Wood Density of Northern Red Oak and Pedunculate Oak Grown in Former Brown Coal Mine in the Czech Republic

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This study deals with the characteristics of wood of two different species of oaks, the non-native northern red oak (*Quercus rubra* L.) and the native pedunculate oak (*Quercus robur* L.), growing in a reclaimed surface brown coal mine in the Czech Republic. The differences in the wood density of the aforementioned species, including the impact of position in the trunk, were examined. The impact of annual ring width and the proportion of latewood on density were also evaluated. The density of *Q. robur* wood reached 707 kg·m^{-3}, which was significantly higher than that of the North American species, which reached 654 kg·m^{-3}. Moreover, in the radial direction, the density increased in the direction from the pith toward the bark for both *Q. rubra*, and *Q. robur*. In the vertical direction, the density reached its highest value at the basal part of the trunk, but statistically, this assertion was only significant for *Q. rubra*. The effects of annual ring width and the proportion of latewood on density were shown to be statistically very low for both oak species.

Keywords: Northern red oak; Pedunculate oak; Reclaimed coal mine; Wood properties; Density; Variability

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INTRODUCTION

In the second half of the 20th century, vast areas of the northwest part of the Czech Republic were subjected to extensive exploitation for brown coal. After the mining activities ended in these surface brown coal mines, they were subsequently filled in and reclaimed. These locations were planted with a wide range of trees, both native Czech species and introduced species originating from other geographic areas. The reclaimed areas, or "spoil tips", represent a completely unique habitat with very rare soil conditions artificially created by human activity (Remeš and Šíša 2007). Spoil tips became the subject of interest of forestry reclamation in the second half of the last century. One of the trees used for reclamation was oak (Kupka and Dimitrovský 2006). The suitability of using pedunculate oak (*Quercus robur* L.) and northern red oak (*Quercus rubra* L.) in the reclamation of brown coal spoil tips was confirmed by Bažant (2010). Although these areas became an interesting source of timber, there has been no assessment of the production capabilities of these sites or of the quality of the produced wood.

Along with the European beech (*Fagus sylvatica* L.), *Q. robur* is one of the most commercially important hardwoods in the Czech Republic. Currently, it takes up approximately 7% of the total forest area, *i.e.*, about 28% of the area occupied by hardwoods (Ministry of Agriculture 2015). Due to its qualitative properties and appearance, it has been widely used in the manufacturing of floors, luxury furniture and veneer, loaded structures, and in timber products of higher added value.

Q. rubra is not a tree species native to the Czech Republic, and knowledge of the properties of this wood is relatively low. *Q. rubra* occurs naturally in eastern North America (Göhre and Wagenknecht 1955). The trees of this species reach a height of up to 30 m and a diameter of about 90 cm (Wagenführ 2000). This is a rapidly growing tree species (Burns and Honkala 1990). *Q. rubra* was introduced to Europe around 1691 and to Bohemia around 1799. It requires less light than native oaks, and it is also less vulnerable to damage by late frosts and insect pests. In the Czech Republic it is primarily used as a soil conservation and land reclamation tree species in forests stands (Hejný and Slavík 1990). Currently, *Q. rubra* occupies approximately 0.19% of the total forest area in the Czech Republic (Ministry of Agriculture 2007).

Wood density is one of the key features of wood quality (Barnett and Jeronimidis 2003), as it affects most of the physical and mechanical properties of wood (Bosshard 1974; Zobel and Van Buitenen 1989). Density is used to estimate the possible uses of a particular tree species and to estimate its strength properties. The association between density and wood strength has been verified in many studies (Niemz 1993; Niklas 1997; Niemz and Sonderegger 2003; Ivković *et al.* 2009; Niklas and Spatz 2010). Wood is a highly variable material due to the nature of its formation and of its structure. Differences can therefore also be found in terms of its density, and not only between tree species, but also among individual trees within a species as well as within a single tree (Kollmann 1951; Tsoumis 1991; Molteberg and Høibø 2006; Vila-Lameiro *et al.* 2006). One of the major factors contributing to the variability in density is the width of annual rings, as well as the often-related proportion of latewood. Whilst it is generally true for softwoods that wood density decreases with increasing annual ring width, the opposite trend applies for ring-porous hardwoods; with increasing annual ring width the proportion of latewood and therefore also wood density increases (Bosshard 1974).

This study examined the potential of a reclaimed surface brown coal mine in the Czech Republic to produce wood with qualities that are attractive for the wood processing industry. The aim of the work was to assess the differences in the wood densities of two different oaks, *i.e.*, the non-native North American *Q. rubra* and the Czech native *Q. robur*. The variability of density in the trunk, in the vertical and horizontal directions, and the impact of annual ring width and proportion of latewood on the wood density in the examined trees were also assessed.

EXPERIMENTAL

Sampling and Samples Preparation

The material used in this study came from the northwestern part of the Czech Republic from the reclaimed spoil tips of sites used for the surface mining of brown coal called Větrák (50.5582150N, 13.8333750E), approximately 2 km west of the city of Bílina (Fig. 1). The filling of spoil tips was completed at the end of the 1950s. Reclamation began in early 1962, during which time hillsides were afforested using various kinds of forest tree species. Among these, *Q. rubra* was one of the most promising forestry tree species. It achieved the highest average growth (4.91 mm) when compared against *Robinia pseudoacacia* (4.31 mm), *Fraxinus excelsior* (3.98 mm), and

Q. robur (3.81 mm). In addition, in this locality it exhibited the most balanced growth in comparison with other tree species (Bažant 2010).

Fig. 1. Czech Republic – location of the sampling plot

Sample trees of *Q. rubra* and *Q. robur* were randomly chosen and cut down. For *Q. rubra*, the diameter of the trunk at a height of 1.3 m above the ground fluctuated from 21.5 to 25 cm and for *Q. robur*, from 23 to 27.5 cm. The height of the *Q. rubra* was around 16 m, and the height of the *Q. robur* was around 13.5 m. According to research carried out by Bažant (2010), the age of both tree species in this locality was 35 years.

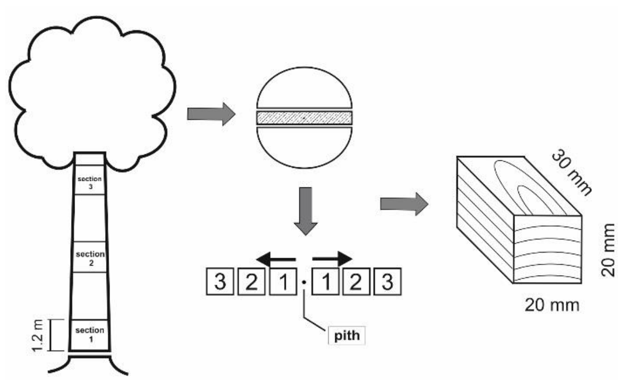

Fig. 2. Sampling of trees and testing samples position in the trees

To compare wood properties, including assessing the vertical variability of the properties, three sections from each sample tree, representing the basal part of the trunk (marked 1), the central part of the trunk (marked 2), and the starting point of the tree crown (marked 3), were cut to a length of 120 cm, as shown in Fig. 2. The cutting of trees was done in north-south direction. The subsequent method of sawing sections was chosen with regard to assessing the horizontal variability of the properties. The obtained sections were then cut into individual boards using a band saw. To assess the horizontal variability, the central boards were always used (north-south orientation) so that it would be possible to unambiguously determine the position of the test specimen in a radial direction relative to the pith. The central boards were cut and processed into lathes with cross-sections of 20 × 20 mm, still with a clearly specified horizontal position in the trunk (where the No. 1 position is the closest to the pith; Fig. 2). The obtained lathes were used as the starting material for the manufacture of test specimens. The test specimens were used to evaluate the physical and mechanical properties of the wood, allowing for the evaluation of the variability of the examined properties in the direction from the pith to the cambium (Hapla *et al.* 2013). In this paper, only on the evaluation of the wood density of oaks is discussed.

Properties Evaluation

To determine density, test specimens were cut from the prepared lathes in a rectangular shape to have dimensions of 20 × 20 × 30 mm (Fig. 2). T

he specimens were free of any defects and growth irregularities, and had clearly identifiable radial and tangential surfaces (ČSN 49 0101 1980). A total of 391 test specimens were evaluated for *Q. rubra* and 432 for *Q. robur*. The wood density (ρ_0) at 0% moisture content was determined according to the following equation (ČSN 49 0108 1993),

$$\rho_0 = \frac{m_0}{V_0} [\mathrm{kg \cdot m^{-3}}] \tag{1}$$

where m_0 is the weight of the test specimen at 0% wood moisture content (kg) and V_0 is the volume of the test specimen at 0% wood moisture content (m^3).

To obtain absolutely dry wood, the test specimens were dried in a laboratory kiln at 103 ± 2 °C until weight stabilization was reached (ČSN 49 0103 1979). To determine the annual ring width and the proportion of latewood in the annual ring, the cross section of the test specimens was scanned at a resolution of 600 dpi. The image was then processed, and the respective characteristics of the annual ring (width and latewood proportion) were evaluated in NIS Elements AR image analysis software (Laboratory Imaging, Prague, Czech Republic).

Data Analysis

A significance level of 95% was used for all statistical analyses. A t-test was used to evaluate the differences between the tested *Q. rubra* and *Q. robur*. The ANOVA and Duncan's multiple-range tests were applied to evaluate the statistically significant differences among the other evaluated factors. Vertical position, horizontal position (position from the pith), individual trees and cardinal point (north-south orientation) were evaluated factors. The linear regression model was used to evaluate the dependence of density on the width of annual rings and proportion of latewood for both types of oaks.

RESULTS AND DISCUSSION

The data in Table 1 show that in the same locality, the wood density of *Q. rubra* achieved a lower value (654 $kg{\cdot}m^{-3}$) than did the wood density of *Q. robur* (707 $kg{\cdot}m^{-3}$). The analyses confirmed a significant difference ($p < 0.001$) between the evaluated types of oaks in terms of density. In contrast to the results of the research by Merela and Čufar (2013), wherein oaks from the red oak group showed a higher density than the oaks from the white oak group (*Q. robur*). The variability of the investigated property was higher for *Q. robur*. Nevertheless, it was markedly low for both tree species, and lower than that normally mentioned in the literature (Glass and Zelinka 2010).

For *Q. rubra*, from the area of the original expansion, Alden (1995) reported a density value of 660 $kg{\cdot}m^{-3}$. From this perspective, the value of the evaluated specimens appears to be comparable. For *Q. rubra* specimens grown in European conditions, Göhre and Wagenknecht (1955) discovered a very similar density of 666 kg·m^{-3}. Other authors have mentioned values close to 660 kg·m^{-3} (Wagenführ 2000) and 620 kg·m^{-3} (Lexa *et al.* 1952).

Table 1. Statistical Characteristics for Density of *Q. rubra* and *Q. robur* Oaks

Species	N	Mean (kg·m^{-3})	Median (kg·m^{-3})	Minimum (kg·m^{-3})	Maximum (kg·m^{-3})	Standard Deviation (kg·m^{-3})	Coefficient of Variation (%)
Q. rubra	391	654	655	555	750	28	4.2
Q. robur	432	707	710	625	815	43	6.1

Under natural conditions in ordinary forest stands in the Czech Republic, the native *Q. robur* has a reported density of 584.3 kg·m^{-3} (Vavrčík and Gryc 2012). Vavrčík *et al.* (2008) reported 618.2 kg·m^{-3} for *Q. robur* in Czech localities. In both cases, neither value reaches the density values obtained for *Q. rubra* from the evaluated spoil tips. Wagenführ (2000) reported a value of 650 kg·m^{-3} for European *Q. robur*, but the *Q. robur* from the spoil tips even exceeds this value. The position (on the basis of density) of the tree species evaluated in this work among commercially important hardwoods in the Czech Republic is shown in Table 2.

Table 2. Commercially Important Hardwoods of Similar Density in the Czech Republic

Commercial Name	Scientific Name	Density (kg·m^{-3})*
Sycamore	*Acer pseudoplatanus*	590
Silver birch	*Betula pendula*	610
Persia walnut	*Juglans nigra*	640
European ash	*Fraxinus excelsior*	650
Pedunculate oak	*Quercus robur*	650 / **707****
Northern red oak	*Quercus rubra*	660 / **654****
European beech	*Fagus sylvatica*	680
Black locust	*Robinia pseudoacacia*	740
European hornbeam	*Carpinus betulus*	790
*Wagenführ (2000) **Results obtained in this work		

Effect of Position on Wood Density in *Q. rubra* and *Q. robur*

The research unequivocally confirmed (see the analysis below for more details) that wood density differs not only between individual types of oaks and trunks within one tree species, but also changes within the actual trunk, both in the horizontal and vertical direction as a result of the different physiological and mechanical functions of its individual parts. Moreover, the distribution of wood density along the radius and along the height of the trunk was such that there was no clear pattern within the tree species or even within the trunk.

In this work, an increase in density from the center of the trunk toward its periphery was confirmed up to a certain limit, beyond which point the density decreased once more. In the horizontal direction, for *Q. rubra* the lowest density value was reached near the pith (647 kg·m^{-3}), whilst the highest values were reached near the bark (661 and

662 kg·m^{-3}). For *Q. robur*, again the lowest density value was in the middle of the trunk (693 kg·m^{-3}), while similarly to *Q. rubra*, the highest values were in the peripheral part of the trunk (720 to 716 kg·m^{-3}), as shown in Table 3. This phenomenon was evidently related to a change in the width of annual rings and the proportion of latewood. If the individual sections were taken into consideration, an increasing trend was evident in the upper two sections, while conversely the course of the density in the basal section was inconclusive for both oaks (Figs. 3 and 4).

In terms of the fluctuation in density with the changing height of the tree, a clear pattern could not be demonstrated for either oak. The highest density value for *Q. rubra* was in the vertical direction in the basal section (666 kg·m^{-3}), while the lowest value was in the middle section (641 kg·m^{-3}), with a minimum difference from the upper section (650 kg·m^{-3}). For *Q. robur*, the highest density was reached in the middle section (710 kg·m^{-3}), while the lowest value was reached in the upper section (702 kg·m^{-3}), with a negligible difference between the sections (Table 3).

Table 3. Wood Density of *Q. rubra* and *Q. robur* depending on Vertical and Horizontal Position

Species	Parameter	Horizontal Position				Vertical Position		
		1	2	3	4	Section 1	Section 2	Section 3
Q. rubra	Mean	647	655	662	661	666	641	650
	Median	640	655	660	665	665	635	650
	Coef. Var.	4.2	4.0	4.5	2.9	3.4	3.5	4.9
Q. robur	Mean	693	709	720	716	709	710	702
	Median	690	710	725	710	715	708	700
	Coef. Var.	6.1	6.5	5.0	7.1	6.6	5.6	6.1

No rationale was found for density in the radial direction, which was similar for both species. Adamopoulos *et al.* (2007) did not find a significant difference in the wood density between the central and peripheral parts of the trunk. Most studies have reported the opposite trend, *i.e.*, a decrease in density in the direction from the pith toward the bark; for example, Vavrčík and Gryc (2012) reported such a density distribution for *Q. robur*, Ayobi *et al.* (2011) for *Q. castaneaefolia*, and Knapic *et al.* (2007) for *Q. suber*. Panshin and Zeeuw (1980) stated that there was very little consistency and no overall dominance of a single pattern in hardwood tree species for density fluctuation with respect to the height of the trunk.

In a multiple-factor analysis ($p < 0.001$), the effects of tree factors, vertical position, and the position from the pith (*i.e.*, the horizontal position) were highly statistically significant for the wood density of *Q. rubra*, whereas the interaction of all of the relevant factors was moderately ($p = 0.001$ to 0.01) significant (Table 4). Knapic *et al.* (2008) and Machado *et al.* (2014) confirmed the significant impact of these three factors on the wood density.

The impact of the cardinal point was not significant ($p > 0.05$). The evaluated samples of *Q. robur* showed a very significant influence of the tree and the position from the pith, and an insignificant impact of vertical position and cardinal point on density, whereas the interaction of all the factors in question was not overly significant ($p = 0.01$ to 0.05) (Table 5).

Table 4. Impact of Individual Factors on Wood Density of *Q. rubra*

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F-test	Significance Level, *p*
Intercept	62557622	1	62557622	117592	*P* < 0.001
1 - Tree	44249	2	22125	42	*P* < 0.001
2 - Vertical Position	23332	2	11666	22	*P* < 0.001
3 – Cardinal Point	1168	1	1168	2	*P* = 0.139
4 - Position from the Pith	15325	3	5108	10	*P* < 0.001
1-2-3-4	7249	5	1450	4	*P* = 0.002
Error	203751	383	532		

Table 5. Impact of Individual Factors on Wood Density of *Q. robur*

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F-test	Significance Level, *p*
Intercept	50848929	1	50848929	63425.24	*P* < 0.001
1 - Tree	409247	2	204623	255.23	*P* < 0.001
2 - Vertical Position	1612	2	806	1.01	*P* = 0.367
3 - Cardinal Point	16	1	16	0.02	*P* = 0.887
4 - Position from the Pith	60098	3	20033	24.99	*P* < 0.001
1-2-3-4	8305	7	1186	2	*P* = 0.043
Error	339125	423	802		

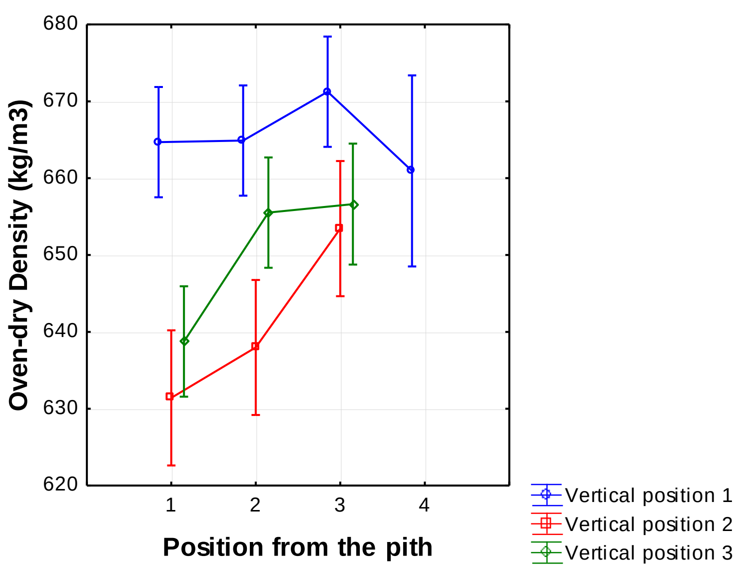

Fig. 3. Horizontal variability of density depending on the vertical position in trunk for *Q. rubra*

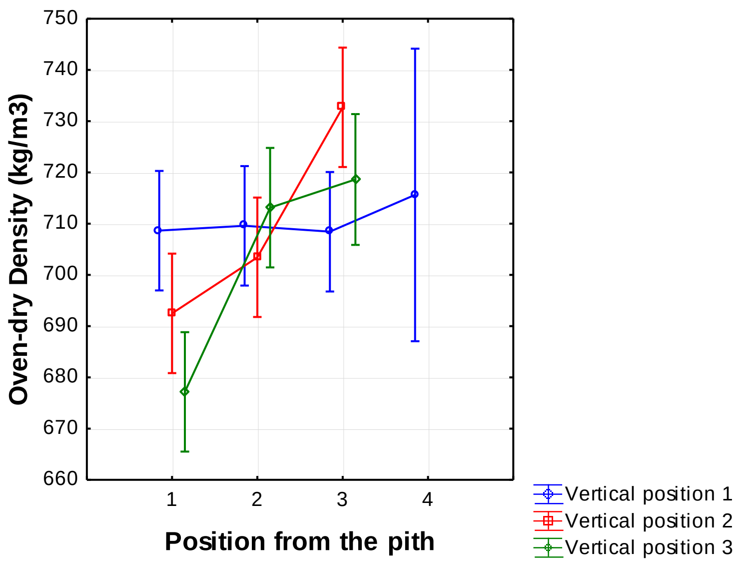

Fig. 4. Horizontal variability of density depending on the vertical position in trunk for *Q. robur*

Annual Ring Width and its Correlation with Wood Density and Proportion of Latewood in *Q. rubra* and *Q. robur*

The average width of the annual ring was similar for both species, *i.e*., 4.4 mm for *Q. rubra* and 4.0 mm for *Q. robur* (Table 6), and there was not a significant difference between the species. The values for the width of the annual rings fluctuated in the range of 2.8 to 7.1 mm for *Q. rubra* and 1.8 to 8.1 mm for *Q. robur*. For *Q. rubra*, the width of the annual rings increased with age in such a way that they reached their highest values in approximately the middle age of trees, and then it once again decreased. The narrowest annual rings were thus found near the pith, and the widest annual rings were located midway between the bark and the pith. For *Q. robur*, the annual ring width exhibited a different trend. The widest annual rings were found near the middle of the trunk, after which their width decreased, such that the narrowest annual rings were found in the peripheral zone of the trunk.

Table 6. Descriptive Statistics for Width of Annual Rings of *Q. rubra* and *Q. robur*

	Mean (mm)	Median (mm)	Minimum (mm)	Maximum (mm)	Standard Deviation(mm)	Coefficient of Variation (%)
Q. rubra	4.4	4.3	2.8	7.1	0.8	18.4
Q. robur	4.0	3.7	1.8	8.1	1.3	33.2

Table 7. Descriptive Statistics for the Latewood in *Q. rubra* and *Q. robur*

	Mean (%)	Median (%)	Minimum (%)	Maximum (%)	Std. Dev. (%)	Coef. Var. (%)
Q. rubra	80.8	81.3	68.8	90.4	4.6	5.7
Q. robur	82.2	84.0	68.2	94.9	7.0	8.5

For *Q. rubra*, the average proportion of latewood reached 80.8% and ranged between 68.8 and 90.4%. For *Q. robur*, the proportion of latewood was 82.2% and fluctuated in the range of 68.2 to 94.9% (Table 7). In terms of statistics, there was no difference between the proportions of latewood amongst the evaluated oaks. The trend in the distribution of the proportion of latewood was the same for both oaks. The highest proportion of latewood was near the pith, while the lowest was near the bark.

In terms of a linear regression analysis, the dependence of wood density on the width of annual rings for *Q. rubra* (coefficient of determination, R^2 = 0.013) and the dependence of wood density on proportion of latewood for *Q. robur* (R^2 = 0.002) was statistically insignificant. The dependence of wood density on the proportion of latewood for *Q. rubra* (R^2 = 0.035) and the dependence of wood density on the width of annual rings for *Q. robur* (R^2 = 0.041) was insignificant. For *Q. rubra*, the impact of the width of the annual rings on the proportion of latewood was inconclusive. Conversely, for Q. *robur* the impact was significant, and these characteristics were very closely correlated with each other (R^2 = 0.704) (Figs. 5 and 6).

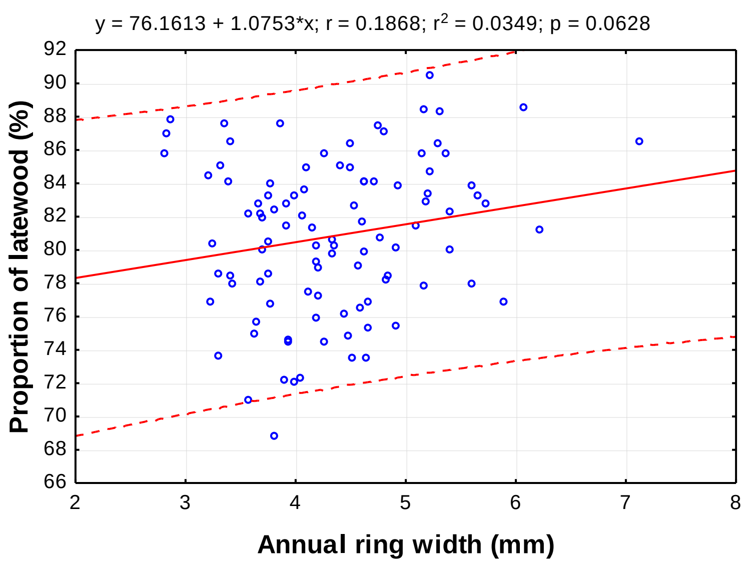

Fig. 5. Dependence of proportion of latewood on the width of an annual ring for *Q. rubra*

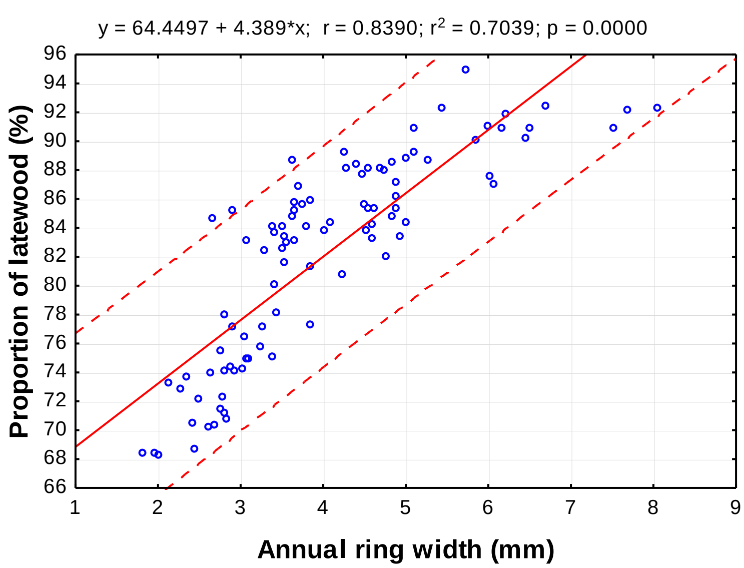

Fig. 6. Dependence of proportion of latewood on the width of an annual ring for *Q. robur*

Although a positive correlation between the density and width of annual rings for ring-porous tree species, or between density and proportion of latewood, is generally assumed (Kollmann 1951; Tsoumis 1991), there are also studies in which this has not been confirmed, which suggests that the issue is much more complicated and that the structure of latewood also plays a role. Knapic *et al.* (2007) found no relationship between the width of the annual rings and the proportion of latewood. Bergès *et al.* (2008) reported a weak or insignificant correlation between density and the width of annual rings and proportion of latewood. Vavrčík and Gryc (2012) mentioned a relatively small dependence of density on the width of the annual ring and of tree density on the proportion of latewood, and they point out the fact that latewood quality affects density in addition to the width of annual rings and the proportion of latewood. Hapla and Becker (1990) point out a small association between density and a considerable variability of latewood density. Romagnoli *et al.* (2014) reported a decrease in density with the increasing width of annual rings.

CONCLUSIONS

1. For specimens sourced from the same location, native *Q. robur* showed a demonstrably higher wood density value than the non-native *Q. rubra*.
2. In terms of density, *Q. rubra* specimens growing in the reclaimed mine habitat achieved the same degree of wood density as those growing in other areas.
3. In contrast, *Q. robur* tested from the reclaimed mine achieved a significantly higher wood density value than did those growing in other localities in the Czech Republic.
4. The overall the variability in the wood density, both within and between individual trees, was low for both species, which was positive news for the forest owner and represented an advantage in terms of processing and utilization.
5. Horizontal position in the trunk was a main factor affecting wood density. The density increased in the radial direction from the pith towards the periphery. At the periphery its variability was at its highest, and there was a slight decrease for both *Q. rubra* and *Q. robur*.
6. In the vertical direction, the density reached its highest values in the basal part of the trunk for *Q. rubra*; for *Q. robur,* the impact of the vertical position was not significant.
7. The dependence of density on the width of annual rings and the dependence of density on the proportion of latewood was very low for both evaluated oak species. There was only a closer dependence between the width of the annual rings and the proportion of latewood for *Q. robur*.

ACKNOWLEDGMENTS

This project was supported by the grant CIGA 2016-4309. The authors would like to express their thanks to the Forests of the Czech Republic, a state enterprise, for kindly providing them with testing material from their forest stands on the former surface mines.

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Article submitted: July 15, 2016; Peer review completed: August 28, 2016; Revised version received: September 1, 2016; Accepted: September 3, 2016; Published: September 15, 2016.
DOI: 10.15376/biores.11.4.9373-9385