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ORIGINAL ARTICLE

Impact of shelterwood regeneration method on mechanical properties of scots pine wood

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Abstract

Key message **Regeneration method effects within-stem variability of mechanical wood properties but has no impact on overall quality of Scots pine logs.**

Abstract In Central Europe, group shelterwood regeneration method relying on natural regeneration is generally considered as an approach that meets the criteria of close-to-nature silviculture. We tested its effect on wood properties in contrast to the clearcutting method with subsequent artificial regeneration by planting in the case of Scots pine (*Pinus sylvestris* L.). Four localities were chosen in the Czech Republic, where both regeneration methods were applied. Sample trees were felled and subsequently evaluated for the impact of the applied regeneration method on wood properties. Modulus of elasticity, bending strength and wood density were used as indicators of wood quality. The impact of the regeneration method on the examined characteristics of the wood was not statistically significant, 78 MPa (megapascal) for shelterwood and 75 MPa for clearcutting method in the case of bending strength, and they are of negligible importance in terms of influencing end-product potential. Much more significant was the impact of the applied regeneration method on the distribution of the properties along trunk radius, where the shelterwood method provides even distribution. Non-destructive methods turned out to be useful tools for elastic properties estimation of wood as the close correlation to modulus of elasticity was confirmed ($r=0.66$ and $r=0.82$ for shelterwood and clearcutting method, respectively).

Keywords Forest stand regeneration · Strength · Stiffness · Density · Variability

Introduction

Scots pine currently occupies more than 16% of the total area of forests in the Czech Republic and is the second most important commercial tree species after Norway spruce (*Picea abies* (L.) H. Karst.) (MACR 2020). In member countries of the EU it covers around 20% of the whole forest area. Due to climatic changes and the dying of forest stands in the middle and lower altitudes, its importance will continue to increase (Hlásny et al. 2011, 2014). At the same time, in these forest habitats mostly endangered by drought, it will be necessary to modify prevailing clearcutting regeneration method towards close-to-nature approaches (Brang et al. 2014; Bolte et al. 2009). Currently, small-scale close-to-nature forest management is considered by numerous authors to be a suitable measure for increasing the stability, resistance and the capacity to adapt to ongoing climate changes (Churchill et al. 2013; Merlin et al. 2015; Spathelf et al. 2015).

Generally little attention is paid to this ecologically-oriented silviculture in stands with the dominance of light demanding trees such as oak species and especially Scots pine. Despite certain obstacles related to natural regeneration here, successful examples with risk prevention against stand disruption by stress factors such as air-pollution and drought periods are reported (Vacek et al. 2016, 2017). At the same time, the majority of research efforts focus on the

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individual aspects of forest management and wood processing as separate disciplines, although the selected silvicultural approach can significantly influence the mechanical properties of wood and the final quality of the raw material produced. In case of Scots pine and other species of conifers, there is a negative correlation between the growth rate of the tree and the quality related properties of the wood. This partly explains generally lower quality of the wood in stands originating from artificial regeneration, especially in the case of lower initial plant densities (Agestam et al. 1998; Jiang et al. 2007; Peltola et al. 2007; Ulvcrona and Ulvcrona 2011; Vincent et al. 2011; Ivković et al. 2013; Pretzsch et al. 2016). Naturally regenerated pine stands or artificially regenerated stands with initial high densities provide wood of high quality.

The shelterwood regeneration of Scots pine stands is currently mostly used in Fennoscandia (e.g., Marcos et al. 2007; Ruuska et al. Axelsson et al. 2014). Ecological and environmental benefits of shelterwood regeneration include maintaining the protective function of the parent stand which lowers temperature extremes and prevent drying out of soil in the summer months (Nilsson et al. 2002; Matías, Jump 2012) and restricts the competition of ground vegetation (Paluch, Bartkowicz 2004; Erefur et al. 2008). Moreover, trees being established under the shelter of parent stand show lower increment and higher share of latewood in the annual ring, which correlates with the increasing wood density (Makinen and Hynynen 2014). Beside this, higher wood quality is further supported by formation of branches of lower diameter with better natural pruning of stems (Auty and Achim 2008). By understanding the influence of silvicultural measures such as forest regeneration and thinning on the properties of wood, it is possible to develop a silvicultural model for a specific final wood quality for different localities (Mörling 2002; Zobel and Buijtenen 1989). The quality of wood is extremely important for the industry and subsequent utilisation of wood. This term may be perceived in different way depending on the technology of processing and aplications. For the industry, the qualitative parameters usually mean the proportion of the heartwood, wood density, amount of defects and especially mechanical properties (utilisation in constructions), i.e. strength and stiffness (Kurjatko 2010).

The aim of this work was to provide information on the impact of the group shelterwood and clearcut regeneration method on wood properties of Scots pine. The clearcutting method represents a regeneration of an even-aged stand in which a new age class develops in a fully exposed microclimate after removal, in a single harvest operation, of all trees in the previous stand, whereas in shelterwood method a new age class develops beneath the moderated microenvironment provided by the residual trees (Adams et al. 1994). Our primary hypothesis is that wood of pine regenerated via the shelterwood method will reach higher values of the investigated properties compared to the clearcutting method. The second hypothesis assumes that the properties of wood will have a more even distribution along trunk radius in the case of shelterwood method. Wood bending strength and modulus of elasticity are used as wood quality parameters for assessing the differences between the regeneration methods. Radial within-stem variation of the tested properties, their correlation to wood density and potential of non-destructive methods to assess stiffness are part of the study.

Materials and methods

Materials

The research was conducted in four localities representing typical areas of Scots pine silviculture in the Czech Republic. The research localities cover the area of western, northern, sothern and eastern Bohemia (Fig. 1). Average annual normal precipitation ranged from 550 mm (Plasy) to 770 mm (Chvojno). In Trebon and Doksy Localities, the average annual sum of precipitation amounts to 650–670 mm. The average annual temperature is the lowest in Plasy (6–7 °C) and the highest in Doksy (8–8.5 °C). Table 1 shows the basic stand and habitat conditions for the given sites. In all cases, these were areas in flat terrain and with a dominant presence of Scots pine in forest stands.

Two stands were selected at each site, the first representing a clearcutting regeneration method and a second the group shelterwood regeneration method. In the first case, the stands were regenerated in blocks of a size of predominantly 0.2 ha to 1.0 ha. According to the minimal requirements for plantation densities in the Czech Republic (Act on Forests No. 289/1995 Coll.; Regulation No. 139/2004 Coll.), the initial plantation density of these stands was superior to

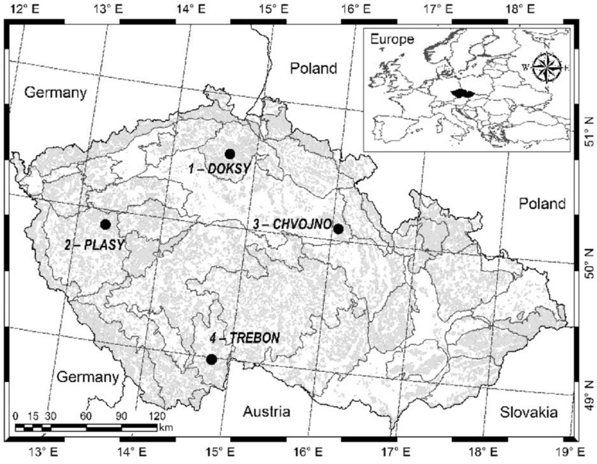

Fig. 1 Location of study areas in the Czech Republic

Table 1 Basic site and stand characteristics (stand summary characteristics according to management plan)

	Locality	Regeneration method	Cambial age*	Height** (m)	DBH*** (cm)	GPS (WGS-84)	Altitude (m a.s.l)	Soil type****	Forest site type
1	Doksy	clearcut	37	17	16	50°33′58.668"N, 14°40′17.575"E	270	Podzol Arenic	*Pinetum acidophilum*
		Shelterwood	31	12	14	50°34′20.084"N, 14°41′9.485"E	270	Podzol Arenic	*Pinetum acidophilum*
2	Plasy	Clearcut	27	12	13	49°55′13.846"N, 13°14′42.748"E	530	Gleyic Podzol	*Querceto-Abietum oligotrophicum*
		Shelterwood	25	11	12	49°55′35.827"N, 13°14′2.424"E	580	Gleyic Podzol	*Querceto-Abietum oligotrophicum*
3	Chvojno	Clearcut	40	21	22	50°3′21.354"N, 16°8′52.095"E	270	Cambisol Arenic	*Fageto-Quercetum acidophilum*
		Shelterwood	34	10	12	50°3′18.602"N, 16°8′59.047"E	270	Cambisol Arenic	*Fageto-Quercetum acidophilum*
4	Trebon	Clearcut	40	12	11	48°50′10.268"N 14°56′33.539"E	470	Podzol Arenic	*Pinetum acidophilum*
		Shelterwood	32	11	10	48°50′13.280"N 14°56′22.976"E	470	Podzol Arenic	*Pinetum acidophilum*

*Based on number of annual rings in DBH

**Average height for Scots pine according to Forest management plan

***Average breast-height diameter for Scots pine according to Forest management plan

****According toViewegh et al. (2012)

9,000 ind.ha^{-1}. Before these stands reached the top height of 15 m, usually two thinning treatments were carried out to decrease the density to 3,500–4,000 ind.ha^{-1}. From the very beginning, the sample trees from clearcut regenerated stands have been growing in an open area in a one-storey even-aged stand. In the second case, regeneration appeared under the shelter of the parent stand with a long regeneration period. In these forest stands, a felling policy was carried out with the objective to support natural regeneration and create a complex forest structure. Here, abrupt cover releases were strictly rejected. The ongoing regeneration period ranges from 30 to 50 years (initial densities in the 0.25 m–4.0 m height class ranged from 5,000 to 20,000 ind.ha^{-1}). In all of the shelterwood stands, the overstory is still present in different stages of final felling. The stands density range from 30 to 50% of full stocking and rotation period ranges from 100 to 150 years.

A total of 7 sample trees were selected from each stand, representing the respective regeneration method, from which the test material was made. An important criterion for selecting samples was the representation of characteristic individuals for the given stand, their vitality and the absence of growth irregularities and defects.

Methods

After cutting, a section for the preparation of mechanical test specimens was taken from each of the sample trees. The legth of the section was 150 cm and it was cut from the trunk base (Fig. 2). Subsequently, a disc was also taken from each section (at the height of 150 cm) for annual ring analyses and for determining a density profile in the radial direction. The sections were then cut into balk on a band saw. From the balks, 20 × 20 mm laths were cut, starting from the area close to the pith and continuing to the bark. Such a sampling method mades it possible to follow the distribution of the examined properties along the trunk diameter (Fig. 2). The lath was cut up to the clear wood test specimens for mechanical properties. The length of the test specimens was 300 mm and the cross section of the specimens was 20 × 20 mm. The test specimens for the density determination were cut up from the ends of the specimens for mechanical tests. The length of the testing samples for density evaluation was 30 mm and the cross section of the specimens was 20 × 20 mm. The test specimens were manufactured so that each sample had clearly-defined radial and tangential area. For more details see section position, lathes positions and test specimen preparation in Fig. 2.

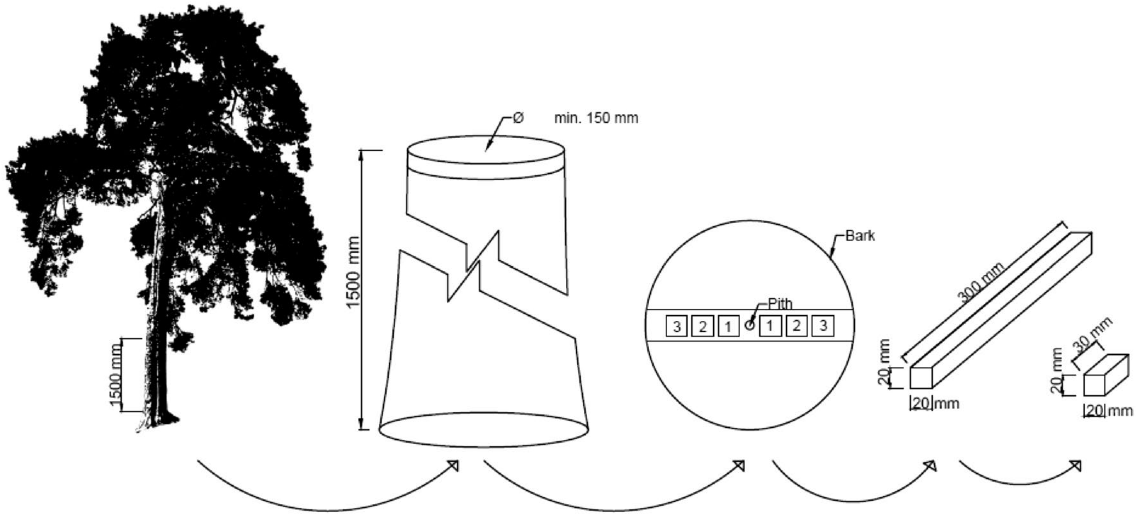

Fig. 2 Cutting diagram for test specimen preparation

To ascertain the quality of Scots pine wood, when using the relevant regeneration method, the mechanical properties of the wood were evaluated, both via destructive and non-destructive methods. Wood density was also evaluated. Samples for mechanical and physical testing were conditioned to 12% equilibrium moisture content under air temperature conditions of 20 °C (± 2 °C) and relative air humidity of 65% (± 5%). Dynamic modulus of elasticity was determined on 432 specimens, static modulus of elasticity on 509 specimens, and bending strength was determined on 509 specimens.

Mechanical properties testing

The dynamic modulus of elasticity was determined via a non-destructive method using the following formula (Moavenzadeh and Cahn 1990):

$$MOE_{dyn} = v^2 \bullet \rho [MPa]. \tag{1}$$

where MOE $_{\text{dyn}}$ is dynamic modulus of elasticity [MPa],

v is the sound wave velocity [m.s^{-1}], ρ is wood density [kg.m^{-3}].

Measurements were made using a Fakopp Ultrasonic Timer with a frequency range of 15 kHz to 300 kHz. In this experiment, 45-kHz piezo-electric triangle shaped transducers for transmitting and receiving were used.

The static modulus of elasticity (MOE) was determined destructively according to standard ČSN 49 0116:

$$MOE = \frac{\Delta F_{max} \bullet {l_o}^3}{4 \bullet b \bullet h^3 \bullet \Delta y} [MPa], \tag{2}$$

where F_{max} is the difference in load forces at 10% and 40% of the total load [N], l_0 is the distance of support centres [mm], b is the width of the test specimen [mm] (width of the radial area), h is the height of the test specimen [mm] (width of the tangential area), Δy is the difference in deflection (deformation) at 10% and 40% of the total load [N].

The static modulus of elasticity and bending strength were determined on test machine Tira 2850 (Tira GmbH, Schalkau, Germany) at a distance of supports 240 mm, i.e. 12 times the height of the test specimen.

The determination of bending strength (σ) was in accordance with standard ČSN 49 0115:

$$\sigma = \frac{3 \bullet F_{max} \bullet l_o}{2 \bullet b \bullet h^2} [MPa], \tag{3}$$

where F_{max} is the maximum load force [N], l_0 is the distance of support centres [mm], b is the width of the test specimen [mm] (width of the radial area), h is the height of the test specimen [mm] (width of the tangential area).

Wood density evaluation

From physical characteristics, the wood density was determined. The specimen dimensions for density determination were 20 × 200 × 30 mm. Wood density ρ was determined in accordance with ČSN 49 0108:

$$\rho = \frac{m}{V} \left[g.cm^{-3}\right] \tag{4}$$

where m is the weight of the specimen [g], V is the volume of the specimen [cm^{-3}].

Wood density was also determined via the densitometric method, which serves to explain the radial trend of wood density distribution in the trunks of the tested trees. The detailed results of these analyses are the subject of another study (Schönfelder et al. 2020); in this paper, only illustrative images are used in the discussion to better understand the impact of the regeneration method on the studied variables.

Annual ring analysis

Discs were polished and scanned on an A3 desktop scanner at a resolution of 800 DPI. Using the measurement function in the NIS Elements AR 4.11 image analysis software (Laboratory Imaging, Czech Republic), the annual ring width was measured in millimetres.

Statistical analysis

To evaluate the impact of regeneration methods on the tested properties, we used the analysis of variance–ANOVA (Fisher's F—test) and Duncan's multiple comparison tests to evaluate the statistical significance of the individual factors. Two-way analysis of variance with fixed effects was employed. The significance level $\alpha = 0.05$ was the same for all statistical analyses. The evaluated factors were the regeneration method and the individual localities that were used as a repetition to make the results conclusive irrespective a site. We also tested the effect of within-stem position in radial direction. A linear regression model was used to assess the effect of density on the bending strength and elasticity characteristics. The linear regression model was also used to assess relationship between static modulus of elasticity and bending strength on dynamic modulus of elasticity, which was determined in a non-destructive manner. Statistical analyses were carried out using STATISTICA 13.2 (Statsoft Inc., USA).

Results

Dynamic modulus of elasticity

Higher values for the dynamic modulus of elasticity were achieved at all localities for stands regenerated via the clearcutting method (Table 2). Only location 3 showed differences in the dynamic modulus of elasticity between the two regeneration methods (Fig. 3). However, none of the localities with a higher dynamic modulus of elasticity value caused due to the regeneration method proved to be statistically significant ($P > 0{,}05$), see Table 6 and Table 7.

Static modulus of elasticity

In all of the localities, the static modulus of elasticity achieved higher values for the shelterwood method of forest regeneration (Table 3). However, the difference between the stands is virtually negligible in practical

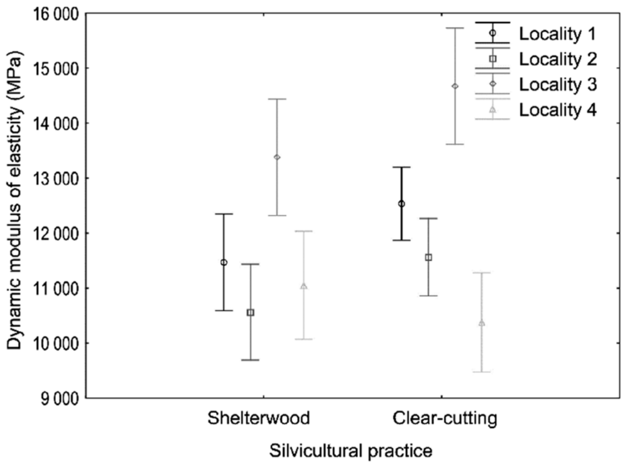

Fig. 3 Impact of site and regeneration method on dynamic modulus of elasticity (ANOVA results)

Table 2 Dynamic modulus of elasticity (in MPa) of individual localities and regeneration method–Descriptive statistics

Locality	Regeneration method	Mean	Minimum	Maximum	Standard deviation	Coefficient of variation (%)	Number of specimens
1	Shelterwood	11,471	6693	18,765	3021	26.3	55
	Clearcutting	12,535	5626	22,737	3423	27.3	62
2	Shelterwood	10,562	4672	17,927	3056	28.9	56
	Clearcutting	11,611	6156	18,447	3009	25.9	64
3	Shelterwood	13,378	9199	19,410	2755	21.8	38
	Clearcutting	14,688	10,839	17,651	2068	14.8	40
4	Shelterwood	11,049	4228	17,198	3960	35.6	39
	Clearcutting	10,374	3825	22,309	4648	47.9	42

Table 3 Static modulus of elasticity (in MPa) of individual localities and regeneration method–descriptive statistics

Locality	Regeneration method	Mean	Minimum	Maximum	Standard deviation	Coefficient of variation (%)	Number of specimens
1	Shelterwood	9814	5391	13,773	2133	21.7	55
	Clearcutting	9559	5014	13,315	2283	24.3	57
2	Shelterwood	9490	5709	14,125	2192	23.1	56
	Clearcutting	9421	5011	15,665	2449	26.0	64
3	Shelterwood	10,150	4086	14,420	2113	20.8	46
	Clearcutting	9854	4589	16,094	2594	27.9	93
4	Shelterwood	9156	4316	12,968	2328	25.4	67
	Clearcutting	8818	3340	13,356	2356	26.7	71

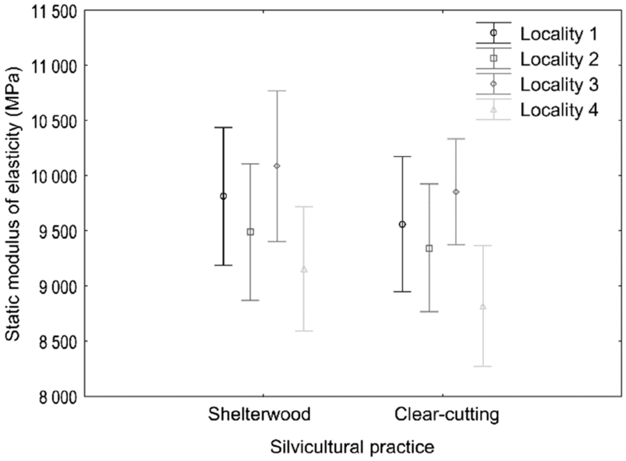

Fig. 4 Impact of site and regeneration method on modulus of elasticity (ANOVA results)

terms. The stand regenerated via the shelterwood method achieves higher values than stands regenerated via the clearcutting method in all of the study localities (Fig. 4). However, none of these higher elasticity values due to regeneration method proved to be statistically significant at any of the localities ($P > 0.05$), see Tables 8 and 9.

Bending strength

Although it seems that the bending strength reached higher values in forest stands managed by shelterwood method in the all localities (Table 4), there was not any striking difference in the bending strength between applied methods in the case of the all localities (Fig. 5). The impact of the regeneration methods on the tested property was again not statistically significant, like in the case of the previous properties ($P > 0.05$), see Tables 10 and 11 .

Correlations between the tested properties

The dependence of strength and elasticity characteristics of wood on wood density was investigated at all of the localities. The bending strength of wood exhibits higher correlation coefficient values than the static modulus of elasticity. A close relationship between the strength properties and wood density was found (Fig. 6).

The dependence of the bending strength and static modulus of elasticity on the dynamic modulus of elasticity was also investigated. As with the dependence of these characteristics on density, the dependency of the studied characteristics on the dynamic modulus of elasticity was higher for the shelterwood method (Fig. 7). On the basis of the results, it can be stated that with increasing density

Table 4 Bending strength (in MPa) of individual localities and regeneration method–descriptive statistics

Locality	Regeneration method	Mean	Minimum	Maximum	Standard deviation	Coefficient of variation (%)	Number of specimens
1	Shelterwood	75	44	94	10	12.9	55
	Clearcutting	74	54	94	10	13.3	57
2	Shelterwood	73	52	91	10	13.5	56
	Clearcutting	73	37	106	13	17.6	64
3	Shelterwood	84	49	108	13	15.7	46
	Clearcutting	80	25	117	20	26.6	93
4	Shelterwood	81	33	112	19	23.4	67
	Clearcutting	79	46	112	17	22.1	71

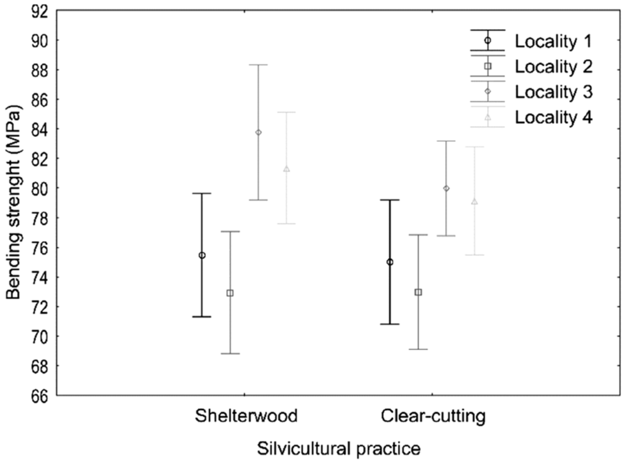

Fig. 5 Impact of site and regeneration method on bending strength (ANOVA results)

and dynamic modulus, the bending strength of the wood also increases. Although non-destructive testing methods using sound wave velocity usually better describe material characteristics than density, no significant difference was found between the correlations of the tested properties to density and to the dynamic modulus of elasticity.

Effect of position

The influence of the regeneration method on the course of wood properties in the radial direction, from the centre of the trunk to its circumference is shown in Fig. 8. It is clear that the stands regenerated via the clearcutting method show a clear trend of increasing density from the pith to the cambium. Adversely, the shelterwood forest regeneration method exhibits uniform distribution of wood properties across the trunk radius. A similar trend of distribution of wood properties along the diameter of the trunk was also found with the strength and elastic characteristics of the examined wood.

Figure 9 shows the results of the annual ring analysis from all samples and Fig. 10 shows an illustrative densitometric record for a better understanding of the distribution of the investigated properties along the trunk diameter. It is clear from both graphs that stands regenerated via the shelterwood method achieve lower annual ring widths at an early stage of growth. After shelterwood felling was carried out, the annual ring width increases and then drops again. Stands regenerated via the clearcutting method show a different course of annual ring thickness over the trunk width. In such regenerated stands, there is a gradual reduction in the annual ring thickness towards the cambium until it is almost stable.

Discussion

In Nordic countries, where Scots pine plays the role of the most important commercial tree species, regardless of the applied regeneration method, in most cases a higher value of strength and modulus of elasticity are reported (Aleinikovas and Grigaliūnas 2006; Kask 2015). Results similar to those of the Nordic countries were described in the conditions of Central Europe (Tsoumis 1991; Wagenführ 2000). In the Czech Republic, Hassan et al. (2013) reported strength characteristic values comparable to our measurements; however,

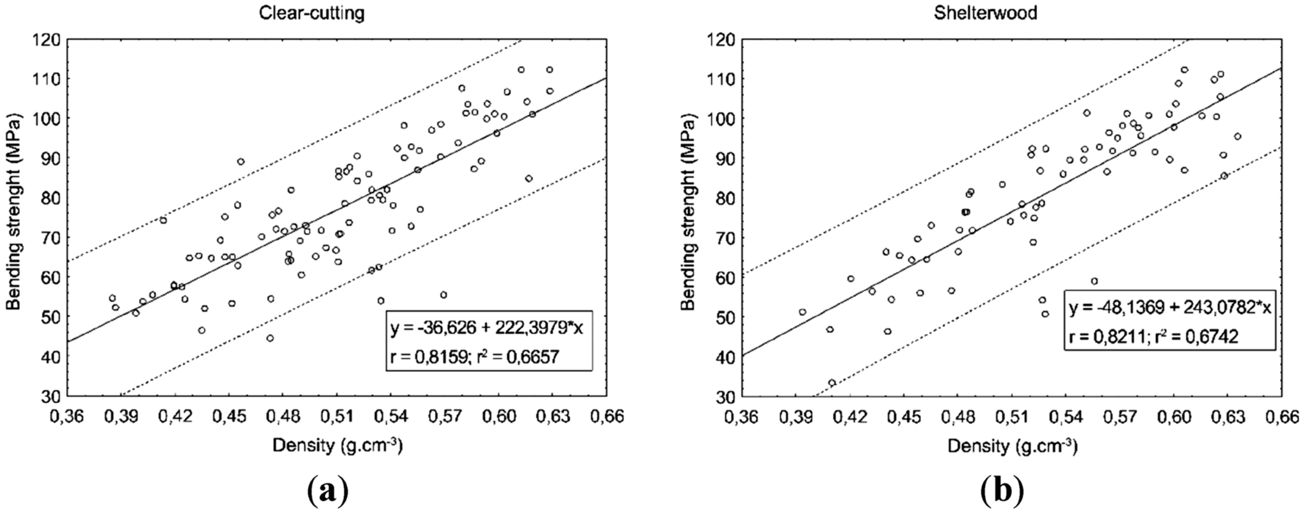

Fig. 6 Relationship between density and bending strength in relation to regeneration method in Locality 4 (**a** clearcutting method, **b** shelterwood method)

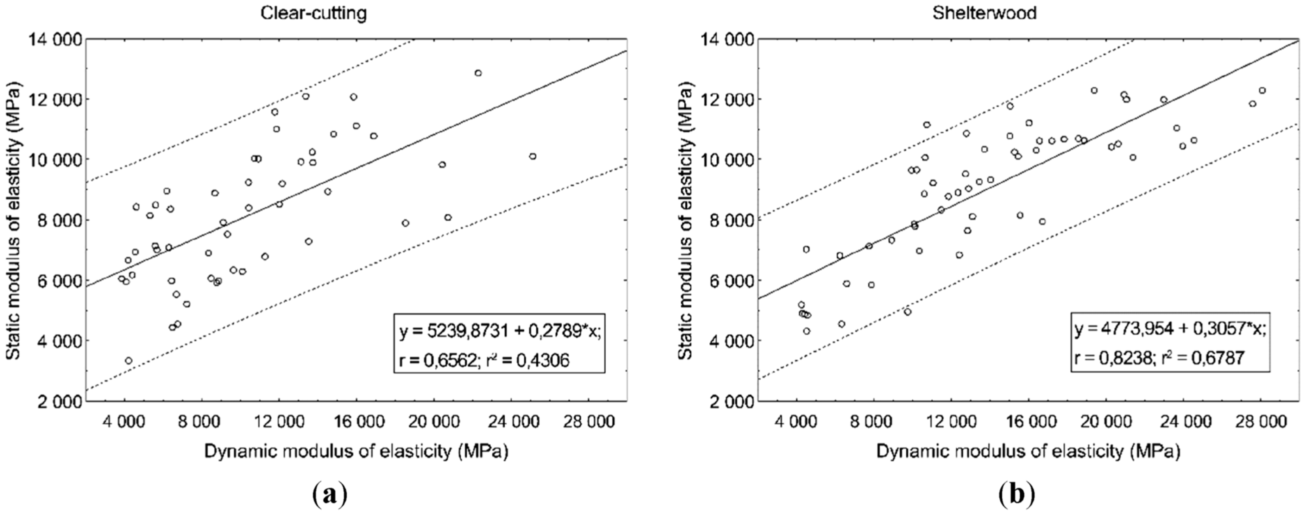

Fig. 7 Relationship between static modulus of elasticity and dynamic modulus of elasticity in relation to regeneration method in Locality 4 (**a** clear-cutting method, **b** shelterwood method)

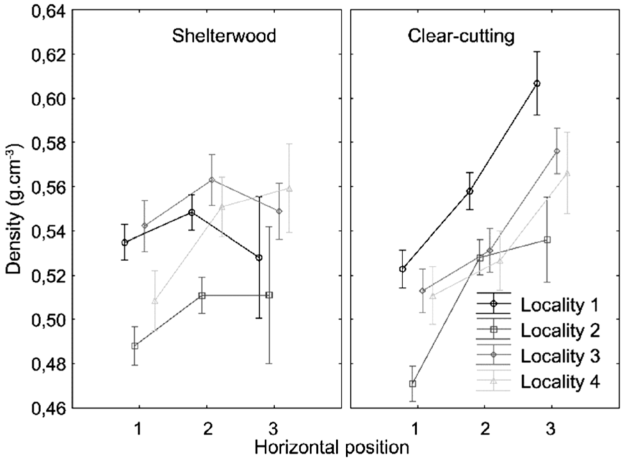

Fig. 8 Impact of regeneration method on the distribution of wood density in the radial position

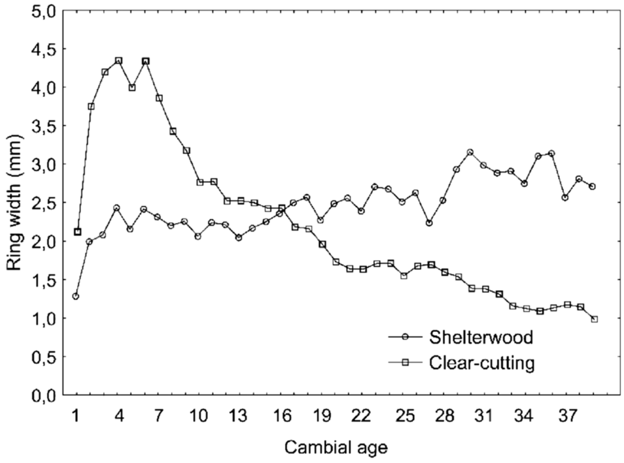

Fig. 9 Changes in ring width with the cambial age of the tree in relation to regeneration methods

Novák (1970) and Požgaj et al. (1993) achieved higher values. The ascertained data (Table 5) fall into the interval of values of dynamic modulus of elasticity specified by Horáček et al. (2012). Lower strength characteristic values than those specified in literature are caused by the low age of the investigated trees, which is significantly lower than the usual felling age of Scots pine in the Czech Republic. It can be assumed that with increasing tree age, the strength characteristics will also increase.

As a part of the experiment, aimed at an assessing the effect of regeneration method, the influence of a localities on wood properties was also investigated. Strength and elasticity properties were the highest at the Locality 3 from this point of view. Although a statistically significant difference was confirmed among the localities, from a practical point of view, differences in strength values are negligible. A statistically significant influence of the site on wood properties was found by Zobel and Buijtenen (1989), Jelonek et al. (2005), Tomczak and Jelonek (2013) and Hautamäki et al. (2014).

The impact of the regeneration method did not appear as a factor in most of the examined strength characteristics that would significantly affect the properties of the wood. However, even this difference is negligible for the final processing of wood. Auty and Achim (2008) found that increased tree competition due to dense natural regeneration contributed to a slower growth rate. The indirect effect of slower growth in naturally regenerated stands is the fact that increased competition at the onset of tree growth leads to the

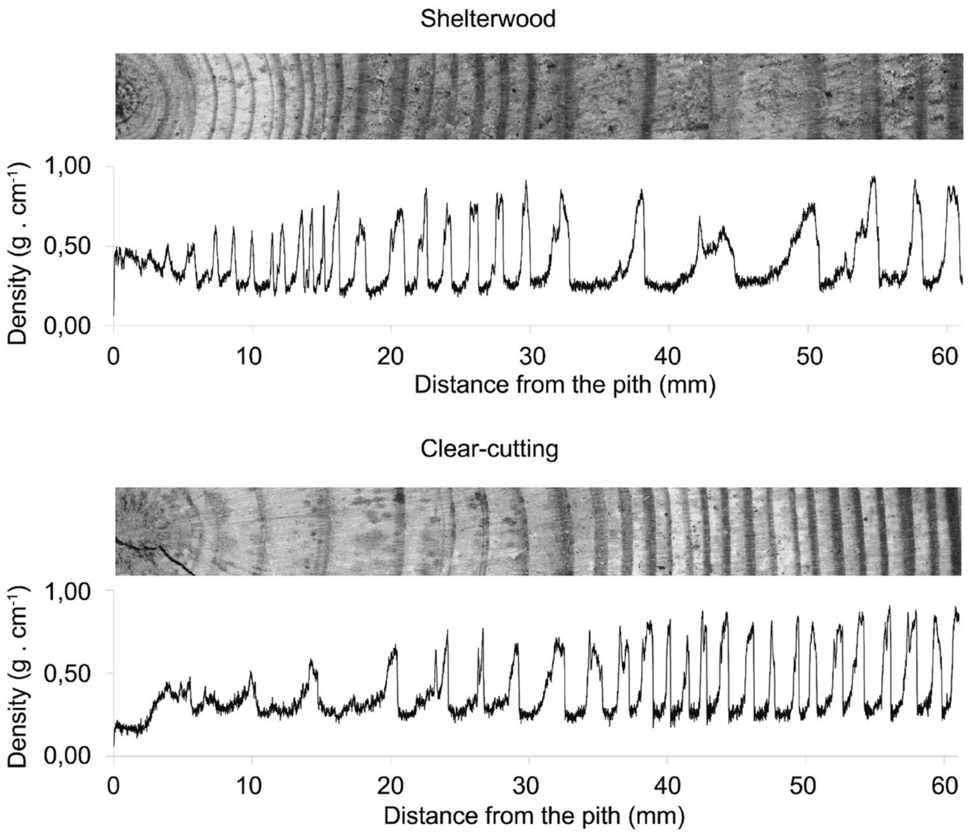

Fig. 10 Densitometric record–effect of regeneration method on wood density (shelterwood method top, clearcutting method bottom)

Table 5 Comparison of the results of Scots pine with various authors

	Bending strength (MPa)	MOE (MPa)	MOE$_{dyn}$(MPa)	Density (kg.m^{-3})
Shelterwood–this study	78	9652	11,755	523
Clearcutting–this study	75	9233	12,224	517
Novák (1970)	100	12,000		520
Tsoumis (1991)	98	11,760		530
Wagenführ (2000)	80	12,000		510
Požgaj et al. (1993)	100.1	10,620		
Kask (2015)	97–100	10,900		
Aleinikovas and Grigaliūnas (2006)	78–98			572–586
Hassan et al. (2013)	74	9015	11,805	453.4
Horáček et al. (2012)			7141–13,000	

creation of a smaller heartwood on the trunk. Mörling and Valinger (1999) report that the number of annual rings in heartwood is almost fixed, but the percentage representation of heartwood in the trunk is due to the growth of the tree at a young age. The slower growth of stands regenerated via the shelterwood method results in homogenous distribution of wood properties along the trunk width. For the final processing of wood, it is thus not as important to know from which part of the trunk the wood comes. Stands regenerated naturally are characterised by higher values of the investigated properties near the pith. This trend can be explained by the small annual ring width in the trunk centre. However, after partial overstory removal, the annual ring width starts to increase, which is reflected in the decrease of wood properties. The decrease in the examined strength characteristics of wood due to the increasing annual ring width is described by Mörling and Valinger (1999) and Gryc et al. (2011). The stands regenerated via the shelterwood method in Locality 2 do not show such an obvious even distribution of the properties compared to naturally regenerated stands. This trend was caused by the early shelterwood felling, where the growth of the stand increased because of increased amount of radiation. The difference in the resulting strength characteristics between the stands with different regeneration method was low, and it is, therefore, questionable whether such small differences in property values have a significant effect on the final processing of wood.

The clearcutting forest regeneration method shows a completely different trend compared to group shelterwood regeneration method. The wood with the lowest values of properties is located in the centre of the trunk, and in the direction from the pith, the examined properties of the wood increase. The annual ring width trend explains to some extent the course of the properties of the stands regenerated in this manner. The influence of the annual ring width on wood properties was described by Kollmann (1951) or Tsoumis (1991). Barnett and Jeronimidis (2003) state that increased wood growth rate leads to a higher proportion of juvenile wood, which negatively affects the properties of the wood in the centre of the trunk (Auty et al. 2016; Macdonald and Hubert 2002; Moore et al. 2017).

The results of regression dependencies point to a high correlation of strength and elasticity characteristics in the dynamic modulus of elasticity. The strong relationship ($r=0.74$) between the dynamic module and bending strength is confirmed, for example, by Horáček et al. (2012). Based on this information, the resulting wood properties values can be predicted without the use of destructive tests. The influence of wood density on the bending strength of wood was less pronounced compared to the dynamic elasticity module. Wood density may not reveal hidden wood defects, but acoustic methods are much more reliable for predicting the resulting properties. Similar results from the use of acoustic methods were also found by Auty and Achim (2008).

In conclusion, it should be noted that in our research we investigated the effect of given silvicultural approach on mechanical properties of wood without taking into account other advantages and disadvantages of both regeneration methods. From ecological point of view there are many studies that confirm the benefits of group shelterwood regeneration method mainly with respect to microsite characteristics (Giuggiolaand 2013) and stability of forest stands as result of their higher structural heterogeneity (Spathelf et al. 2015).

Conclusions

The primary hypothesis that pine wood regenerated by the shelterwood method will reach higher values of the investigated properties compared to the clearcutting method was not confirmed. It was, therefore, necessary to accept the alternative hypothesis, that the properties are almost identical regardless of the regeneration method. This is quite a surprising result even with regard to the lower age of the studied trees.

The secondary hypothesis that the properties of wood will have a more even distribution along radius in the case of the shelterwood method was confirmed, and it is such the most important benefit in terms of utilisation of logs grown in this way in the woodworking industry.

The trunks from the stands regenerated through the clearcutting method exhibited an increasing trend in wood properties from the pith to the cambium. Therefore, the radial within-stem position played an important role in the terms of properties and consequent utilization. On the other hand, trees regenerated through the shelterwood method had a uniform distribution of characteristics along the trunk width. From the view of wood processing industry it is thereby not important which part of the trunk is used in this case.

The non-destructive methods for detecting of dynamic modulus of elasticity can be used as a reliable indicator of strength properties, based on the confirmed high correlation with bending strength and static modulus of elasticity.

Author contribution statement OS, AZ, VB and LB: designed the research and wrote manuscript. AZ, VB and LB: performed data analysis, contributed to data description and reviewed manuscript. JV: provided data and reviewed manuscript. All authors read and approved the manuscript.

Appendix

See Tables 6, 7, 8, 9, 10 and 11.

Table 6 Tests of significance for dynamic modulus of elasticity

Effect	SS	DF	MS	F	*p*
Intercept	5.130E+10	1	5.130E+10	4635.359	0.000
Locality	6.368E+08	3	2.122E+08	19.179	0.000
Silvicultural practice	1.739E+07	1	1.739E+07	1.571	0.210
Locality*Silvicultural practice	1.0487E+08	3	3.494E+07	3.157	0.024
Error	4.150E+09	388	1.106E+07		

Error: Between *MS* mean squares, *DF* degrees of freedom, *SS* sum of squares, *F* Fisher ´s test, *p* significant level

Table 7 Duncan's multiple range test for dynamic modulus of elasticity

MS = 11,068,000		**L1**	**L1**	**L2**	**L2**	**L3**	**L3**	**L4**	**L4**
DF = 388		**S**	**C**	**S**	**C**	**S**	**C**	**S**	**C**
L1	**S**								
L1	**C**	0.527							
L2	**S**	0.444	0.187						
L2	**C**	0.737	0.732	0.299					
L3	**S**	0.051	0.149	0.007*	0.091				
L3	**C**	0.004*	0.021*	0.000*	0.010*	0.332			
L4	**S**	0.782	0.391	0.588	0.567	0.030*	0.002*		
L4	**C**	0.150	0.046*	0.442	0.087	0.000*	0.000*	0.218	

*Values are significant at $p < 0.05$. Error: Between *MS* mean squares, *DF* degrees of freedom. *L* Locality, *S* Shelterwood, *C* Clearcutting

Table 8 Tests of significance for static modulus of elasticity

Effect	SS	DF	MS	F	*p*
Intercept	4.433E + 10	1	4.433E + 10	8016.692	0.000
Locality	6.826E + 07	3	2.275E + 07	4.114	0.006
Silvicultural practice	7.202E + 06	1	7.202E + 06	1.302	0.254
Locality*Silvicultural practice	6.136E + 05	3	2.045E + 05	0.037	0.990
Error	2.770E + 09	501	5.531E + 06		

Error: Between *MS* mean squares, *DF* degrees of freedom, *SS* sum of squares, *F* Fisher ´s test, *p* significant level

Table 9 Duncan's multiple range test for static modulus of elasticity

MS = 5,531,000		**L1**	**L1**	**L2**	**L2**	**L3**	**L3**	**L4**	**L4**
DF = 501		**S**	**C**	**S**	**C**	**S**	**C**	**S**	**C**
L1	**S**								
L1	**C**	0.549							
L2	**S**	0.476	0.869						
L2	**C**	0.323	0.640	0.736					
L3	**S**	0.548	0.263	0.216	0.130				
L3	**C**	0.925	0.518	0.443	0.296	0.582			
L4	**S**	0.173	0.395	0.464	0.665	0.058	0.156		
L4	**C**	0.038*	0.123	0.152	0.244	0.008*	0.033*	0.426	

*Values are significant at $p < 0.05$. Error: Between *MS* mean squares, *DF* degrees of freedom, *L* Locality, *S* Shelterwood, *C* Clearcutting

Table 10 Tests of significance for bending strength

Effect	SS	DF	MS	F	*p*
Intercept	2,924,868	1	2,924,868	11,864.22	0.000
Locality	6364	3	2121	8.61	0.000
Silvicultural practice	311	1	311	1.26	0.262
Locality*Silvicultural practice	274	3	91	0.37	0.774
Error	122,771	501	247		

Error: Between *MS* mean squares, *DF* degrees of freedom, *SS* sum of squares, *F* Fisher ´s test, *p* significant level

Table 11 Duncan's Multiple Range Test for Bending Strength

MS = 246.53		L1	L1	L2	L2	L3	L3	L4	L4
DF = 501		S	C	S	C	S	C	S	C
L1	S								
L1	C	0.872							
L2	S	0.426	0.497						
L2	C	0.414	0.476	0.987					
L3	S	0.008*	0.005*	0.000*	0.000*				
L3	C	0.135	0.112	0.028*	0.026*	0.214			
L4	S	0.058	0.046*	0.008*	0.007*	0.397	0.633		
L4	C	0.199	0.174	0.051	0.047*	0.140	0.764	0.468	

*Values are significant at $p < 0.05$. Error: Between *MS* mean squares, *DF* degrees of freedom. *L* Locality, *S* Shelterwood, *C* Clearcutting

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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