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Shrinkage of Scots pine wood as an effect of different tree growth rates, a comparison of regeneration methods

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Abstract

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The Scots pine (*Pinus sylvestris* Linnaeus) is one of the most important commercial tree species in Central Europe, yet we know very little about the variability of its wood properties. The aim of this study is to primarily analyse the impact of different tree growth rates and site characteristics on the shrinkage of Scots pine wood. The investigated forest stands are located at two sites of the Czech Republic that are characteristic for Scots pine silviculture. At each site, sample trees were selected from two stands representing two variants of the silvicultural treatment, i.e. a clear-cutting and shelterwood system with long regeneration period. Wood shrinkage in radial and tangential directions and volumetric shrinkage were determined in accordance with Czech standards. Lower values of shrinkage were found out in forest stands regenerated by the shelterwood method. The wood in the central part of the trunk shows lower shrinkage values than in the basal part in both stands. The unambiguous effect of the horizontal position in the trunk stem was demonstrated in forest stands regenerated by the clear-cutting method, whilst stands regenerated by the shelterwood method showed a more even distribution of shrinkage along the trunk width. Furthermore, it was found that the shrinkage of the Scots pine has a medium dependence on wood density.

Keywords: *Pinus sylvestris* L.; wood physical properties; dimensional changes; management system; stand structure

The Scots pine (*Pinus sylvestris* Linnaeus) is the second most important coniferous tree species in the Czech Republic. The annual production volume of this species is about 1.4 million m^3, and its wood has a wide range of uses with application primarily in the construction industry for carpentry. The high resin content is limiting for cabinetmaking work. Scots pine wood is also used for the production of plywood, sleepers, poles and hop pillars, mining struts, packaging, wood pulp, fibre, and in the paper industry (Fellner et al. 2007; Czech Statistical Office 2017). Despite the high utilization of pine in the Czech Republic, awareness of the quality of its wood and the factors that affect it is relatively small.

In assessing the wood quality, in addition to density, shrinkage is primarily one of the basic physical properties. These dimensional changes, associated with wood moisture fluctuations constitute important information for the wood-processing industry;

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they fundamentally affect the processing and use of individual types of wood, and even the properties of wood products (Zeidler 2013). The range of shrinkage differs for the three basic directions, namely the longitudinal, radial and tangential directions. Wood without growth defects shrinks most in the tangential direction and least in the longitudinal direction (Tsoumis 1991; Požgaj et al. 1997; Pang 2002). Extensive studies have shown that there are several primary factors that affect wood shrinkage. These include, in particular, wood density, wood position in the stem along the width and height, content of the extractives, the difference between heartwood and sapwood, tree-ring width, and thereby also the related proportion of late wood and the difference between juvenile and mature wood (Gryc, Holan 2004; Raiskila et al. 2006). External factors affecting the resulting physical properties include climatic changes, altitude, site conditions and silvicultural treatments (Macdonald, Hubert 2002; Liziniewicz 2014). An important factor, already mentioned above, is the site. Zobel and van Buijtenen (1989) identified the habitat as one of the factors that relates to wood properties that is most difficult to identify because it is a criterion of soil and climate quality, collectively referred to as the quality (value) of site (Worrell, Malcolm 1990). In addition to direct growth effects, the soil moisture regime is one of the factors of tree stability that is influenced by the used silvicultural method (Macdonald, Hubert 2002). In the Czech Republic, pine stands are most often regenerated artificially. Many studies attribute the tree spacing as having the greatest impact on the resulting wood quality. The faster growth of pine trees with greater spacing results in higher production of wood mass in a stand, but also in larger tree-ring width and higher amount of knots (Haapanen, Pöykkö 1993). The effect of fast tree growth, reflected in tree-ring width and higher share of early wood composed of thin-walled cells, adversely affects the wood density and consequently the resulting wood properties. In the Scots pine, large spacing as a result of artificial regeneration leads to lower wood quality compared to naturally regenerated stands (Haapanen, Pöykkö 1993). Even less information about wood quality is available for highly structured stands managed according to the principles of close-to-nature silviculture (Vacek et al. 2016).

Silviculture and wood quality are understood as separate stand-alone issues in the Czech Republic. Abroad, however, the situation is quite different. The issue of assessing the influence of silvicultural treatment and site on wood properties is still a current topic in Europe, even in countries with advanced forestry such as Germany, Poland or Finland (Beck 2000; Peltola et al. 2007; Jelonek et al. 2008). The aim of this work is to determine the shrinkage of Scots pine wood from forest stands with different silvicultural treatments from the locations characterised by pine silviculture in the Czech Republic, to evaluate the variability of shrinkage depending on the horizontal and vertical position in the stem, and to assess the extent to which it is influenced by wood density.

METHODS

The research was carried out at the Doksy and Chvojno sample sites, both of which are characterized by an important representation of Scots pine (*Pinus sylvestris* L.) in cultural stands. The harvest took place in stands that are typical of these sites with regard to site conditions, and they represent different silvicultural practices (Table 1). The forest stands in the Doksy site are owned by the Doksy Municipal Forests and are located in Natural Forest Area PLO 18 – Severočeská pískovcová plošina and Český ráj (North Bohemian Sandstone Plateau and Bohemian Paradise), where the average rainfall is

Table 1. Average sample values from the selected forest stands

Region		Forest stand 1	Forest stand 2
Doksy	forest site type	0K	0K
	silvicultural treatment	shelterwood	clear-cutting
	DBH (mm)	169	187
	tree height (m)	13.0	18.1
Chvojno	forest site type	2I	2I
	silvicultural treatment	shelterwood	clear-cutting
	DBH (mm)	205	224
	tree height (m)	15.2	21.7

0K – (*Querceto-Fagi-*) *Pinetum acidophilum*, 2I – *Fageto-Quercetum illimerosum acidophilum* (Plíva 1971)

550 mm, the average temperature is between 7 and 8°C and the altitude is 450 m a.s.l. The forest stands from the Chvojno site are owned by Lesy České republiky, s. p. (Forests of the Czech Republic) and are located in Natural Forest Area PLO 17 – Polabí (Labe River basin), where the average annual precipitation is 680 mm, the average temperature is around 8°C and the altitude is 362 m a.s.l.

Forest stand 1 is characterized by a two-aged two-storeyed structure. Sample trees represent individuals growing under the canopy of parent trees. Forest stand 2 was established after a clearcut, thus sample trees are represented by individuals growing in an even-aged single-storeyed stand without the suppression of parent trees. Seven sample trees were selected from each stand from which the test material was made. An important criterion for sample selection was the representation of characteristic individuals for the relevant stand, their vitality and the absence of growth irregularities and defects.

A total of 28 sample trees were selected, which were felled during the winter period to minimise injuries on forest stands, in order to assess the wood shrinkage from both sites. To evaluate the vertical variability of the assessed properties, two sections were taken from each tree in the direction from the base to the crown. The section length was 1.5 m, and the diameter of the section was not smaller than 150 mm. The basal section was taken from the area of the DBH, and the central section was taken at 1/3 of the tree height (Fig. 1). The trees raised under the shelter on the Doksy site did not reach the required dimensions in the 1/3 trunk length and were not therefore taken from the crown region. A disk for tree-ring analysis was taken from each section. From the individual sections, central planks of approximately 4 cm in thickness were cut out using a band saw. The lumber thus prepared was placed in a sheltered space with free access to the air. The purpose of this operation was to reduce wood moisture to a value that allows for the production of test specimens. The central planks were further longitudinally cut into 20 × 20 mm prisms with marking of the direction from the pith to the cambium. The prepared material served as the basis for the preparation of 20 × 20 × 30 mm test specimens. This production process enabled monitoring of the variability of wood properties across the radii of the trunk, i.e. in the horizontal direction (Fig. 1).

The examined physical properties included oven-dry density, i.e. the density in an absolute dry state, as well as shrinkage in tangential direction, radial direction and volumetric shrinkage. In total, 2,216 specimens were tested for density at 0% moisture content (MC), and simultaneously for shrinkage. The quality of all the samples complied with the standard ČSN 49 0101 and did not contain any irregularities or growth defects and compression wood.

The standard ČSN 49 0108 was used to assess the density. The density at 0% MC (ρ_0) was evaluated according to Eq. 1:

$$\rho_0 = \frac{m_0}{V_0}\ \left(\text{g·cm}^{-3}\right) \tag{1}$$

where:

m_0 – mass of the specimen at 0% MC (g),

V_0 – volume of the specimen at 0% MC (cm^3).

Wood shrinkage in individual directions (β_i) was ascertained in accordance with the standard ČSN 49 0128 and Eq. 2 was used:

$$\beta_i = \frac{a_{iw_1} - a_{iw_2}}{a_{iw_1}} \times 100\ (\%) \tag{2}$$

where:

a – dimension of the specimen in a certain direction (mm),

i – index indicating a certain direction,

w_1 – initial MC of the specimens (%),

w_2 – final MC of the specimens (%).

Instead of dimensional changes at a given MC, volume changes in the specimens were analogously used for volumetric shrinkage. Drying at 103 ± 2°C resulted in the absolute dry state of the examined specimens. The test specimens were soaked in distilled water to achieve the fibre saturation point.

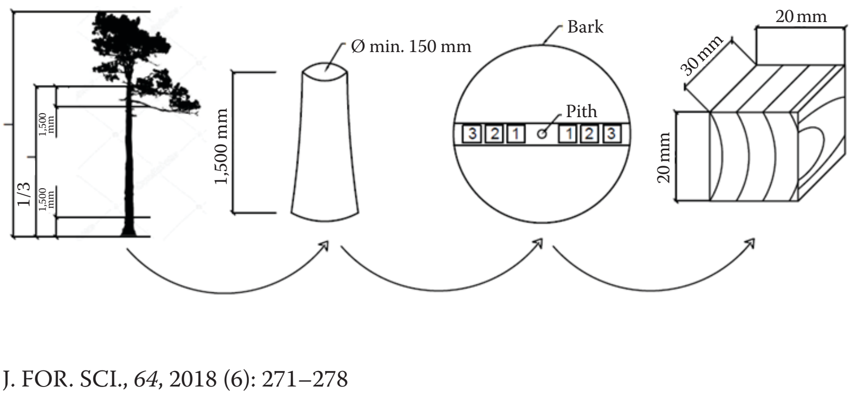

Fig. 1. Tree sampling and preparation of the test specimens

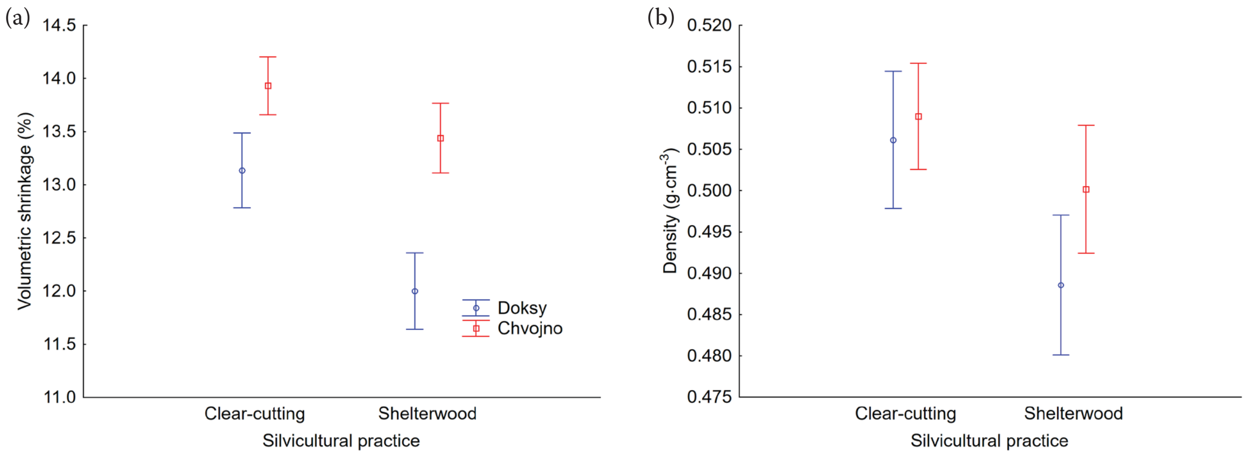

Fig. 2. Comparison of volumetric shrinkage (a) and density (b) at the Doksy and Chvojno sites

Multifactor ANOVA tests (Fisher's *F*-test) and Duncan's multiple range tests were used to evaluate the statistical significance of individual effects. The significance level α = 0.05% was used for all statistical analyses. The evaluated factors were the vertical position (along the trunk height), horizontal position (position from the pith to the bark), silvicultural treatment and site. A linear regression model was used to assess the effect of density on shrinkage. Statistical analyses were carried out using the STATISTICA program (Version 12, 2013).

RESULTS AND DISCUSSION

The Doksy site shows a statistically significant difference between the examined wood characteristics due to the silvicultural measures; for the Chvojno site the significant influence of the measures on the properties of pine wood was not proved. Fig. 2 illustrates the effect of the management method on density and wood volumetric shrinkage, whose trend corresponds to radial and tangential shrinkage. At the Doksy site, in the stand regenerated by the shelterwood method, the density reached a value of 0.489 g·cm^{-3}, shrinkage in tangential direction 7.2%, in radial direction 4.9% and volumetric shrinkage 12%. On the contrary, the wood of the forest stand regenerated by the clear-cutting method showed different shrinkage and density values, i.e. shrinkage in tangential direction 8.0%, in radial direction 5.1% and volumetric shrinkage 13.1%. The wood density in this stand reached 0.506 g·cm^{-3}. At the Chvojno site, the wood of the stand regenerated by the shelterwood method had a shrinkage value of 7.8% in tangential direction, in radial direction 5.3%, volumetric shrinkage 13.4% and the density of 0.500 g·cm^{-3}. The wood from the stand regenerated by the clear-cutting method showed shrinkage 8.0% in tangential direction, in radial direction 5.7 and 13.9% volumetric shrinkage. The wood density reached a value of 0.508 g·cm^{-3}.

Table 2 shows the comparison of the observed values with literature. It can be seen from the table that the shrinkage in radial direction, reported by Awoyemi (2003), was surprisingly high – only 20% lower than the tangential shrinkage, while Tsoumis (1991), Požgaj et al. (1997), Dinwoodie (2000), and Wagenführ (2002) found out lower shrinkage values in radial direction. In tangential direction, Tsoumis (1991), Požgaj et al. (1997), Dinwoodie (2000), and Wagenführ (2002) specified higher shrinkage values. Lower values of volumetric shrinkage and shrinkage in tangential direction than those reported by Tsoumis (1991) were found in the stand regenerated by the shelterwood method at the Doksy site, while the remaining two stands managed by the clear-cutting

Table 2. Comparison of results obtained by foreign authors

		Awoyemi (2003)	Dinwoodie (2000)	Požgaj et al. (1997)	Wagenführ (2002)	Tsoumis (1991)	Farsi et al. (2013)
Density (g·cm^{-3})		–	0.513	0.407	0.490	0.490	0.457
Shrinkage (%)	volumetric	–	–	–	11.2–12.4	12.5	10.7
	radial	6.01	3	4.1	3.3–4.5	4	–
	tangential	7.53	4.5	8.3	7.5–8.7	7.7	–

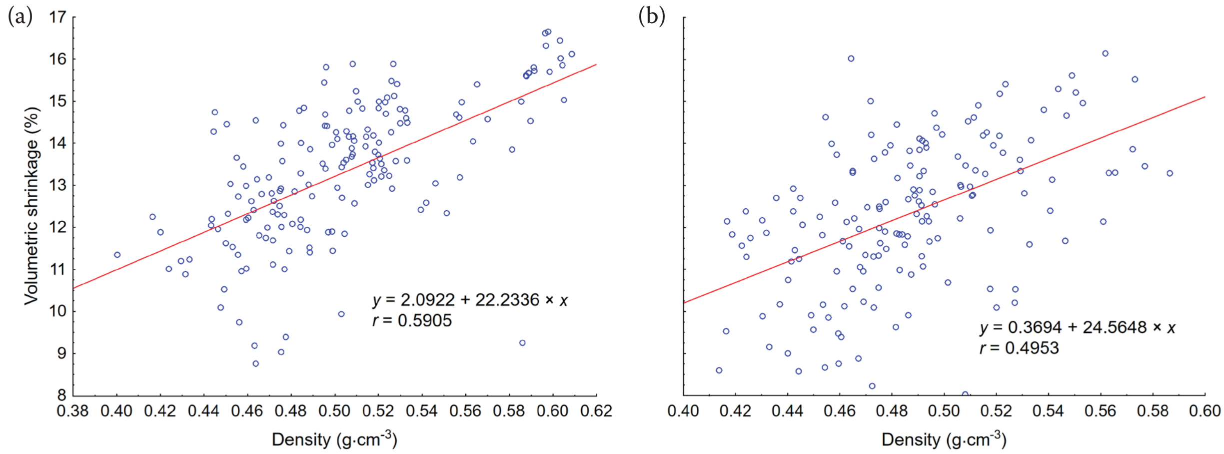

Fig. 3. Correlation between density and shrinkage in relation to silvicultural treatment (Doksy site): clear-cutting (a), shelterwood (b) system

method showed higher shrinkage values. Lower values of tangential shrinkage than those specified by Wagenführ (2002) were determined for such regenerated stands. The remaining two stands managed by the clear-cutting method fall within the tangential shrinkage interval. The stand regenerated by the shelterwood method at the Doksy site reached the same values of volumetric shrinkage as Tsoumis (1991) and Wagenführ (2002) reported. However, Farsi et al. (2013) found out lower volumetric shrinkage than that ascertained in all the investigated stands. Tsoumis (1991) and Wagenführ (2002) reported a medium density value of 0.490 g·cm^{-3} at 0% moisture content, and the same values were reached for the stands regenerated by the shelterwood method at the Doksy site. The remaining stands showed higher values. A lower density value was found out by Požgaj et al. (1997) and Farsi et al. (2013). But higher wood density values than those ascertained in the investigated stands were observed by Dinwoodie (2000).

From the results obtained, it can be stated that higher values of shrinkage and density were found out in the stands regenerated by the clear-cutting method. The higher shrinkage values in each direction for these stands can be explained by the higher wood density. The positive relationship between density and shrinkage is shown in Fig. 3. The influence of density on wood shrinkage was found by Shmulsky and Jones (2011) and Farsi et al. (2013). The dependence of density on shrinkage was shown to be medium in all the stands (Fig. 3), whilst a low and medium dependence was also found by Koubaa et al. (1998). The influence of the site on wood shrinkage and density was ascertained at the Doksy and Chvojno sites. The two sites in Doksy and Chvojno show different values of density and shrinkage. The Chvojno site reached higher shrinkage and density values than the values found at the Doksy site. Different shrinkage and density values at different sites were demonstrated by Tomczak and Jelonek (2013), Hautamäki et al. (2014) and Wood et al. (2016).

Fig. 4 indicates the distribution of shrinkage and wood density in horizontal direction in the stem

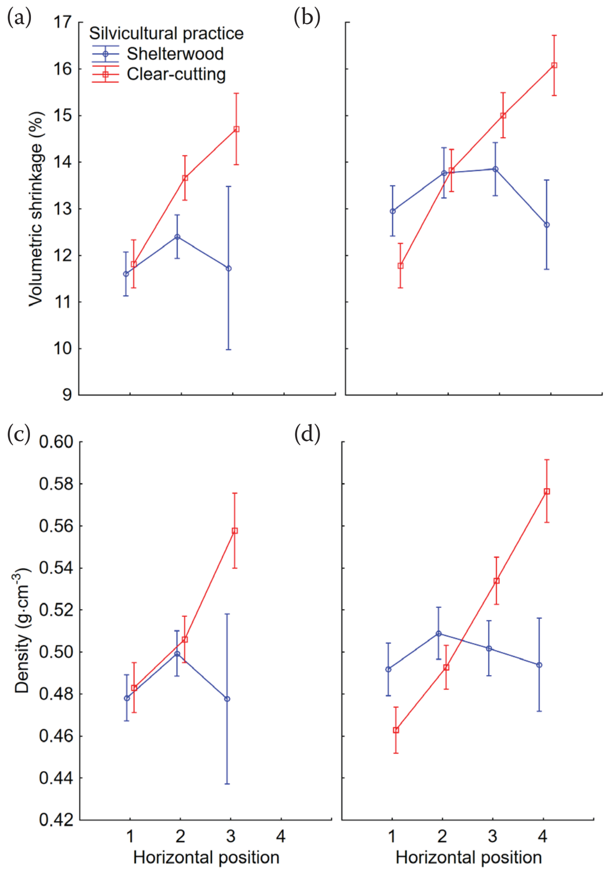

Fig. 4. Effect of the horizontal position on volumetric shrinkage – Doksy (a), Chvojno (b) and density – Doksy (c), Chvojno (d)

1 – position close to the pith, 4 – position close to the bark

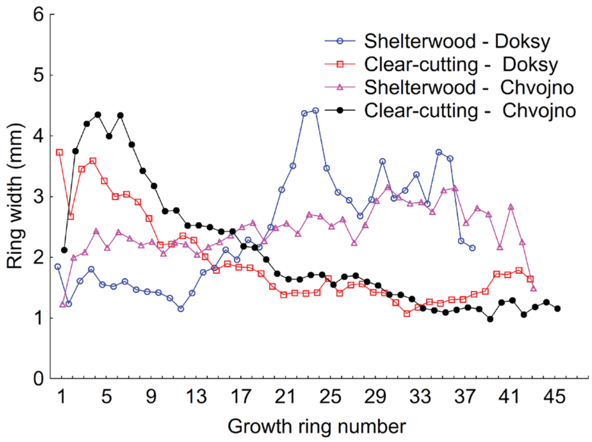

Fig. 5. Tree-ring analysis

according to the applied silvicultural treatment and site. In the shelterwood method, density and shrinkage are evenly distributed over the width of the trunk. A slight decrease in wood density in the shelterwood method is caused by an increase in the tree-ring width after shelterwood felling in the parent stand (Fig. 5). The impact of increasing tree-ring width on shrinkage and wood density was described by Šķēle et al. (2002). The stands regenerated by the clear-cutting method indicate a growing tendency from the pith to the cambium, and there is a significant difference between the different sections compared to the shelterwood method. The trend of increasing density and shrinkage from the pith to the bark due to reduced light and growth conditions in the growing stand was described by many authors (Kollman 1951; Krahmer 1986; Tsoumis 1991; Koubaa et al. 1998; Möttönen, Luostarinen 2006; Kord et al. 2010; Ivković et al. 2013).

In order to assess the variability of the wood properties, it is necessary to consider in which part of the trunk the wood is located. The influence of the silvicultural treatment on wood shrinkage and density in the basal and central part of the trunk is shown in Table 3. It can be seen from the table that wood shrinkage in the basal part of the tree indicates higher shrinkage values for the stands regenerated by the clear-cutting method. With regard to the shelterwood method, at the Chvojno site, the influence of the vertical position in the stem on shrinkage was not found, and it could not be shown on the Doksy site due to small stem diameters and missing samples. The obtained results indicate a uniform distribution of wood shrinkage along the trunk height of this stand, but the wood density was affected by the vertical position in the stem. The clear-cutting restoration method shows a completely different trend. Higher density and shrinkage values were observed in the basal part of the trunk. Higher density and shrinkage values were also found in the basal part of the trunk by other authors (Repola 2006; Muñoz et al. 2008; Farsi et al. 2013).

Fig. 5 indicates the pattern of tree-ring widths from the investigated sites. It is clear that stands regenerated by the shelterwood method show a lower tree-ring width at the early stage of growth. After shelterwood felling, the tree-ring width increases from the pith to the bark and then the width decreases again. A similar trend was described by Eriksson et al. (2006). Stands regenerated by the clear-cutting regeneration method show the opposite trend. The tree-ring width gradually decreases from the pith to the cambium until it becomes almost constant. The same results were also obtained by Nicholls and Brown (1974) and Tomczak et al. (2007). The tree-ring width trend explains the pattern of wood density of the investigated stands, wherein samples with a small tree-ring width have higher wood density. Wood density subsequently decreases with the gradual increase in the tree ring width.

Table 3. Influence of the vertical position on shrinkage (%) and density ($g \cdot cm^{-3}$) in stands at the Doksy and Chvojno sites

		Basal section		Middle section	
		shelterwood	clear-cutting	shelterwood	clear-cutting
Doksy					
	radial	4.9 ± 1.39	5.1 ± 1.02	–	5.0 ± 0.64
Shrinkage ± SD	tangential	7.2 ± 1.52	8 ± 1.66	–	8.1 ± 1.40
	volumetric	12 ± 2.15	13.1 ± 1.89	–	13.0 ± 1.52
Density ± SD		0.489 ± 0.04	0.506 ± 0.05	–	0.456 ± 0.04
Chvojno					
	radial	5.3 ± 1.38	5.7 ± 1.82	5.2 ± 1.44	5.0 ± 1.75
Shrinkage ± SD	tangential	7.8 ± 1.56	8 ± 1.96	7.5 ± 1.69	7.0 ± 1.79
	volumetric	13.4 ± 2.23	13.9 ± 2.88	13.0 ± 2.12	12.5 ± 2.85
Density ± SD		0.500 ± 0.05	0.508 ± 0.07	0.434 ± 0.05	0.436 ± 0.05

SD – standard deviation

CONCLUSIONS

This paper evaluates selected properties of Scots pine (*Pinus sylvestris* L.) wood as a result of the silvicultural treatment at the Doksy and Chvojno sites in the Czech Republic. The Chvojno site has higher values of shrinkage and density compared to the Doksy site. The effect of silvicultural treatment was assessed in stands which were regenerated by the shelterwood and clear-cutting methods. The stands regenerated by the shelterwood method showed lower shrinkage and density values than the stands regenerated by the clear-cutting method. The clear-cutting method indicates a clear trend of shrinkage along the cross-section of the trunk, showing increasing shrinkage values from the pith to the cambium due to decreasing light and growth conditions, resulting probably in a higher latewood share. From the point of view of practice, the differences in both density and shrinkage values are negligible depending on the treatment. Much more significant is the fact that the shelterwood method indicates a uniform distribution of shrinkage and density along the radii of the trunk. The even distribution of wood shrinkage along the trunk height was also demonstrated for these stands. From a qualitative point of view, the position in the trunk the wood comes from is not therefore essential for the final wood processing in the case of shelterwood method.

References

Awoyemi L. (2003): Reversibility of dimensional changes in birch (*Betula pubescens*) and Scots pine (*Pinus sylvestris* L.) wood. Taiwan Journal of Forest Science, 19: 97–101.

Beck W. (2000): Silviculture and stand dynamics of Scots pine in Germany. Forest Systems, 9: 199–212.

Czech Statistical Office (2017): Lesnictví – 2017. Tab. 1.8 Těžba dřeva dle krajů. Prague, Czech Statistical Office.

Dinwoodie J.M. (2000): Structure of timber. In: Timber: Its Nature and Behaviour. 2nd Ed. New York, Taylor & Francis Group: 1–35.

Eriksson D., Lindberg H., Bergsten U. (2006): Influence of silvicultural regime on wood structure characteristics and mechanical properties of clear wood in *Pinus sylvestris*. Silva Fennica, 40: 743–762.

Farsi M., Kiaei M., Miar S., Kiasari S.M. (2013): Effect of seed source on physical properties of Scots pine (a case study in Neka, Iran). Drvna Industrija, 64: 183–191.

Fellner J., Teischinger A., Zschokke W. (2007): Spektrum dřevin: vyobrazení, popis a srovnávací údaje. Wien, pro-Holz Austria: 111.

Gryc V., Holan J. (2004): Influence of position within the tree stem according to growth-ring width of spruce (*Picea abies* /L./ Karst.) with compression wood. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, 4: 59–72.

Haapanen M., Pöykkö T. (1993): Genetic relationships between growth and quality traits in an 8-year-old half-sib progeny trial of *Pinus sylvestris*. Scandinavian Journal of Forest Research, 8: 305–312.

Hautamäki S., Kilpeläinen H., Verkasalo E. (2014): Factors and models for the bending properties of sawn timber from Finland and north-western Russia. Part II: Scots pine. Baltic Forestry, 20: 142–156.

Ivković M., Gapare W., Wu H., Espinoza S., Rozenberg P. (2013): Influence of cambial age and climate on ring width and wood density in *Pinus radiata* families. Annals of Forest Science, 70: 525–534.

Jelonek T., Pazdrowski W., Tomczak A., Szaban J. (2008): The effect of social position of a tree in the stand and site on wood quality of Scots pine (*Pinus sylvestris* L.). Electronic Journal of Polish Agricultural Universities, 11: 10.

Kollmann F. (1951): Technologie des Holzes und der Holzwerkstoffe. Berlin, Heidelberg, Springer-Verlag: 1050.

Kord B., Kialashaki A., Kord B. (2010): The within-tree variation in wood density and shrinkage, and their relationship in *Populus euramericana*. Turkish Journal of Agriculture and Forestry, 34: 121–126.

Koubaa A., Hernández R., Beaudoin M. (1998): Shrinkage of fast-growing hybrid poplar clones. Forest Products Journal, 48: 82–87.

Krahmer R.L. (1986): Fundamental anatomy of juvenile and mature wood. In: Robertson D. (ed.): Proceedings of the Technical Workshop: Juvenile Wood. What Does it Mean to Forest Management and Forest Products?, Bellingham, Nov 7, 1985: 12–16.

Liziniewicz M. (2014): Influence of spacing and thinning on wood properties in conifer plantations. [Ph.D. Thesis.] Alnarp, Swedish University of Agricultural Sciences: 62.

Macdonald E., Hubert J. (2002): A review of the effects of silviculture on timber quality of Sitka spruce. Forestry, 75: 107–138.

Möttönen V., Luostarinen K. (2006): Variation in density and shrinkage of birch (*Betula pendula* Roth) timber from plantations and naturally regenerated forests. Forest Products Journal, 56: 34–39.

Muñoz G.R., Cañas M.A.S., Soalleiro R.R. (2008): Physical properties of wood in thinned Scots pines (*Pinus sylvestris* L.) from plantations in northern Spain. Annals of Forest Science, 65: 507.

Nicholls J.W.P., Brown A.G. (1974): The relationship between ring width and wood characteristics in double-stemmed trees of radiata pine. New Zealand Journal of Forestry Science, 4: 105–111.

Pang S. (2002): Predicting anisotropic shringkage of softwood Part 1: Theories. Wood Science and Technology, 36: 75–91.

Peltola H., Kilpelainen A., Sauvala K., Raisanen T., Ikonen V. (2007): Effects of early thinning regime and tree status on the radial growth and wood density of Scots pine. Silva Fennica, 41: 489–505.

Plíva K. (1971): Typologický systém ÚHÚL. Brandýs nad Labem, ÚHÚL: 119.

Požgaj A., Chovanec D., Kurjatko S., Babiak M. (1997): Štruktúra a vlastnosti dreva. Bratislava, Príroda: 485.

Raiskila S., Saranpää P., Fagerstedt K., Laakso T., Löija M., Mahlberg R., Paajanen L., Ritschkoff A.C. (2006): Growth rate and wood properties of Norway spruce cutting clones on different sites. Silva Fennica, 40: 247–256.

Repola J. (2006): Models for vertical wood density of Scots pine, Norway spruce and birch stems, and their application to determine average wood density. Silva Fennica, 40: 673–685.

Shmulsky R., Jones D.P. (2011): Forest Products and Wood Science: An Introduction. 6th Ed. New York, Wiley-Blackwell: 477.

Šķēle K., Alksne A., Cīrule D., Hrols J. (2002): Anatomical structure and physical properties of pine (*Pinus sylvestris* L.) wood in Latvia. Proceedings of the Latvia University of Agriculture, 5: 68–74.

Tomczak A., Jelonek T. (2013): Radial variation in the wood properties of Scots pine (*Pinus sylvestris* L.) grown on former agricultural soil. Leśne Prace Badawcze (Forest Research Papers), 74: 171–177.

Tomczak A., Pazdrowski W., Jelonek T., Stypula I. (2007): Vertical variability of selected macrostructural properties of juvenile wood organization in trunks of Scots pine (*Pinus sylvestris* L.) trees. Acta Societatis Botanicorum Poloniae, 76: 27–33.

Tsoumis G.T. (1991): Science and Technology of Wood: Structure, Properties, Utilization. New York, Van Nostrand Reinhold: 494.

Vacek S., Vacek Z., Bílek L., Simon J., Remeš J., Hůnová I., Král J., Putalová T., Mikeska M. (2016): Structure, regeneration and growth of Scots pine (*Pinus sylvestris* L.) stands with respect to changing climate and environmental pollution. Silva Fennica, 50: 1564.

Wagenführ R. (2002): Dřevo – obrazový lexikon. Prague, Grada Publishing, a.s.: 348.

Wood L., Smith D., Hartley I. (2016): Predicting softwood quality attributes from climate data in interior British Columbia, Canada. Forest Ecology and Management, 361: 81–89.

Worrell R., Malcolm D.C. (1990): Productivity of Sitka spruce in northern Britain. 1. The effects of elevation and climate. Forestry, 63: 105–118.

Zeidler A. (2013): Shrinkage of Turkish hazel (*Corylus colurna* L.) wood and its within-stem variation. Zprávy lesnického výzkumu, 58: 10–16.

Zobel B.J., van Buijtenen J.P. (1989): The effect of silvicultural practices on wood properties. In: Wood Variation: Its Causes and Control. Berlin, Heidelberg, Springer-Verlag: 218–248.

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