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PRODUCTION POTENTIAL AND WOOD QUALITY OF DOUGLAS FIR FROM SELECTED SITES IN THE CZECH REPUBLIC

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ABSTRACT

This study deals with production and wood quality of Douglas fir (*Pseudotsuga menziesii* (MIRBEL) FRANCO). The growth of Douglas fir was compared with the growth of Norway spruce under the conditions of the School Forest Enterprise at Kostelec nad Černými lesy. The diameter, height, volume of the mean tree and the volume stock per hectare were used as the input for the model growth assessment. Douglas fir achieved considerably higher values than Norway spruce in all the indicators. The volume of the mean tree of Douglas fir was almost three times that of the spruce, and the volume stock of Douglas fir was more than 35 % greater. Wood density, shrinkage, compression strength, bending strength, impact strength and hardness were tested on representative sample trees to evaluate the wood quality. Douglas fir wood quality was comparable to its native habitat. Compared to the native commercial softwoods, Douglas fir wood was similar to that of Norway spruce or Scots pine.

KEYWORDS: Douglas fir, production potential, growth, wood quality.

INTRODUCTION

Douglas fir is considered to be one of the most promising geographically non-native tree species for use in forestry not only in the Czech Republic, but also other European countries, especially Germany, France and the United Kingdom (Šindelář and Beran 2004). The reason is that this species conforms to the majority of requirements made on introduced species (Otto 1993). The principal cause of the interest is its high wood production volume as described by authors not only in the Czech Republic (e.g. Hofman 1964; Wolf 1998 a, b; Kantor et al. 2001; Kantor 2008; Kantor and Mareš 2009; Kinkor 2011; Martiník 2003; Podrázský et al. 2013), but also in neighbouring European countries (Huss 1996; Burgbacher and Greve 1996; Greguš

1996). However, the economic importance of Douglas fir is also unchallenged in areas of its native presence (Hermann and Lavender 1999) as well as distant locations such as New Zealand (Ledgard and Belton 1985).

In contrast to a relatively large amount of the above works, assessing the production quantities of Douglas firs, studies focusing on evaluation the quality of wood from introduced tree species, whether in the Czech Republic or in its close vicinity, are rather sporadic. The quality of Douglas fir wood has been examined, for example, by Göhre (1958) and Hapla (2000), the impacts of cultivation measures on the wood quality by Hapla and Knigge (1985) and Hapla (1997). The Czech setting only saw the singular work from mid 20th century mentioned above (Hofman 1964).

At present, Douglas firs are growing on an area of approx. 5600 ha in the Czech Republic, which represents about 0.22 % of the Czech forests. Stands of the first three age class are predominant, while the area of stands older than 100 years is only 50 ha (Beran and Šindelář 1996). However, it has been evident in the recent years that the planting of introduced conifers has been decreasing, probably due to considerable complications and obstacles on the part of the state administration (Šindelář and Beran 2004).

Douglas fir wood

Douglas fir is a heartwood species. The sapwood is whitish to pale yellow, and relatively narrow. The heartwood colour depends on the habitat and growth rate, and is highly variable from yellow-brown to a red hue (Bormann 1984; Wagenführ 2004; Wiemann 2010). The annual rings are distinct, and the transition from earlywood to latewood is abrupt (Panshin and De Zeeuw 1980). The wood is strong, moderately hard and very stiff. It is easily machined and dried. It has intermediate durability and is difficult to impregnate with preservatives (Bormann 1984). Wagenführ (2004) says that the best technological quality wood has a growth ring spacing between 1 and 2 mm. Wood with wide growth rings is prone to splintering when cutting (Rendle 1969). In the native areas, the wood is widely used for timber, plywood and cellulose. Its main application is in the building industry as a framework material (Alden 1997; Bormann1984). It is regarded as an excellent material for glue lams (Rendle 1969). Douglas fir is the most important tree species for timber manufacturing in the USA (Bormann 1984).

The objective of this paper is to analyse the production potential and evaluate Douglas fir wood quality on the model site of the School Forest Enterprise (SFE) of the Czech University of Life Sciences in Prague, and thus obtain more exact information for decision-making concerning the potential expansion of its cultivation and for Czech wood processing industry.

MATERIAL AND METHODS

The study area of the SFE is situated at an altitude of 300-520 m, approx. 30-55 km southeast of Prague; the average annual temperature ranges between 7.5-8.5°C, and the long-term total annual precipitation is approx. 650 mm. Within the 6734 ha of forest land, Douglas firs grow in 98 stands, in which it represents 5 to 100 %. The reduced area on which Douglas firs grow are 14.56 ha, which translates into 0.22 % of the total size of the forest stands managed by the School Forest Enterprise, which approximately corresponds to the share of this species within the Czech Republic.

For the purposes of the model comparison of the growth potential of Douglas fir and Norway spruce on this site, we analysed all the stands where these species are present, achieving a quantified volume of wood (Douglas fir n = 58, Norway spruce n = 3215), based on the Forest Management Plan. The mean diameters and heights of both species were used as the input for the model derivation of the time progress of the diameter and height increment. We employed the Korf growth function for this purpose (Korf 1939):

$$y(t) = A \exp\left(\frac{k}{1-n} t^{1-n}\right), \qquad A \in \mathrm{R},\, k > 0,\, n > 1 \tag{1}$$

The current annual increment was calculated as the first derivation of the Korf function.

The parameters A, k and n were estimated using the least square method; we used the Levenberg-Marquardt algorithm and the Statistica statistic software, Version 9 (StatSoft®).

The mean annual increment of both the quantities was then determined as

$$PP(t) = \frac{y(t)}{t} = \frac{A \exp\left(\frac{k}{1-n} t^{1-n}\right)}{t} \tag{2}$$

and the age of the stand in which the meanannual increment culminates as

$$t_{PP} = \sqrt[n-1]{k} \tag{3}$$

The current annual increment is defined by the formula

$$BP(t) = y'(t) = A \exp\left(\frac{k}{1-n} t^{1-n}\right) \frac{k}{t^n} \tag{4}$$

and the culmination age for the currentannual increment

$$t_{BP} = \sqrt[n-1]{\frac{k}{n}} \tag{5}$$

In addition, we studied the growth of Douglas fir in detail on felled sample trees in the permanent research plots. These sample trees were then used for evaluating the wood quality. Sections collected for growth ring analyses were then used for assessing the vertical and horizontal variability of selected properties in a stem (Jelonek et al. 2009). Moreover, three sections 150 cm long were taken from each sample tree, representing the areas of the stem base, the centre part of the stem and the crown area (Hof et al., 2008; Langum et al. 2009; Lukášek et al. 2012), in particular for assessing the bending strength and the impact strength. The sections obtained were further cut into planks and left to dry naturally. The cutting and further processing of the stem sections, the preparation and selection of testing samples were carried out following standardised procedures in accordance with Czech national standards (ČSN 49 0101 1980; ČSN 49 0103 1979), so that the experimental results could be compared with the literature. The following tests of physical and mechanical properties were performed in order to assess the qualitative parameters of the wood of this introduced tree species. Physical properties included wood density (as per ČSN 49 0108 1993) and wood shrinkage in radial and tangential directions and volumetric shrinkage (as per ČSN 49 0128 1989). Mechanical properties included compression strength along the fibres (as per ČSN 49 0110 1977), bending strength (as per ČSN 49 0115 1979), impact strength(as per ČSN 49 0117 1979), and hardness according to Brinell (HB) (as per BS EN 1534 2001).

The determination of each of the properties proceeded in line with the above mentioned standards. Testing samples 20 x 20 x 30 mm were used for determining wood density, shrinkage, compression strength and hardness. Testing samples 20 x 20 x 300 mm were used for determining bending strength and impact strength.

Wood density and all the tests for mechanical properties we set for 12 % moisture content. Given the pronounced anisotropic behaviour of wood, hardness was tested both perpendicular to the fibres and along the fibres. Likewise, wood shrinkage was evaluated in both the radial and tangential directions. Volumetric shrinkage was also evaluated. The maximum shrinkage was assessed in all the cases, means the change in dimensions associated with the reduction in moisture content from fibre saturation point to 0 % moisture content.

RESULTS AND DISCUSSION

Growth characteristics of Norway spruce and Douglas fir on SFE model site

The time trend of the reporting diameter and height growth of Norway spruce and Douglas fir on the SFE model site is shown in Figs. 1 and 2. The parameters of the Korf function are shown in Tab 1. The analyses carried out document the growth superiority of Douglas fir to spruce. That said the time trend of the current and mean height increment is similar for both the species. The culmination of current increment occurs at 14 years of age for Douglas fir (being almost 80 cm); the current height increment of the spruce culminates at 16 years, being 64 cm. The mean height increment of Douglas fir culminates at 29 years (56 cm); the spruce culminates somewhat later, at 32 years (45 cm). The time trend of the diameter growth differs somewhat more between the two species. The current diameter increment of Douglas fir culminates at 17 years, reaching an annual maximum of 88 mm; its mean diameter increment culminates at 40 years (67 mm). The current diameter increment of the spruce occurs at 14 years of age (57 mm), whereas its mean diameter increment culminates at 31 years, reaching a maximum of 45 mm. In both cases, the increment decreases faster after the culmination in Douglas fir; however, the decrease is not very deep compared to the spruce.

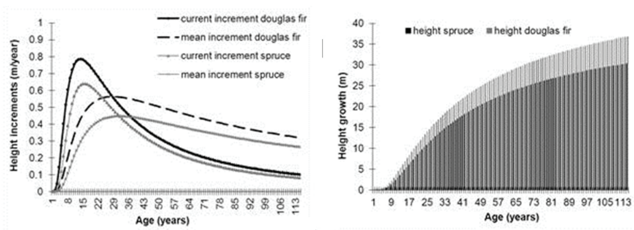

Fig. 1: Trends of current and mean height increment of Douglas fir and spruce on SFE site at Kostelec nad Černými lesy, equalised using the Korf function.

The maximum achieved diameter (asymptote of the growth function) was determined at 90.5 cm for the spruce and 115.3 for Douglas fir; the maximum height was 42.6 m for the spruce and 53.9 m for Douglas fir. The volume of the timber to the top of 7 cm including the bark for these values corresponds to 7.6 m^3 for the spruce a 25.2 m^3 for Douglas fir.

The average stand height of Douglas fir derived from the Korf function in 50 and 100 years old stands corresponds to 25.2 and 35.1 m respectively. In the case of spruce, the average stand height amounted to 20.6 and 28.9 m respectively. These values correspond to the 2nd site class derived from growth tables for the Czech Republic (Černý et al. 1996) and 3rd site class derived from growth tables for northern Germany (Bergel 1985).

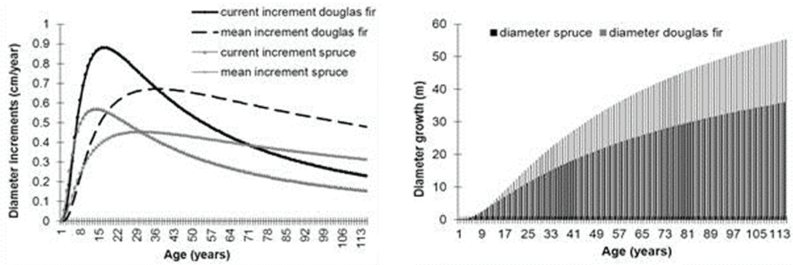

Fig. 2: Trends of current and mean diameter increment of Douglas fir and spruce on SFE site at Kostelec nad Černými lesy, equalised using the Korf function.

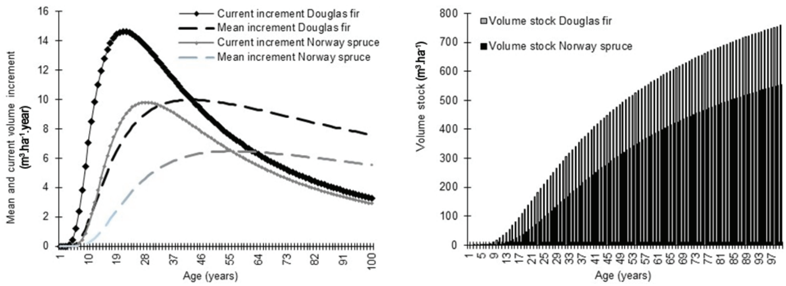

Fig. 3: Trends of current and average stand stock increment of Douglas fir and the spruce on SFE site at Kostelec nad Černými lesy, equalised using the Korf function.

The model trend of the spruce and Douglas fir volume stock is shown in Fig. 3. The production superiority of Douglas fir is also evident in this parameter: at 100 years, it achieves an average equalised volume stock of 750 $m^3.ha^{-1}$, which is approx. 35 % more than spruce volume stock (550 $m^3.ha^{-1}$). The current volume increment culminates at the age of 21 years in Douglas fir, achieving an increment of more than 14.5 $m^3.ha^{-1}$ and volume stock of 152 $m^3.ha^{-1}$. That is 7 years earlier than spruce (increment of 9.8 $m^3.ha^{-1}$ and stock of 129 8 $m^3.ha^{-1}$). The mean annual increment in Douglas fir stand stock culminates at 43 years (the increment being approx. 10 $m^3.ha^{-1}$ and the volume stock 429 $m^3.ha^{-1}$); it is 13 years later in spruce (increment 6.5 $m^3.ha^{-1}$, volume stock 362 $m^3.ha^{-1}$). These production parameters are somewhat higher than the values determined in the Písek district (Podrázský et al. 2013). They documented culmination of the volume increment at a somewhat later age (current increment at 23.5 years, mean at 46.7 years), at lower increment values (current 12.5 $m^3.ha^{-1}$/year; mean 8.4 $m^3.ha^{-1}$/year) as well as volume stock (144 and 392 $m^3.ha^{-1}$ respectively). The stand volume stock at 100 years was also approx. 100 $m^3.ha^{-1}$lower.

A potential increase in the share of Douglas fir to the detriment of spruce on the SFE model site (approx. 6000 ha) would lead to an unquestionable increase in the potential wood production. Based on the analyses conducted, an increase in the share of Douglas fir from 0.2 at present to 5 % would increase the annual volume increment by up to 1000 m^3 on average.

Tab. 1: Estimated parameters of Korf growth function for studied production properties of spruce and Douglas fir on SFE site at Kostelec nad Černými lesy.

Model Parameters	DBH (cm)		h (m)		Volume stock (m³)	
	Spruce	Douglas fir	Spruce	Douglas fir	Spruce	Douglas fir
A	90.53830	115.33600	42.57730	53.85970	893.437	1175.060
k	6.26461	10.31920	23.63690	16.08220	82.4197	40.672
n	1.53502	1.64788	1.91321	1.82843	2.09819	1.987

Tab. 2 presents the values of physical and mechanical properties of Douglas fir wood assessed. Wood density of 488 kg.m^{-3} at 12 % moisture content corresponds to values given by Alden (1997) for the native are as for Interior North (480 kg.m^{-3}) or Interior West (500 kg.m^{-3}); the values in the coastal areas are higher (540 kg.m^{-3}). Higher values are also given by Göhre (1958) 542 and Dinwoodie (2000) 590 kg.m^{-3}.

Tab. 2: Assessed physical and mechanical properties of Douglas fir wood.

Wood Properties		Mean ± SD	CV (%)	N
Density	(kg.m^{-3})	488±40	8.2	505
Shrinkage tangential	(%)	7.7 ± 0.8	11.0	265
Shrinkage radial	(%)	4.6 ± 0.6	12.5	265
Shrinkage volumetric	(%)	12.2 ± 1.2	9.9	265
±				
Compression strength	(MPa)	42.1 ± 7.5	502	17.9
Bending strength	(MPa)	87 ± 13	72	15.3
Impact strength	(J.cm^{-2})	4.6 ± 1.8	54	38.4
HB perpendicular	(MPa)	13.5 ± 3.3	750	24.4
HB parallel	(MPa)	31.5 ± 6.2	467	19.8

Density reaches the highest values at the base of the stem and decreases upwards, to start increasing again from the middle of the stem up (Fig. 4). A similar trend is given for Douglas fir by Pong et al. (1986). Acuna and Murphy (2006) state a low effect of the height on the variability of Douglas fir wood density. In radial direction, from the pith to the bark, wood density increases, with the highest value being close to the bark (Fig. 5). Such horizontal distribution of wood density in the stem is also stated by Gartner et al. (2002).

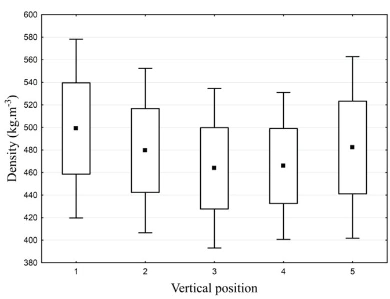

Fig. 4: Variability in Douglas fir wood density in vertical direction from the stem base to the crown.

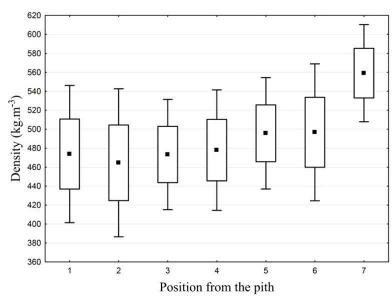

Fig. 5: Variability in Douglas fir wood density in radial direction from the pith to the bark.

Shrinkage in the tangential direction (7.7 %) and the radial direction (4.6 %) as well as volumetric shrinkage (12.2 %) corresponds to data from native sites as well as from other areas. Generally, the differences among authors are small. All the three types of shrinkage assessed show a similar trend in the stem, with decreasing shrinkage with increasing height.

Compression strength of the wood of 42.1 MPa corresponds to the data for InteriorSouth 43.0 MPa (Alden, 1997). This is a relatively low value, since Alden (1997) gives 52.1 MPa for Interior West, Tsoumis (1991) 51.0 MPa and Niemz (1993) 50.0 MPa. However, Polman and Militz (1996) concluded a similar value in the Netherlands. A clear trend has not been confirmed in the vertical direction; compression strength first decreases as the height increases, to then attain a value similar to that of the base in the crown. Compression strength is the lowest near the pith; it grows towards the trunk periphery and attains the highest value near the bark. The increasing trend from the pith to the trunk periphery was confirmed by Jelonek et al. (2009).

The measured bending strength of 87 MPa is relative high. The highest value from the assessed areas is given by Alden (1997) for InteriorNorth 90.3 MPa. A higher value is only given by Göhre (1958) 98.5 MPa; other authors give lower values. Bending strength increases with the growing height within the stem, and the highest values are attained in the base of the stem.

With respect to the great variability in the property, impact strength of 4.6 $J.cm^{-2}$ is comparable to results of other authors, ranging between 3.8 – 6.5 $J.cm^{-2}$ .As with bending strength, impact strength decreases from the base to the crown area, with the greatest strength attained in the base part of the stem.

The Brinell hardness of 13.5 and 31.5 MPa perpendicular to and along the fibres, respectively, corresponds to the values given by Topaloğlu and Ay (2010). Especially for the hardness along the fibres, both Göhre (1958) and Wagenführ (2000) give considerably higher values around 50 MPa. The hardness perpendicular to the fibres increases from the pith to the bark, with the highest values at the periphery of the trunk. Vertically, this hardness is the highest at the base of the stem, then it decreases and the decrease gives way to a gradual increase from the middle of the stem up. The trend in the hardness along the fibres in the horizontal direction within the stem is similar to that of the hardness perpendicular to the fibres. It first decreases along with the stem height, and then grows again from the middle of the stem towards the crown area.

Where evaluated, the dependence of the tested mechanical properties on wood density was shown to be relatively low. The highest value of the coefficient of determination (R^2) of 0.45 was attained for the hardness perpendicular to the fibres. The coefficient R^2 was only 0.43 and 0.33 for compression strength and the hardness along the fibres respectively (Fig. 6). Although literature states wood density as one of the best predictors of the strength characteristics, it is only of limited applicability for estimating the strength and hardness in this case.

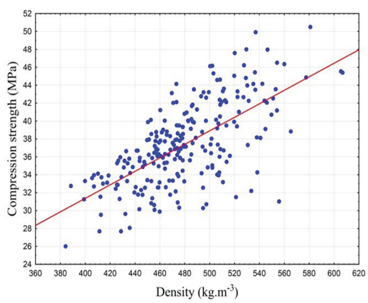

Fig. 6: Dependence of compression strength on wood density.

The comparison of the wood quality of the Douglas firs studied is based on generally given values for the Central European area. Tabs. 3 and 4 compare the results with physical and mechanical properties of economically important native coniferous tree species. Based on the physical properties assessed, the Douglas fir wood can be regarded as an analogy to Scots pine wood. However, the study focusing on the quality of spruce wood from the same area (Salem et al. 2013) gives higher values for both density and shrinkage than are given commonly. The assessment of the comparison with native coniferous tree species based on mechanical properties is not univocal. The wood corresponds to Norway spruce with its hardness and impact strength. It outperforms all the species except larch with its bending strength. However, this value is not exceptional compared to Salem et al. (2013). On the other hand, its compression strength does not even match silver fir.

Tab. 3: Comparison of physical properties of Douglas fir wood with commercial native softwoods.

		Pseudotsuga menziesii	***Abies alba*1)**	***Picea abies*1)**	***Pinus sylvestris*1)**	***Larix decidua*1)**
Density	($kg.m^{-3}$)	488	450	470	510	590
Shrinkage tangential	(%)	7.7	7.2 – 7.6	7.8 – 8.0	7.5 – 8.7	7.8 – 10.4
Shrinkage radial	(%)	4.6	2.9 – 3.8	3.5 – 3.7	3.3 – 4.5	3.3 – 4.3
Shrinkage volumetric	(%)	12.2	10.2 – 11.5	11.6 – 12.0	11.2 – 12.4	11.4 – 15.0

1) WAGENFÜHR (2000)

Tab. 4: Comparison of mechanical properties of Douglas fir wood with commercial softwoods.

		Pseudotsuga menziesii	***Abies alba*1)**	***Picea abies*1)**	***Pinus sylvestris*1)**	***Larix decidua*1)**
Compression strenght	(MPa)	42.1	47	50	55	55
Bending strenght	(MPa)	87	73	78	80	95
Impact strength	($J.cm^{-2}$)	4.6	4.2	4.6	4	6
HB perpendicular	(MPa)	13.5	13.0 – 16.0	12	19	19
HB parallel	(MPa)	31.5	30	32	40	53

1) WAGENFÜHR (2000)

CONCLUSIONS

The growth and production of Douglas fir significantly outperformed the production and growth characteristics of the most productive native tree species – Norway spruce – in all the assessed parameters. The analysis results were comparable to an analogous survey in another part of the Czech Republic. Cultivation of Douglas fir clearly leads to an increase in the volume production of forest stands, including when replacing the spruce. With its wood quality, Douglas fir assessed mostly achieved average values, comparable to data from some regions of its native area. It has a favourable high bending strength, on the contrary most sources mention greater hardness. Based on the assessed properties, it is comparable to Norway spruce or Scots pine wood. Only its hardness does not match the qualities of any of the major native coniferous species. It should not be used as a substitute for larch wood, with which an inexperienced user may frequently confuse it based on its appearance, because it does not match the qualities of larch. Still, Douglas fir can definitely be regarded as an attractive complement to wood of the Czech native tree species.

When assessing the potential for the use of Douglas fir, these results have to be complemented with its relatively more favourable influence on the soil compared to spruce (e.g., Podrázský et al. 2009, 2010; Menšík et al. 2009) and the ability of Douglas fir to produce mixed stands with native tree species and reproduce naturally. For these reasons, it is realistic to consider the option to use Douglas fir as one of the possible alternatives for Norway spruce in appropriate lower and middle-elevation habitats.

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