erfolgreich eingesetzt werden.

Schlagworte: Walnuß, Holzqualität, physikalische Eigenschaften, strukturelle Charakteristika, Kernholz, junges Holz, reifes Holz

1. Introduction

The high esthetic/decorative as well as commercial values of walnut wood, acknowledged since centuries ago, are due to both color and appearance (Evelyn, 1664; Poskin, 1926; Dumitriu-Tataranu, 1960; Stanescu, 1979; Hart, 1994; Desch and Dinwoodie, 1996; Becquey, 1997; Stanescu et al., 1997; Sofletea and Curtu, 2007). The pronounced intra-specific color variability in common walnut *Juglans regia* L. (Rameau et al., 1989) has allowed the differentiation of geographical varieties, depending on the degree of uniformity, darkness and streakiness. These varieties have become commercial varieties, of which *Ancona*, *French*, *Circassian*, and *English* walnut are the best known (Jane, 1956).

In *Juglans* species the heartwood formation is stimulated by the abundance of parenchyma – the site where metabolites are elaborated (Panshin and Zeeuw, 1970) – which compensates for the low starch content (Wagenführ, 1989). However, the scale and rate of heartwood formation in black walnut (*Juglans nigra* L.) do not depend on the volume of anatomical resources involved but on the metabolic frame provided by the transition zone (Nelson, 1975; 1976).

During heartwood formation a large amount of secondary metabolites, extractable in hydrocarbons or warm water, are mobilized in the transition zone (Uprichard, 1963). These metabolites can provide a deep incrustation of cell walls (Kininmonth, 1972), especially in the S_2 layer of the secondary wall (Kuo and Arganbright, 1980). The transition zone in the heartwood is a space with intermediate values of physical properties (Hillis, 1968a) but with high physiological activity (Hillis, 1968b), highly sustained enzymatically mostly in the latewood (Dehon et al., 2002), and consisting of a semi-anaerobic active metabolism including polymerization of phenols (Frey-Wyssling and Bosshard, 1959).

A high proportion of these metabolites have chromatic characteristics explaining the individuality of heartwood. In *Juglans* species, the similar content of polyphenols in young plants and stump shoots suggests the stability of color through vegetative propagation (Jay-Allemand et al., 1987). Variations of color on the same sample, which are the consequence of uneven distribution of secondary metabolites within the heartwood (Zheng et al., 2009), or the symptom of an abnormal coloration (Bauch, 1984), represent important qualitative defects in walnut wood (Phelps et al., 1983). The uneven diffusion of color precursor in the space of future heartwood, showing pronounced longitudinal lines – a trademark of some walnut provenances – indicates difficult conditions of vegetation (Bamber, 1987). The environment influences the wood color of common walnut by soil water content (Savill, 2013); this is also the case of pedunculate oak (*Quercus robur* L.) but not of sessile oak (*Quercus petraea* (Mattuschka) Liebl.) (Klumpers et al., 1993).

The occurrence of tension wood, abundant in some *Juglans* species, especially in the root xylem (Höster and Liese, 1966), adds an extra variable to the color issue, which affects especially the brightness (Barbacci et al., 2008).

It was assumed until recently (Fady et al., 2003) that the environment had a dominant influence on the qualitative traits of walnut wood. The influence of environment on traits influencing heartwood formation is dominant (Rink and Phelps, 1989), without excluding a substantial genetic gain acquired by selection (Woeste, 2002). The same dominant contribution of environment to heartwood formation was also determined in the case of radiata pine *Pinus radiata* D. Don (Nicholls and Brown, 1974) while genetics (not environment) plays a massive role in heartwood variability in larch *Larix* sp. (Pâques, 2001).

Genetic improvement of walnut wood aims at producing a darker wood in the largest proportion of transverse section of the trunk. Accordingly, the main selection criteria are brightness (wood color) and proportion of heartwood. The side-effects are contradictory: in case of black walnut, Rink and Phelps (1989) suggested the reduction of height growth to obtain a substantial gain in wood darkness while, on the contrary, Woeste (2002) reported a direct proportionality between the trunk diameter and size of heartwood. In common walnut, the promotion of tall trees by silvicultural interventions favors resistance to diseases and frosts, two traits with high and moderate heritability, respectively (Díaz and Férnandez-López, 2005). In the programs for the genetic improvement of walnut, the wood quality and vigor are convergent selection criteria (Dufour and Jay-Allemand, 1986). However, the phenotype correlation between the growth traits and degree of wood brightness imposes a compromise in adopting the selection criteria.

The size of the heartwood is the best expression of the potential of raw material to provide decorative textures (Bowyer et al., 2003). In producing veneer from walnut wood, the sapwood (which is particularly vulnerable to the woodworm *Anobium punctatum* de Geer) is considered nonusable, sometimes even being removed (Savill, 2013). To avoid this loss, steaming of lumber before seasoning is frequently practiced; the initial humidity of wood as well as working temperature are crucial for producing the most favorable effects on product color (Brauner and Loos, 1968). In common walnut wood, sapwood is more receptive than heartwood in terms of coloring when boiling in order to prepare the slicing of veneer, the irreversible changes of color occur after a minimum of 10 hours (sapwood) compared to 36 hours (heartwood) of treatment (Charrier et al., 2002).

For many wood uses, density is identified with the quality itself; the mechanical properties (Zhang, 1996) and pulp yields (Zobel and Bujtenen, 1989) are its direct consequences. The sense in which the indicator value of density is manifested differs depending on various uses of wood. Out of *Juglans* sp. of commercial interest in Europe, common walnut shows the lowest porosity and, implicitly, the highest density (about 670 kg m^{-3}, at 15% moisture content; cf. Savill, 2013); consequently its physical and mechanical properties of wood are superior to those of black walnut and butternut (*Juglans cinerea* L.) (Anonymous, 1941).

Taking into account this background information, the research reported in this paper have sought to assess the quality of common walnut wood using physical properties and structural features and outlining the factors involved in the size variation of such markers.

2. Material and methods

2.1 Sampling

The fieldworks were derived from common walnut trees in a privately owned 35-years-old mixed broadleaved plantation (species composition: 40% common walnut, 30% wild cherry *Prunus avium* L., 20% field maple *Acer campestre* L., and 10% hornbeam *Carpinus betulus* L.), on the Teleki Forest Estate in central Romania. The stand is located in the Sub-Carpathian Hills close to the Peris village (Mures County), at the interface with the Transylvanian Plateau (46°41'34"N 24°41'33"E); elevation 410 m, aspect south, slope 15°. The natural vegetation consists of mixed broadleaves dominated by sessile oak.

The wood samples were collected from five common walnut trees selected in the areas with higher stand stocking. Prior to felling, diameters at breast height and total heights of these trees were measured. The north and east directions were marked on the bark of these trees. The five trees had diameters at breast height ranging between 15 and 20 cm and total heights between 15.7 and 19 m. After de-branching, the trees were transversally cut every 2 m. From each resulting section, a disc was extracted and identification data as well as north and east directions were marked. Along with the disc, two smaller samples were extracted from each stem section, one from the inner-wood and the other from the outer-wood of sections. The samples were weighed in the field immediately after collection to allow the determination of moisture content. All samples were packed in sealed containers. In this part of sampling the material consisted of 42 discs (8 or 9 per tree) and 84 samples for the determination of moisture content. Immediately after collection, all samples were transported to the laboratory.

A second phase of sampling was necessary for the measurement of color in radial section. In this respect, each disc was split along the north–south axis, and a sample of 1 cm width was extracted from the disc. The two remaining halves of the discs were cut on the east–west direction.

The samples for determining the conventional density resulted after delineation of the two radii of the sample, by cutting to the pith direction, and separation of radii into three sectors with dimensions corresponding to the zones determined by the occurrence of heartwood: sapwood (S3), transition to heartwood (S2) and heartwood (S1) – this was the third phase of sampling. The samples originating from the trunk and not containing heartwood were separated into two or three samples of the same length. The numbering of sectors started from the pith. There were 216 samples from this phase.

2.2 Measurement of structural features

Two structural features were examined: (1) the width of growth rings (RW) and (2) the size of heartwood, expressed by two variables: proportion of heartwood (percentage of under-bark area of section, HP) and the number of growth rings as part of heartwood.

Prior to that the smoother face of each disc was sanded using finer and finer grains down to 120x. The polished surfaces were cleaned and marked for the four cardinal directions; numerical codes were marked on the discs for the identification of samples. The samples were subsequently photographed for the determination of proportion of heartwood using the AUTOCAD 2010 program. The professional pack WinDENDRO™ 2006 was used to measure the growth rings. The working procedure (Régent Instruments, 2007) involved scanning discs with a high-resolution EPSON scanner and importing images into the WinDENDRO software, with which the identification and semi-automatic delineation of growth rings was performed (Figure 1).

The results of measurements were downloaded into a .txt file converted into a database using Microsoft Excel, containing the raw data on ring widths. Because of the pseudo-diffuse or diffuse to semi-ring porous distribution of vessels in the annual growth architecture of common walnut (Schweingruber, 1990; Geldhauser, 1993; Beldeanu, 1999; 2008), the separation of latewood from earlywood is imprecise. In these circumstances, only the delineation of growth and the measurement of growth rings were performed.

2.3 Determination of physical properties

Water content, density and color were the wood properties examined in the experimental material. The wood color was explored using the portable chroma meter CR 400 (Konica-Minolta, 2007). Its measuring head has an aperture of 8 mm and is equipped with a xenon lamp. Measurements were carried out with CIE standard illuminant C, at an angle of 0° of illumination diffusion. The instrument was set for three consecutive scans of the same surface. For the mathematical transposition of color, the chromatic system CIELAB (syn. CIE 1976 (L*a*b*); cf. Hunt, 1998), providing a colour characterization of wood species (Teischinger et al., 2012) and considered the most popular tool in the study of wood color (Janin, 1987), was chosen. This system decomposes tri-dimensionally the reflected spectrum using the following axes of coordinates: L^* - lightness, a^* - expresses redness or greenness, b^* - expresses yellowness or blueness.

The color space CIELAB was also explored with the derived measures:

h – hue angle, calculated as:

$$h = \arctan\left(b^*/a^*\right) \tag{1}$$

C^* - chroma, a measure of saturation:

$$C = \sqrt[2]{a^{*2} + b^{*2}} \tag{2}$$

ΔE – color differences, with relation:

$$\Delta E = \sqrt[2]{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \tag{3}$$

The components of color have been measured on one of the radial faces of each segment of sample, after the absorption of dust, which is an important source of errors. The measurements were carried out after the material reached the equilibrium water content (12±2%) with the environment in the laboratory where it was stored during the conditioning period (temperature 20±2°C, air humidity 65±5 %). Each surface was probed with the chroma meter in three points and the mean of the values was calculated. The pos-

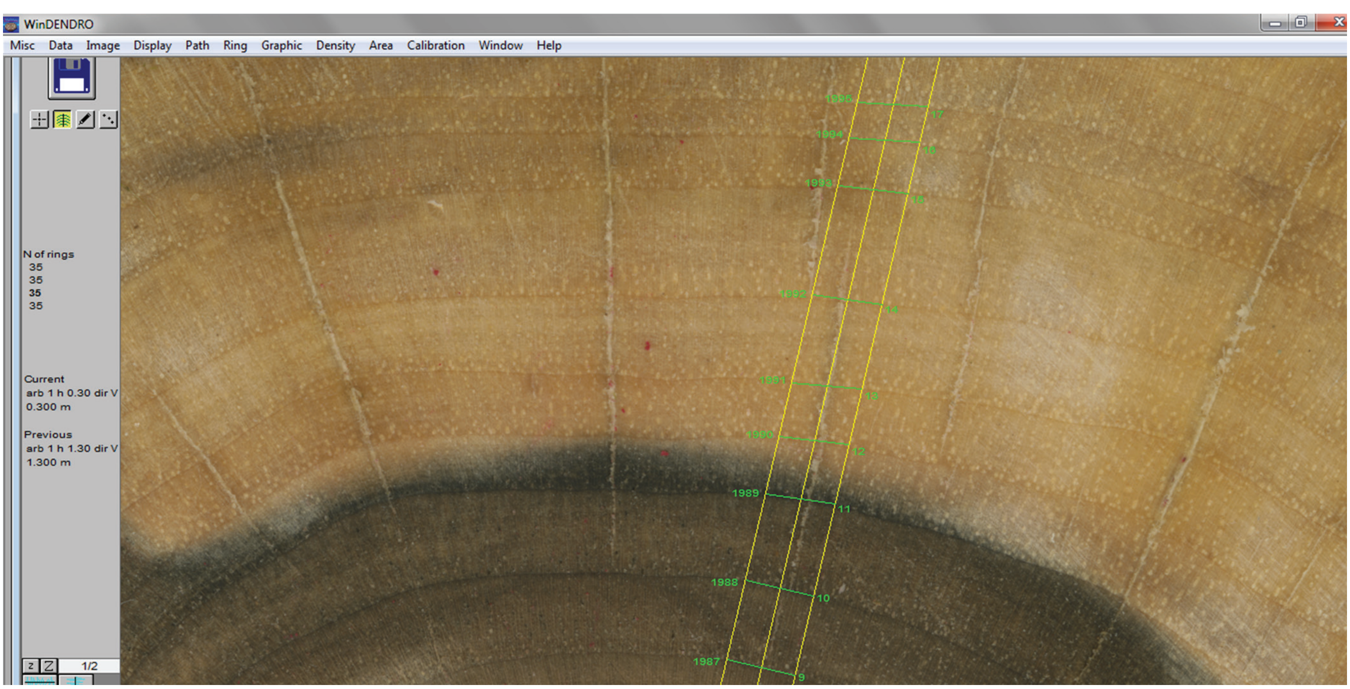

Figure 1. The path of growth ring measurement.
Abbildung 1. Meßstrecke für die Jahrringmessung.

sible change in common walnut wood color with age was analyzed by comparing the field material with a control sample of decorative veneer taken from common walnut wood, part of the collection of the Faculty of Silviculture and Forest Engineering in Brasov-Romania. The control sample consisted of 17 pieces which were subject to the same color determinations as the sampling trees, stratified using the same system (i.e., part of sapwood, transition zone, or heartwood).

The moisture content (MC) was determined using the ovendrying method and expressed as a ratio (%) between the mass of water in the sample and the mass of fully dried sample (Kollmann and Côté, 1968).

The method of maximum moisture content (Keylwerth, 1954) was used to determine the basic (conventional) density (BD). The mean value of 1.53 $g \cdot cm^{-3}$ (Stamm, 1929; Wilfong, 1966) was adopted in the relation used for the calculation of specific gravity of wood substance. The samples were brought to the saturation point by boiling in distilled water (Polge, 1963) down to their total immersion, a process lasting for up to 6 hours. The water was replaced from time to time in order to remove the hydrosoluble extractives that could lead to bias in determination (Taras and Saucier, 1967). The samples were weighed after cooling and then dried down to 0% water content. In the calculation of conventional density, only the weighing carried out before and after drying the samples were used (Smith, 1954).

The anhydrous state of wood, needed for the determination of BD and MC, was obtained using a moisture analyzer (precision of 1 mg), in fact a miniature artificial kiln equipped with a halogen bulb for warming up. The samples were exposed to a temperature of 103±1°C until

Table 1. Reference values for analyzed physical and structural indices of common walnut.
Tabelle 1. Referenzwerte für die analysierten physikalischen und strukturellen Kennwerte von Walnuß.

Wood property		Range (minimum/average/maximum)	Source of information/author's sampling
MC (%)		-/-/105	Vorreiter, 1963
BD ($g \cdot cm^{-3}$)		-/0.52/-	*** 2014
*L** (%)		57.4/39.5	Teischinger et al., 2012 The two values define untreated(dry)/wetted surface
*a**		10.9/21.1	
*b**		24.7/49.9	
*C**		27.1/54.4	
h		66.1/67.0	
*L** (%)	SW	-/87/-	Burtin et al., 1998 Age of trees: 17 years. Measurements performed on radial section, at 0.15 m height, in heartwood (HW), transition zone (TZ) and sapwood (SW)
	TZ	-/82/-	
	HW	-/52-60/-	
*C**	SW	-/18/-	
	TZ	-/21/-	
	HW	-/18-20/-	
h	SW	-/74/-	
	TZ	-/70/-	
	HW	-/63-68/-	
*L** (%)	SW	48/55/64	Control sample, see the text
	TZ	46/50/53	
	HW	36/47/57	
*a**	SW	6.2/9.4/12.4	
	TZ	9.2/10.7/12.3	
	HW	5.6/7.1/10.2	
*b**	SW	17.3/23.1/26.6	
	TZ	19.3/22.2/25.7	
	HW	14.8/17.9/20.9	

a constant mass was achieved (Kollmann and Côté, 1968; Williamson and Wiemann, 2010). The drying process was conducted electronically in standard profile and completed when the mass difference was less than 1 mg over 30 seconds (Ohaus, 2001).

2.4 Processing of experimental data

The calculation of indicators BD, MC, *h*, *C**, and Δ*E** was carried out using Microsoft Excel. The raw data of RW, HP, *L**, *a** and *b**, along with synthesis indicators, were imported into STATISTICA 8.0 (StatSoft, 2007), the instrument for data processing and graphical representation. The mathematical processing of data was implemented in accordance with Zar (1974). For producing the regressions, variables with percentage values were arcsin(square root) transformed. For the cluster analysis the single linkage as amalgamation rule as well as Euclidian distances as measure unit were adopted. For the interpretation of results the distributions of experimental variables were compared with the values reported by other researchers (Table 1).

Regarding the color components the comparison with the control sample, obtained by observing the tangential section of wood, is valid as the longitudinal sections are confounded by/to the level of mean color indices (Sullivan, 1967).

Table 2. Descriptive statistics of non-stratified distributions of analyzed indices.
Tabelle 2. Descriptive Statistik der nicht-stratifizierten Verteilung der analysierten Kennwerte.

Variable	Mean	Median	Minimum	Maximum	Coefficient of variation (%)	*W* / *p**
RW (mm)	3.00	2.72	0.098	24.45	55.34	0.94/0.061
HP (%)	2.81	0	0	15.15	142.64	0.74/<0.001
MC (%)	78.34	73.97	22.48	192.28	41.34	0.92/<0.001
BD ($g \cdot cm^{-3}$)	0.520	0.515	0.416	0.684	9.04	0.97/<0.01
*L** (%)	79.62	83.06	51.14	87.95	11.39	0.75/<0.05
*a**	1.96	1.72	–4.94	6.96	84.58	0.97/<0.05
*b**	19.47	19.35	14.28	38.61	11.55	0.83/<0.05
h	83.76	84.71	70.00	89.97	5.53	0.93//<0.001
*C**	19.64	19.45	14.54	38.92	11.21	0.82/<0.001

* W statistics from Shapiro-Wilk normality test (if p≤0.05 then the hypothesis of normality should be rejected)

Table 3. Statistical significance of the influence of some factors on the indicators.
Tabelle 3. Signifikanz-Analyse bezüglich des Einflusses unterschiedlicher Faktoren auf die analysierten Kennwerte.

Variables	Factors (independent discrete variables)			
	Tree	Height's cross section	Radius	Segment on radius*
	H statistic from Kruskall-Wallis test/*p* probability**			
RW	39.11/<0.001	27.03/0.001	14.75/0.002	-
HP	7.93/0.09	22.90/0.004	-	-
MC	41.68/<0.001	8.23/0.31	-	3.80/0.05
BD	17.50/0.002	7.34/0.39	13.14/<0.001	9.56/0.008
*L**	31.55/<0.001	68.76/<0.001	1.27/0.74	141.72/<0.001
*a**	33.08/<0.001	75.16/<0.001	1.39/0.71	158.80/<0.001
*b**	3.23/0.52	16.64/0.02	0.52/0.92	33.4/<0.001
h	29.18/<0.001	61.78/<0.001	1.50/0.68	159.28/<0.001
*C**	3.33/0.50	15.65/0.03	0.38/0.94	21.90/<0.001

* Discrete variable with the following values: 1 for heartwood, 2 for transition zone, and 3 for sapwood

** Significance level 0.05

3. Results

3.1 The range of variability of indices and sources of variation

The qualitative traits showed a considerable dimensional heterogeneity, increasing in the order $h \rightarrow BD \rightarrow C^* \rightarrow L^* \rightarrow b^* \rightarrow MC \rightarrow RW \rightarrow a^* \rightarrow HP$ (Table 2).

The chroma and saturation attributes of color, as well as wood density were the variables most clustered around the averages. In contrast, the proportion of heartwood and the a^* component of color, with values on both sides of origin of color coordinates, were highly dispersed.

The instability of red–green chroma is the consequence of a different degree of heartwood formation in subjected trees. However the displacement of the range toward red was clear with only 8% of the values of variable a^* being negative. In those sections where heartwood formation was observed its proportion was 6% on an average. Twenty-two out of the 42 discs did not contain any heartwood so that the median moved toward the 0 value (Table 2).

The absolute water content of the experimental material (Table 2) exceeded the values from the references (Table 1) and reflected the physiological needs imposed by the onset of growing season (end on March, the moment when the field material was collected for investigations). The sapwood–heartwood gradient of water content of investigated material was less than and of a different sign than in black walnut (Kollmann and Côté, 1968).

The sample trees showed radial increments much higher than the values from the old literature (Hugo, 1951). The average series of RW showed a slightly decreasing trend after 9 years, once the transition from earlywood to latewood occurred. The minimum annual values ranged, from tree to tree, between 0.1 and 0.8 mm. The lower limit was reached at 7.3 m height from the ground. The maximum annual values, frequently between 5 and 10 mm, reached 24.4 mm at the age of 9 years and height of 3.3 m; in fact, this value is a severe outlier, explained by the local presence of double heart. The central trend of distribution of density was similar to the values from the literature (Table 1).

With some exceptions (a^*, average series of RW, and h), the distributions of experimental variables were skewed and peaked (the skewness and kurtosis values were not included into the tables).

Especially b^* and C^* were skewed to the left and extremely leptokurtic, while L^* showed a typical exponential-decreasing trend.

With one exception (RW), the distributions of research variables were not normal (Gauss-type) (Table 2) and consequently their analysis used non-parametric statistics. The wide variability of examined indicators required the stratification of their experimental distributions. The stratification variables used were: tree, location of section in relation to the tree collar (ground), the radius of section in relation to the cardinal directions as well as the sector along the radius owing to the zoning determined by the presence of heartwood (Table 3).

The proportion of heartwood, the yellowness and chroma of color do not vary between trees; however all measured traits segregated considerably on at least one of subsequent levels marked into the trunk space. Another striking observation (Table 3) was the absence of girth variability of wood color. Besides, the radial variability (between rings or sectors delineated by radii) is unanimous. Instead there was no statistical reason to sustain the modification of water content and density depending on the distance from the tree collar (ground).

The matrix of multiple comparisons associated with the non-parametric test used (which was not displayed) shows that the between-tree variations are not consistent because of the trees no. 4 and 5 (belonging to lower Kraft classes) and sometimes to tree no. 3. The absence of heartwood in tree no. 4 was chromatically different but only depending on brightness, redness, and hue angle (Figure 2A-E).

Consequently the occurrence of heartwood did not significantly modify the color on yellow-blue coordinate, at least in the analyzed life stage (early maturity). The specific micro-site conditions (slopes of humid micro-depressions) probably explain the physical and structural non-conformism of wood in trees no. 4 and 5: the much higher water content reversely distributed in the transverse section than in other trees (water content of sapwood was lower than that of inner-wood; Figure 2F) as well as slower increments (Figure 2G). The box-plot diagrams (Figures 2G and 2H) suggest a certain functional dependence/correlation between wood density and growth, which will be discussed later on (Section 3.3).

All research factors have achieved the stratification of growth series (Table 3). For instance, depending on height, an S-shaped trend of RW, reaching the peak at the base of the crown (section 7–11 m), was distinguished (Figure 3). The radial regularity of RW, pretty well synchronized with the distance from the ground, makes quite transparent the location of juvenile wood within the transverse section (Figure 4).

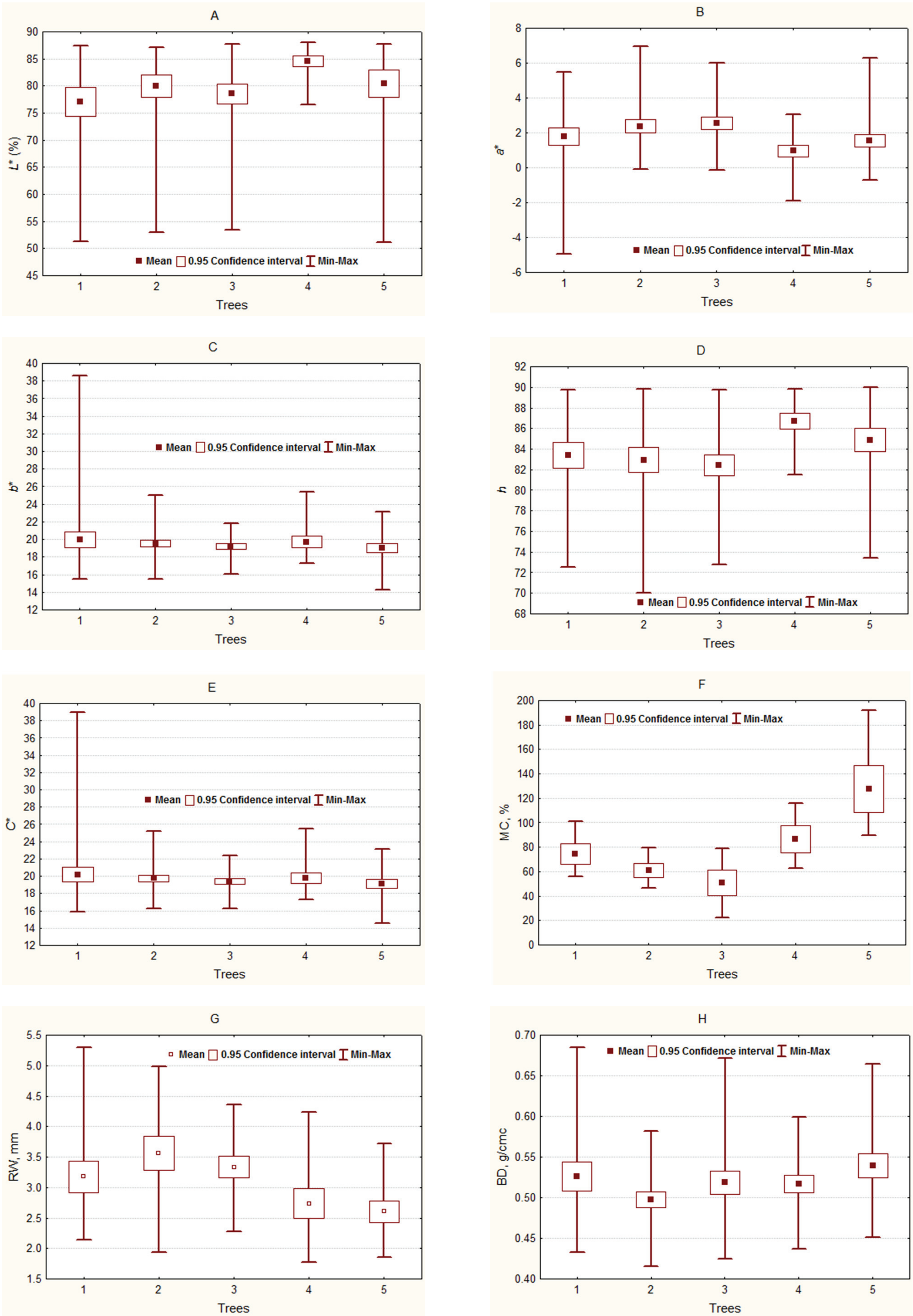

Figure 2A-H. Variation of physical properties and structural features by tree (A: L*, B:a*, C:b*, D:h, E:C*, F:MC, G:RW, H:BD).
Abbildung 2A-H. Variation der physicalischen Eigenschaften und strukturellen Charakteristika nach Probebäumen (A: L*, B:a*, C:b*, D:h, E:C*, F:MC, G:RW, H:BD).

The average series of RW by height sections allows the delineation of three radial sectors of structural development: *juvenile wood*, in the first 8–9 rings from the pith; a *transition sector* toward mature wood, completed by the age of 18–19 years; and *mature wood*, in acropetal expansion. The tangential direction is one of the coordinates of anisotropic characteristics RW and BD (Table 3). The stratification of experimental values of RW depending on the location of measurement of radius in relation to cardinal directions shows the quite surprising association of wider rings to the north direction (Figure 5). The radius on the shaded side accumulated more wood substance, a fact demonstrated by the central trend of characteristic BD. The range of BD on the two cardinal directions was similar.

3.2 Current state of heartwood formation and definition of heartwood

If the tree no. 4 is ignored, the non-stratified content of heartwood does not show a significant in-between tree variation (Table 3). Its axial trend (Figure 6) is better explained by a third-degree curve.

There was considerable variation between trees, especially regarding the size of heartwood at the trunk base; in this area the non-transformed HP ranges between 0% and 13%. No heartwood was found higher than 9.3 m height. This suggests that heartwood formation started at 25–29 years of age. The location of heartwood in longitudinal section of trunk suggested a delay of its formation of up to 2 rings/m of height, the lower one being encountered in trees growing slowly. The peculiar cases of trees no. 2 and 3, with abnormal peripheral coloration associated with a wound in the section of 0.30 m height and narrower heartwood than in the upper sections (at upper heights) suggest a delay of heartwood formation because of wound closure.

All qualitative indicators but especially color could be used to separate the three radial zones in which the transverse section was divided (Table 3). However, although the radial variation of red color, brightness and hue was discriminatory in relation to each of the three zones, the differences in yellowness and chroma between the transition zone and sapwood were not statistically significant (Table 4).

Neither could „conventional wood density" be used to separate the three radial zones satisfactorily. Especially, the transition zone was identified with heartwood in relation to wood density, so the significant influence of radial zone is determined by the tangible differences between sapwood and heartwood.

Consequently, it is possible to compartmentalize the cross-section depending on the size of some qualitative indices under the pressure of heartwood formation (Table 5).

Corroborating the indications offered by color indices the displacement of dominant wavelength toward red color along with heartwood formation is deduced. The fact that the negative values of a^* have been recorded almost without exception in sapwood can not be neglected. The tree-to-tree variation resulted in a wider diversity of values of BD in the heartwood than in the other two radial zones. The lowest values of BD were recorded in the transition zone toward heartwood.

3.3 Relationships between indices

The cluster analysis identified two important groupings (Figure 7):

- brightness and water content;
- color and structural indices.

Table 4. Statistical coverage of differences between the wood in the transition zone and the wood in the other two radial zones.
Tabelle 4. Vergleichende Analyse zwischen dem Holz der Übergangszone und dem Holz in den anderen beiden radialen Zonen.

Variable	Comparison with heartwood	Comparison with sapwood
	Probabilities (significance level 0.05)	
BD	0.95	0.13
L^*	<0.001	<0.001
a^*	<0.001	<0.001
b^*	<0.001	0.20
h	<0.001	<0.001
C^*	<0.001	0.59

Table 5. The range of color in radial stratification of examined material.
Tabelle 5. Variationsbereich der Farbe bei radialer Stratifikation des analysierten Materials.

Variable	Heartwood	Transition from sapwood	Sapwood
	Hingespread (1st quartile to 3rd quartile)		
L*	56.65–75.53	78.09–83.73	83.25–86.37
a^*	3.09–4.77	1.76–3.04	0.42–1.38
b^*	15.99–19.70	18.53–20.22	18.79–21.00
h	74.54–80.42	81.20–84.87	85.73–88.48
C^*	16.59–19.95	18.67–20.33	18.83–21.00

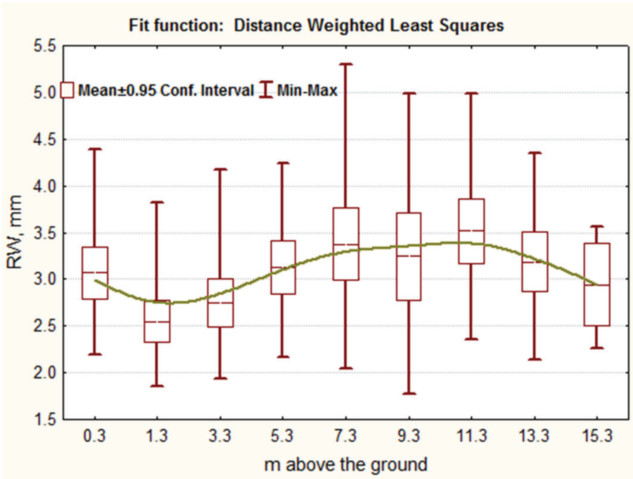

Figure 3. Ring width (RW) range in axial stratification.
Abbildung 3. Bereich der Ringbreite (RW) bei axialer Stratifikation.

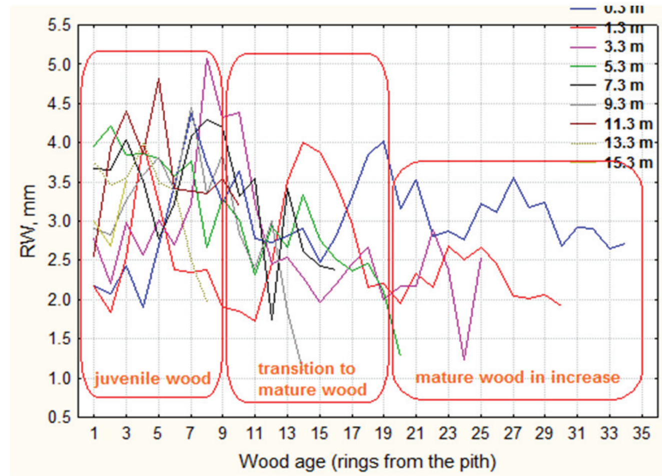

Figure 4. Radial variation of growth ring width (RW) at different tree heights.
Abbildung 4. Radiale Variation der Ringbreite (RW) bei verschiedenen Baumhöhen.

The intensity of relations between the cluster members was evaluated using the coefficients of simple non-parametric correlation Spearman (*R*) – these values were not shown in the tables. The values of these coefficients stress the governing role played by the wood water content on brightness of wood in heartwood (*R*= –0,675, $p<0.05$). Because the color indices were measured on air dried wood, one can infer an influence of water content of green wood on the degree of white in its color. The higher water content hinders the migration of visible spectrum toward red (*R*(MC, *a**–sapwood)= –0.454, $p<0.05$), strengthens the yellowness (*R*(MC, *b**–sapwood)= +0.487, $p<0.05$), without influencing the degree of expansion of heartwood (*R*(MC,HP)= –0.032). Also, trees with higher growth rates retained more water (*R*(MC,RW)= –0.675, $p<0.001$).

The conventional wood density is a variable of association only for the red color (Figure 8), being in a relation of reverse proportionality. With this exception, the color seems not transmitting any indication, statistically significant, to wood density. Neither the increment is an explicit variable for the parameter BD, its contribution to the variability of wood density being only 8%, despite the relation suggested in Figure 3.

The color parameters *L**, *a**, and *b** are in general correspondent (|*R*|= 0.41…0.71). The only exception is the size of red color of heartwood, which does not seem to be af-

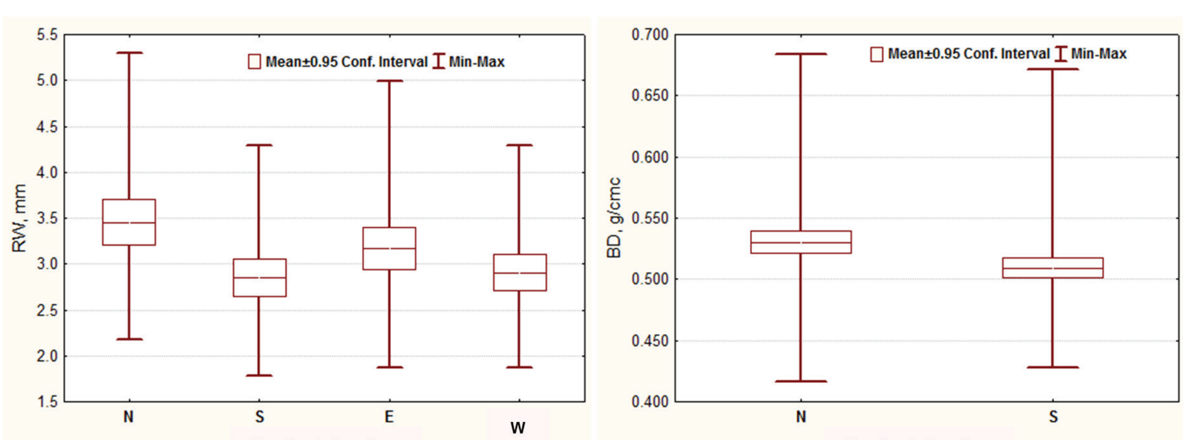

Figure 5. Range variations of ring width (RW, left) and basic density (BD, right) in relation to cardinal directions (N = north; S = south; E = east; W = west).
Abbildung 5. Variationsbereich der Ringbreite (RW, links) und Dichte (BD, rechts) in Verhältnis zu den Hauptrichtungen (N = Norden; S = Süden; E = Osten; W = Westen).

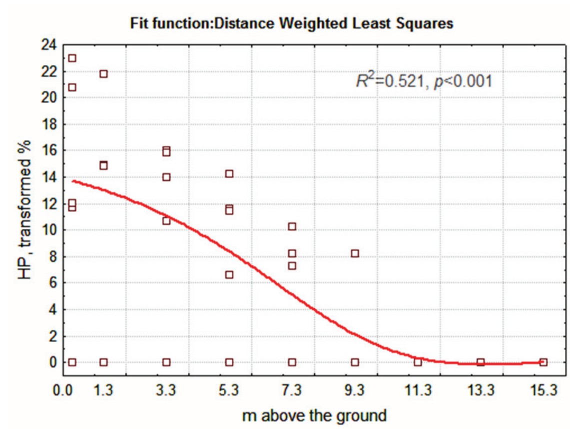

Figure 6. Regression of relative heartwood content depending on the distance from the ground (R^2 from Spearman rank order correlation).
Abbildung 6. Regression des relativen Kernholzanteiles in Abhängigkeit von der Höhe über dem Grund.

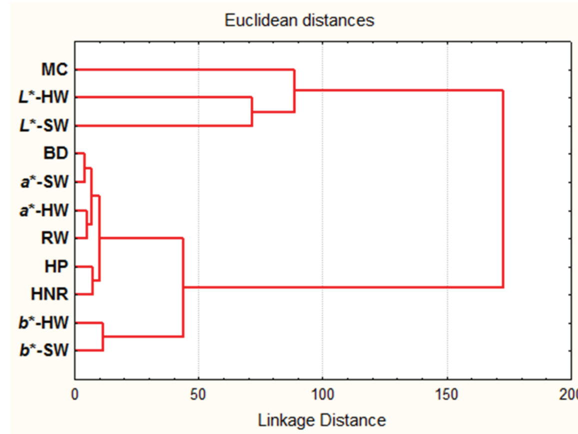

Figure 7. Tree diagram of relations between the analyzed qualitative wood variables.
Abbildung 7. Clusteranalyse des Zusammenhanges zwischen den einzelnen untersuchten qualitativen Holzvariablen.

fected by the color in sapwood. The brightness of heartwood is strongly correlated (R= –0.775) with its size (HP), this result suggests a certain ageing of heartwood; in the discs where HP is lower the heartwood is younger and consequently brighter. The correlation between HP and NHR is the strongest (R= –0.918, p<0.001).
There is no correlation between radial growth and size of heartwood. On the other hand, RW is a measure of whiteness in the heartwood; in wider growth rings the heartwood is brighter. This correlation, with important silvicultural implications, is shown in Figure 8. The magnitude of radial growth also contributes to the size of yellow color (R^2 = 0.295).

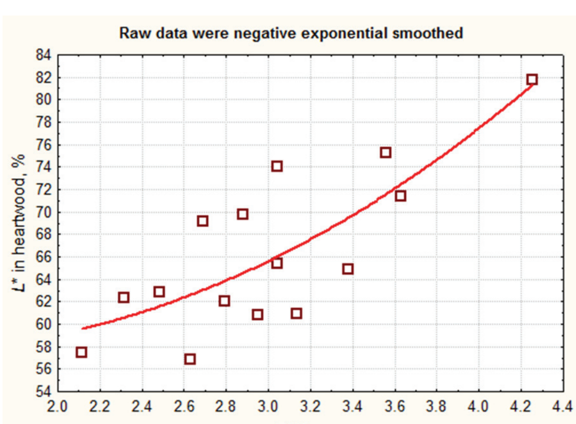

Figure 8. Dependence of heartwood brightness on the rate of radial growth of trees.
Abbildung 8. Abhängigkeit der Helligkeit des Kernholzes von der Rate des Radialzuwachses.

4. Discussion

4.1 Quality anisotropy

The magnitude of variability of physical properties and structural features found in the sample material confirms the common experience that tree-to-tree variations are less than the intra-tree variations, the radial direction being their dominant source (Zobel and Bujtenen, 1989; Koga and Zhang, 2004). The differences between trees (two out of five sampled trees, those growing in particular site conditions) are the result of micro-depressions. In the absence of more samples and without extrapolating, one can assume a strong influence of the environment on qualitative phenotypes in common walnut, further explaining their geographical segregation (Jane, 1956).
The homogeneous distributions of wood density and water content along the trunk, as well as of color in the girth direction, are advantageous in technological terms. The distribution of wood density depending on height, without any trend quantified mathematically and confirmed statistically, places the investigated population among the rare cases of provenances/species without significant axial variations in this trait. The lack of anisotropy of wood density in common walnut could be temporary; the development of heartwood will probably strengthen the dispersion of magnitude of wood density along the trunk, in the ontogeny of subjects (Yang and Hazenberg, 1991). There was a certain trend of wood density growing up to 7.30 m in height, which was not confirmed statistically. In three out of five sampling trees, the wood in the highest section

is heavier than the one closest to the ground. The result is surprising in the context of diminishing proportion of heartwood with height and its absence beyond the height of 10 m (Figure 6) as well as presumptive reduction of the content of extractible substances from heartwood with height, as in larch (Uprichard, 1963) or black locust (*Robinia pseudoacacia* L.) (Adamopoulos et al., 2005).

The increase in wood density with height is characteristic of the species with lower content of latewood (Okkonen et al., 1972). The conventional density is one of the measured traits with a high degree of homogeneity around the average (Table 2). This does not exclude the possibility of stratifying their experimental values, at least in the transverse section, in case of four out of five sample trees (Table 3). The tree-to-tree variation in wood density in common walnut (Table 3) offers the opportunity of selection based on this trait, as much as it is the only wood property that can be genetically manipulated in special cultures (Zobel and Bujtenen, 1989). However, the influence of the environment can make the prediction of wood density impossible under certain site conditions (Lima et al., 2000).

4.2 Growth-wood quality relationship in common walnut wood

As in the case of other *Juglans* species, the growth–structure relationship was uncertain in the examined sample. In black walnut, for instance, the growth rate does not modify either the porosity (expressed by the vessel lumen area percentage) or the radial permeability of sapwood (Chen et al., 1998). In oak and other ring-porous broadleaved species, the amount of radial growth influences the suitability of wood for veneer production by adjusting the ratio between the anatomical components of growth ring (Pechmann and Aufsess, 1973).

The disproportion of radial growth of trees depending on girth has been known for many years (Glock, 1941). Its association with cardinal directions has remained controversial (Timell, 1986), being confirmed only sporadically (i.e., Süss and Müller-Stoll, 1970). In our sample, the potential of north direction to attract more wood biomass than the other radii/directions, even under the limits of a weak eccentricity, was observed. However, the wood density was not growth-related, as seen in a large number of species (Singh, 1987), especially part of the diffuse-porous group (Fukazawa, 1984).

The radial growth in common walnut affects the radial variations of some chromatic coordinates of wood color. In pedunculate oak, the width of growth rings does not join the color space CIELAB, while in sessile oak, this partnership has become transparent with the stratification of experimental data based on tree age (Klumpers and Janin, 1992). The sense of this correlation is opposed to the one identified in common walnut and provides advantages to the trees with narrow growth rings (in oak wood used for decorative purposes, the lightness, associated with narrower growth rings, is more and highly appreciated).

4.3 Dynamics of heartwood formation

The comparison with the color of the control sample (Tables 1 and 5) endorses the assumption of change in heartwood color in common walnut over time, even under the conditions of an important influence of geographical provenance. There may also be variations of wood density in time, expressed by the relative difference between the density of heartwood and sapwood, which changes with time. For instance, in case of black walnut trees of 10 years, the heartwood is heavier than the sapwood with only 5% (Rink and Phelps, 1989). In case of our material, the differences between sapwood and heartwood were not categorical, not to mention the confusion between the transition zone and sapwood taking into account the momentary wood density (Table 4). The variation in common walnut wood color is also confirmed by the segregation of polyphenol spectrums over time (Jay-Allemand et al., 1987). Consequently, with the biological age of trees, the spectrum of reflection shifts toward the longer wavelengths of visible spectrum, characterizing the adult wood of common walnut (Moslemi, 1967).

A similar trend is seen when comparing the current values of color indices at 35 years of age with the ones reported in common walnut of different ages. In comparison with the wood of 17-year-old trees, for instance, the migration of central trend (especially of hue) is recorded. The red color and brightness are the most solid discriminate factors of wood color at 35 years of age compared to larger common walnut logs for veneer production. The wide range of heartwood brightness in sampled trees, with some values corresponding to older trees, is an indication of likely changes.

In oaks, the age of trees influences the evolution of wood color (Klumpers et al., 1993). In time, the proportion of yellow color decreases and the vividness of wood color lessen. In this context and correlated with our results, one can assume that the changes in color (diminishing of brightness and yellow color, in parallel with the increase in red component; Table 5), produced relatively quickly and related to the occurrence of heartwood, anticipate the long-term changes in wood color in common walnut.

Our results confirm the weak correlation between the density of heartwood and its brightness, as in the case of black walnut (Rink and Phelps, 1989). In black walnut, the investigations carried out on veneer slices have shown that the brightness is the color parameter with the highest discriminatory potential of color, the chromaticness being minimum (Moslemi, 1967); brightness is the only parameter allowing the visual detection of differences in color between samples (Phelps et al., 1983).

The peculiar examples of distribution of heartwood formation depending on height in this research suggest the priority of wound closure over the formation of heartwood. Based on this fact, one can assume that the occurrence of abnormal discoloration in the proximity of wounds attracts the highest share of secondary metabolites to the heartwood disadvantage.

5. Conclusions

The physical and structural identity of common walnut wood was characterized by a series of traits believed to be the indicators of wood quality. The reciprocal relations between these traits could suggest the best silvicultural way for managing the growth and development processes of this valuable tree species.

(a) There was a wide spread of values of structural features and of water content. At the same time, the color indices were strongly grouped around the averages, facilitating the easier definition of the common walnut wood in that phase of development. The only exception is the red–green color, dimensional spread of which, in both senses of coordinates, allows the discrimination of heartwood from sapwood.

(b) All experimental distributions are stratified following at least one of the analyzed factors: tree and its structural directions (i.e., longitudinal, radial, and tangential). The radial anisotropy is the most pronounced. The longitudinal stability of density and water content, the inter-tree stability of color saturation, as well as the homogeneity of all color indices on the girth were re-marked.

(c) The heartwood covers up to 12.5% of the cross-section, including the wood of 1–10 growth rings. The structural-color peculiarities of trees grown in special micro-sites (depressions) suggest that the heartwood formation could be inhibited by the excess of water.

(d) The annual rate of bioaccumulation has allowed the separation of stages of radial development of structure using the width of growth rings: juvenile wood, composed of the first 8–9 rings from the pith, a transition zone to the mature wood (10 rings), and mature wood under-way to be formed.

(e) The stratification of distributions of conventional density and water content along the radii directions have shown the shift of central trend from the north radius toward higher values.

(f) The wood density is not a reliable criterion for differentiating the sapwood from heartwood. On the other hand, brightness, redness and hue's color can be used for this differentiation.

(g) The influence of water content of standing trees on the color components (i.e., L^*, a^*, b^*) is residual after drying. In trees with high water content the red color can not be used, even after wood drying, for the distinction of heartwood. Current water content does not provide any indication of the heartwood content.

(h) The size of wood density is quite isolated in mathematical terms from the other indicators/traits. The annual radial growth is not an explanatory variable for the size of heartwood but relates strongly (direct proportionality) with the brightness of heartwood.

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