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INFLUENCE OF SELECTED FACTORS ON WOOD DENSITY VARIABILITY IN GRAND FIR (*ABIES GRANDIS* /DOUGLAS/ LINDL.)

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ABSTRACT

Grand fir ranks among the promising tree species that have been introduced into the Czech Republic, particularly as a potential substitute for the native European silver fir. This article deals with wood density of grand fir coming from Czech sites and selected factors which influence its variability. Sample trees of grand fir representing different sites were tested for wood density at 12 % moisture content according to the national standards. The obtained value 403 $kg \cdot m^{-3}$ is somewhat lower than the density achieved by grand fir in native areas. Horizontal position within the stem proved to be the most important factor affecting the density. Density increased with increasing distance from the centre of the stem towards the bark, reaching its highest values at the perimeter of the stem. Individual trees were found to be another major source of variability. On the contrary, the effect of vertical position on the density variability was low. The cardinal directions proved to have practically no effect. Density was also found to have no major dependence on the width of annual rings, as R^2 was only 0.44.

KEYWORDS: Introduced species, grand fir (*Abies grandis* Douglas/ Lindl.), wood, density, variability.

INTRODUCTION

Wood density is regarded as one of the most important characteristics of wood, significantly influencing the majority of its other physical and mechanical properties (Bosshard 1974, Zobel and Van Buitenen 1989). It is often perceived as one of the main indicators of quality (Barnett and Jeronimidis 2003). There is a very close correlation between density and the strength characteristics of wood (Kolmann 1951, Niemz and Sonderegger 2003, Sonderegger et. al. 2008), so it can be used as an indicator for the primary assessment of mechanical properties (Niemz

1993, Perelygin 1965, Vikram et al. 2011). Unlike for other materials, density of wood fluctuates depending on moisture. It is therefore desirable to always determine the density for a specific moisture content. For practical reasons, wood density at 12 % moisture content is typically expressed (Požgaj 1997).

Density of wood and all its properties in general, are subject to great variability. Differences can be found among genera and species, among sites, and even among trees on one site. In fact, differences can even be observed within a single tree (Kollmann 1951, Panshin and De Zeeuw 1980, Tsoumis 1991, Zobel and Van Buitenen 1989). Characteristic properties of wood may be inherent to different tree species, but are largely influenced by the surrounding environment, including silvicultural practises (Barnett and Jeronimidis 2003, Jozsa and Middleton 1994). Variability is caused by differences in the wood structure, notably the width of annual rings and the proportion of late wood (Adamopoulos et al. 2010, Dekort 1991). The proportion of juvenile wood also plays an important role (Guler et al. 2007, Pazdrowski 2004).

Knowing the variability of wood properties is essential in terms of both wood production and, more importantly, wood applications. Having information, that a certain portion is heavier and stronger or lighter, is important for processing. The suitability of wood for a specific purpose is then typically determined by the variability in a given property. Awareness of the variability in the required property is therefore desirable (Green et al. 1999, Panshin and De Zeeuw 1980).

When assessing variability within a tree, it can be observed that a certain characteristic of the wood follows a certain trend. The variability depends on vertical position within the stem as well as the distance from the centre of the stem (Zobel and Van Buitenen 1989). Variability in properties with increasing height in the stem is quoted by a large body of literature (Gartner et al. 2002, Gutiérrez et al. 2006, Johnson and Gartner 2006, Langum et al. 2009, Molteberg and Høibø 2006, Pong et al. 1986). Variability in properties within the stem in the horizontal direction has also been confirmed by numerous authors (Jelonek et al. 2009, Langum et al. 2009, McKimmy and Campbell 1982). It has been documented for coniferous trees that wood density decreases upwards towards the treetop, and grows with increasing horizontal distance from the pith (Haygreen and Bowyer 1989, Panshin and De Zeeuw 1980, Požgaj et al. 1997).

Factors contributing to the vertical variability include primarily the width of annual rings, the wood structure (Bosshard 1974) and the different proportion of juvenile wood in different parts of the stem (Zobel and Van Buitenen 1989). The presence of juvenile wood is quoted as one of the main causes of horizontal variability, particularly in coniferous trees (Barnett and Jeronimidis 2003, Panshin and De Zeeuw 1980, Zobel and Van Buitenen 1989). Juvenile wood is a zone at the centre of the stem occupying approximately 5 to 20 annual rings. It exhibits a different structure, and thus different wood properties, compared to mature wood (Haygreen and Bowyer 1989, Zobel and Van Buitenen 1989). Other causes of variability in wood density in the horizontal direction are the width of annual rings and the frequently related proportion of late wood (Požgaj et al. 1997, Kolmann 1951, Niemz 1993). It is generally the case with coniferous trees that wood density decreases with the increasing width of annual rings. The assumption is that increasing width of annual rings results in a lower proportion of late wood and thus lower wood density (Bosshard 1974).

The number of tree species in the Central European region is relatively poor. Introducing geographically non-indigenous forest trees is a way of enriching the species composition of forest stands. Besides the Douglas Fir (*Pseudotsuga menziesii* /Mirbel/ Franco), grand fir (*Abies grandis* / Douglas/ Lindl.) appears to be a prospective tree species, particularly from a production potential point of view (Beran and Šindelář 1996).

Grand fir is a tree species native to the northwest of North America (Burns and Honkala 1990). Under favourable conditions, the tree may grow up to 90 m tall and 1.8 m in diameter (Wagenführ 2000). At present, grand fir occupies 0.04 % of the total forested area of the Czech Republic (Report on the state of forest and forestry in the Czech Republic, 2006). The wood is almost white to grey-white in colour. Heartwood is not visible. The wood is soft and light, not very durable. Resin canals are not present. The wood is dimensionally stable, easy to work, dry and impregnate. The presence of wet heartwood may be a problem due to bacterial infection. The wood is easy to glue. It is used for construction framing purposes (Wagenführ 2000). In its native area, the wood is mostly used for pulp and cellulose production (Burns and Honkala 1990). Grand fir is a topical issue in Czech forestry, but current works mostly concentrates on how to grow the tree (Podrázský 2003, Podrázský and Remeš 2009). Papers assessing the quality of wood of grand fir from Czech sites are missing.

This article is part of the outcome of an extensive study focused on assessing the potential of grand fir wood originating from Czech sites. The aim of the paper is to evaluate density of grand fir wood as one of the main factors influencing the physical and mechanical properties of the wood. The study also assessed selected factors influencing the density variability. Especially the influence of vertical and horizontal position in the stem, as well as orientation in the cardinal directions, individual trees and the width of annual rings were evaluated.

MATERIAL AND METHODS

In order to assess the properties of grand fir wood and the sources of their variability four trees were felled. The sample trees were collected in forest stands of the Forest Establishment of the Czech University of Life Sciences (CULS) at Kostelec nad Černými lesy, approximately 35 km east of Prague (Fig. 1). The area is characterised by an average annual temperature of 8.14°C, average total annual precipitation of 662.6 mm, and an average growing season of 150-160 days. Individual sites were distributed between elevations of 325 and 430 metres a.s.l. Tauchman (2011) provides a more detailed description of the sites.

Fig. 1: Location of the sampling plots in the Czech Republic.

Each of the felled trees came from a different stand. The diameter of felled trees ranged between 27 and 32 cm; the tree height ranged between 25.3 and 27.7 m. Based on counting the annual rings, the age of the trees ranged from 30 to 40 years.

The north orientation was marked on each stem before felling. After felling, each sample tree was debranched, measured and cut into several sections. Sections 1.5 m long representing the basal, central and crown part of the tree were collected from each of the trees. The purpose of this activity was to obtain material for evaluation of vertical variability in the stem. A disc was cut from each section in order to measure the width of annual rings. Lukášek et al. (2012) describe the stem division method and detailed section collection method.

Next, a central plank, 60 mm thick and running north-south through the stem, was cut out of each section using a band saw. The central plank was the base material for the cuttings and subsequent manufacture of test objects, particularly for assessing the variability of the characteristic in question in the radial direction. Slats were cut off progressively from the pith to the bark, and were then formatted to the final dimensions of the testing samples, rectangular cuboids with a base of 20 x 20 mm and length along the fibres of either 30 or 300 mm, depending on the property assessed and the requirements of standards. Zeidler (2013) describes in more details the methodology for manufacturing the testing samples for evaluation of horizontal variability of wood properties within the stem, as well as the shape of the samples.

This paper deals with the assessment of wood density. Testing samples 20 x 20 mm in cross section and 30 mm long along the fibres were used for evaluation. Totally 1093 samples were used. Wood density at 12 % moisture content (ρ_{12}) was determined in accordance with national standard ČSN 49 0108 (1993) using the following formula:

$$\rho_{12} = \frac{m_{12}}{V_{12}} \qquad (\mathrm{kg \cdot m^{-3}}) \qquad (1)$$

where: m_{12} - the weight of the testing sample at 12 % moisture content (kg),
V_{12} i - the cubic volume of the testing sample at 12 % moisture content (m^3).

In order to achieve 12 % moisture content, the testing samples were placed in an air-conditioned chamber for a long time, where they were exposed to temperature of 20 ± 2°C and relative air humidity of 65 ± 5%. The samples were periodically checked by weighing, and density assessment was carried out after the weight had stabilised.

The influence of the width of annual rings on wood density was also assessed for selected samples. For this purpose, the front ends of these testing samples were scanned using an 800 dpi scanner. After image calibration, the width of annual rings was measured using the NIS – Elements AR image analysis software, and the average annual ring width of each testing sample was calculated.

The value of grand fir wood density presented here is the arithmetic mean for the total number of testing samples objects. In addition, selected descriptive static data were calculated, which primarily characterised the variability in the property.

A multi-factor ANOVA was applied to determining the sources of variability in the property assessed. A single-factor ANOVA was applied to assessing the differences between the data sets. Where a statistically significant difference was confirmed, Tukey's multiple comparison test was employed. A regression analysis was performed to assess the dependence of wood density on annual ring width, and the degree of dependence among the quantities examined was assessed. A linear regression model was employed to estimate the dependence. The regression line equation was determined and the determination coefficient was calculated in each case. The differences were considered to be statistically significant if the significance value was lower than $\alpha = 0.05$.

RESULTS AND DISCUSSION

Wood density of grand fir at 12 % moisture content was 403 $\mathrm{kg \cdot m^{-3}}$. The variability of the examined property expressed by a coefficient of variation is 11.7 %. Tab. 1 shows the other descriptive statistics.

Tab. 1: Wood density of grand fir at 12 % moisture content – basic descriptive statistics.

N	**Median**	**Minimum**	**Maximum**	**Standard deviation**	**Coefficient of variation**
	(kg·m^{-3})	**(kg·m^{-3})**	**(kg·m^{-3})**	**(kg·m^{-3})**	**(%)**
1080	397	314	554	47	11.7

Density of grand fir wood from Czech sites corresponds with values stated by other authors (Tab. 2). Alden (1997) quotes 449 kg·m^{-3} for the native areas, meaning that obtained density is lower in comparison.

Tab. 2: Comparison of wood density of grand fir with other authors.

	Measured density	**Wagenführ (2000)**	**Hapla, Wellhausen (2003)**	**Hofman (1963)**
Density (kg·m^{-3})	403	430	395	390

For the indigenous European silver fir (*Abies alba* Mill.) Lexa et al. (1952) quote density of 440 kg·m^{-3}. The grand fir therefore does not match the indigenous species quality in terms of density. Due to the close correlation of density with other characteristics, notably strength, these properties can also be expected to show lower values. This introduced species so does not attain values of the major indigenous commercial tree species, namely Norway spruce (*Picea abies* (L.) Karst.) with 509 kg·m^{-3} (Salem et al. 2013) and Scots pine (*Pinus sylvestris* L.) with 510 kg·m^{-3} (Lexa et al. 1952). For this reason, the species is primarily predetermined not for timber production but rather for cellulose production, as noted by Folies et al. (1991), or for the production of agglomerated materials (Hapla 2006, Vos and Kharazipour 2010).

The variability in wood density of grand fir is influenced, at a statistically significant level, primarily by horizontal position in the stem and by the origin of the tree, as well as vertical position in the stem, orientation to the cardinal points (north-south), or a combination of these factors (Tab. 3). The above mentioned factors are responsible for 89 % of the wood density variability.

Tab. 3: Influence of examined factors on wood density of grand fir.

Source of variation	**Significance level**	**R^2**
Horizontal position	***	28.8
Tree	***	22.4
Tree x Vertical position	***	11.7
Vertical position	***	8.3
Tree x Horizontal position x Vertical position	***	4.6
Orientation x Horizontal position	***	4.4
Tree x Horizontal position	***	2.6
Tree x Orientation x Horizontal position	***	2.0
Tree x Orientation x Horizontal position x Vertical position	***	1.6
Tree x Orientation	***	1.2
Orientation	***	0.8
Horizontal position x Vertical position	**	0.2
Tree x Orientation x Vertical position	**	0.2
Orientation x Horizontal position x Vertical position	**	0.2
Orientation x Vertical position	-	0.05

(***) $p < 0.001$, (**) $p < 0.01$, (-) $p > 0.05$

The distribution of density in the stem of grand fir is as follows. The density increases horizontally from the stem centre towards the cambium (Fig. 2). The highest density of 516 kg·m^{-3} is achieved at the perimeter of the stem, the lowest density (383 kg·m^{-3}) at the centre of the stem near the pith. This trend is statistically proved and all the positions differ statistically significantly (Tab. 4).

The growing trend from the pith to the bark is generally expected in coniferous trees, and has been confirmed for many coniferous species (Gutiérrez et al. 2006, Jelonek et al. 2009, Jyske et al. 2008).

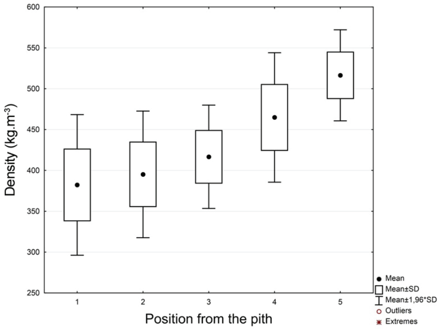

Fig. 2: Horizontal variability of wood density within the stem of grand fir.

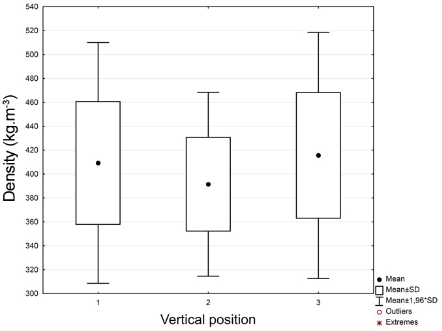

Fig. 3: Vertical variability of wood density within the stem of grand fir.

Tab. 4: Significance levels for the effect of horizontal position on wood density of grand fir.

Position from the pith	1	2	3	4	5
1		***	***	***	***
2	***		***	***	***
3	***	***		***	***
4	***	***	***		***
5	***	***	***	***	

(***) $p < 0.001$

No clear trend was established for density distribution in the vertical direction. The density first decreases towards the centre with increasing height, reaching a lowest density of 392 kg·m^{-3}, then grows to a maximum of 416 kg·m^{-3} in the crown area (Fig. 3). The value in the central section differs statistically significantly from both the basal and the crown sections. The basal and crown sections cannot be discerned (Tab. 5).

Tab. 5: Significance levels for the effect of vertical position on wood density of grand fir.

Vertical position	1	2	3
1		***	-
2	***		***
3	-	***	

(***) $p < 0.001$, (-) $p > 0.05$

Differences were also observed among individual trees (Fig. 4). The lowest density (378 kg·m^{-3}) was registered in sample tree 2. However, it cannot be discerned statistically from sample tree 4. The highest density (433 kg·m^{-3}) was measured in sample tree 1. It differs from the other trees statistically significantly (Tab. 6).

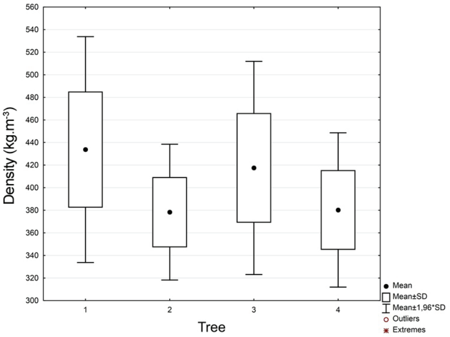

Fig. 4: Differences among individual trees of grand fir.

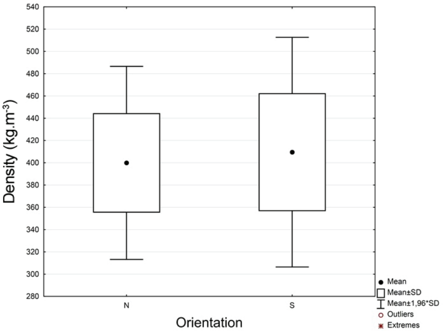

Fig. 5: Differences depending on the orientation within the stem (N – North, S – South).

Tab. 6: Significance levels for the effect of the tree on wood density of grand fir.

Tree	1	2	3	4
1		***	***	***
2	***		***	-
3	***	***		***
4	***	-	***	

(***) $p < 0.001$, (-) $p > 0.05$

Density in the stem also differs depending on north-south orientation (Fig. 5). Although the differences between the northern and southern sides are not great (400 and 410 kg·m^{-3} respectively), the analyses showed a statistically significant difference (Tab. 7).

Tab. 7: Significance levels for the effect of orientation on wood density of grand fir.

Orientation	N	S
N		**
S	**	

(**) $p < 0.01$

The width of annual rings is another important factor affecting density. The relation between annual ring width and wood density in grand fir proved to be statistically significant. Wood density decreases with increasing width (Fig. 6). The inverse relationship between wood density and annual ring width is confirmed by Gryc and Vavrčík (2009), Jyske et al. (2008) and Mc Kimmy and Campbell (1982).

The value of the coefficient of determination was 0.44. The equation for the linear regression model used is:

$$Y = 483.0858 - 16.47 * X; \qquad (2)$$

$$(R = -0.66;\ p > 0.001;\ R^2 = 0.4369)$$

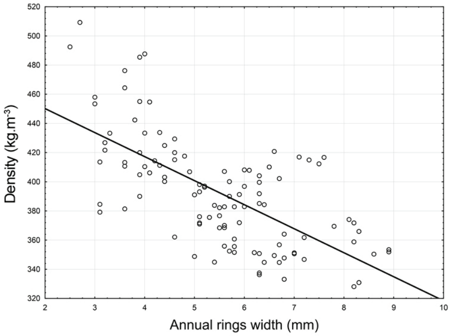

Fig. 6: Correlation between wood density and annual ring width.

Although wood density of coniferous trees decreases with increasing annual ring width, the statistical correlation is low (Tsoumis 1991). DeBell et al. (1994) quote the coefficient of determination of 0.39, Zubizarreta et al. (2009) quote the coefficient of correlation as 0.60 – 0.66, while Jyske et al. (2008) give it as 0.33 – 0.60. The width of annual rings of grand fir so cannot be used as the sole criterion for estimating wood density because other factors exist as well.

CONCLUSIONS

Density of wood of grand fir from the Czech sites is similar to that in neighbouring countries, but is somewhat lower compared to native sites. The wood quality is inferior compared to indigenous fir species as well as other major commercial conifers, and thus cannot be considered an adequate substitute for the native tree species based on density.

Processing and utilisation of grand fir wood needs to take into account the density variability and related properties. The density variability is greatest in the radial direction. The lowest density is in the centre of the stem, increasing towards its perimeter and reaching a maximum near the cambium. Differences among individual trees also need to be considered. The effect of height in the stem and orientation is negligible. Although the effect of the width of annual rings is observable and wood density decreases with increasing annual ring width, this factor should not be overrated since $R^2 = 0.44$ only.

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