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Douglas-fir outperforms most commercial European softwoods

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ABSTRACT

One of the main ideas of non-native tree species introduction into forest stands is to replace declining native species. The same is also valid for industry; the wood of native species should be replaced by a wood of the same or even better quality. Douglas-fir is often compared to other coniferous tree species based on its production. This study compared Douglas-fir wood properties with European commercial species, namely Norway spruce, Scots pine, and European larch. Trees representing different sites and ages were tested for wood density, shrinkage, and compression strength. In all cases, Douglas-fir outclassed spruce and pine in density and strength. The difference was striking, especially for spruce, where the density was surpassed by Douglas-fir by more than 100 kg.m^{-3} (above 25%). In the case of compression, the strength of Douglas-fir was up to 12.3 MPa higher (above 33%) compared to spruce. The only species that obtained higher figures was larch. Wood shrinkage was comparable to European softwoods. Therefore, Douglas-fir wood can be regarded as an excellent and promising substitute for the European processing industry.

1. Introduction

Non-native plant species introductions in other regions represent a basis of global agriculture and, in some countries, industrial forestry, especially in tropical and subtropical countries. Contrariwise, Central Europe is a very conservative region, where both foresters and nature conservation strictly reduce possibilities for introduced species utilisation in the recent forest plantations and stands (Baláš et al., 2019). Because of the healthy status dynamics of forests, the situation nowadays demands more variable attempts (Fürst et al., 2007; Lorz et al., 2010). Introduced species were predominantly used in cases of large-scale forest decline, like gypsy moth calamity in the 1920ies or during air pollution damages, or for afforesting extreme sites, degraded pastures and reclamation sites (Baláš et al., 2019; Vacek et al., 2021).

Norway spruce (*Picea abies* (L.) Karst.) is the most important tree species in Central Europe, covering about 50% of the forest area in the Czech Republic (e.g. Štefančík et al., 2018). Climatic extremes and the forest structure, connected with bark beetle outbreaks and amplified by ecologist pressure calling for more natural species composition, as well as unfavourable effects on the forest site, determine its area decrease to 30–40% in the following decades (Oulehle and Hruška, 2005; Podrázský et al., 2016; Remeš et al., 2020). Scots pine (*Pinus sylvestris* L.) is the second most important commercial species, occupying about 16% of the forested area. Both species represent the backbone of the present timber industry in the Czech Republic and other Central European countries. The timber industry can be soon limited in the available source (Synek et al., 2014).

Recently, the large scale decline of native conifers has increased the urgency of forest stand restoration and timber substitution by some alternative species, if possible, with comparable or superior properties to minimize economic problems of the timber industry and wood processing technologies (Čater, 2021; Podrázský, 2016). Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) has been one of the very successful cases of species introduction, representing the most critical introduced tree species in the temperate zone worldwide. Its importance in some European countries is immense, having even a higher proportion than native species (France, Germany, Italy etc.; Mondek et al., 2021; Petkova et al., 2014; Popov, 2014).

Douglas-fir is the most important introduced tree species in the Czech Republic, occupying approximately 6000 ha currently (Mondek and Baláš, 2019). Its importance for timber production and environmental effects was repeatedly summarized (Kubeček et al., 2014;

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Podrázský et al., 2013). Many studies have already analysed its impact on forestry's economic and production aspects (Feliksik and Wilczyński, 2003; Kantor, 2008; Kantor and Mareš, 2009; Remeš et al., 2020; Pulkrab et al., 2014). Douglas-fir contribution to forest soils, soil biological characteristics and herb layer communities observed Kupka et al. (2013), Menšík et al. (2009), Podrázský et al. (2014, 2016) or Podrázský et al. (2020).

Considering the production and environmental potential of this species, the partial substitution of Norway spruce by Douglas-fir is supposed as a proper way to cover demands for high-quality conifer timber in the future and to lower the non-desirable effects of native conifer cultivation outside their natural range. Its excellent productivity and less "degradation" potential (compared to other conifers) support its use to a limited extent (Baláš et al., 2019; Podrázský, 2016; Podrázský et al., 2020). In the Czech conditions, the share of introduced tree species at the maximum level of 7% is assumed. They eliminate almost all adverse effects of this species introduction; cultivation as admixed species at the level 30 – 40% is recommended (Podrázský et al., 2015). The selection of proper provenances is a crucial aspect at any time (Kšír et al., 2015; Petkova et al., 2014; Popov, 2014).

The high production capacity of Douglas-fir and the quality of the produced timber has long been of interest to many European countries (Göhre, 1958; Hapla, 2000; Todaro and Macchioni, 2011; Bawcombe, 2012; Rais et al., 2014; Drewett, 2015). Douglas-fir wood is also receiving attention in other countries worldwide, where it has been successfully introduced (Lausberg et al., 1995; Kimberley et al., 2017). A considerable effort is still devoted to Douglas-fir wood properties and its potential (Acuna, 2006; Acuna and Murphy, 2006; Langum et al., 2009; Spiecker et al., 2019). In Central Europe, Giagli et al. (2019) tested Douglas-fir wood's selected physical and mechanical properties. They compared them to commercial European softwoods based on literature. They concluded that Douglas-fir wood was qualitatively better, particularly compared to spruce. Remeš and Zeidler (2014) also studied Douglas-fir in this region. The production potential was evaluated, wherein Douglas-fir significantly exceeded spruce. Some physical and mechanical properties of wood were also compared in this work. Based on comparing the literature, the authors state comparable values with spruce and pine. The strength properties and density of Douglas-fir wood in the Netherlands were compared with the data of other European timber species by Polman and Militz (1996). Based on a comparison with literature, they reported higher bending strength and density values for Douglas-fir than Norway spruce wood. The stiffness of Douglas-fir in Germany was studied by Blohm et al. (2016). In Belgium, Pollet et al. (2017) concluded that with its density and mechanical properties, Douglas-fir wood resembles larch rather than spruce, once again based on comparison with the values of other authors. Moreover, the potential of Douglas-fir lumber for structural uses in Belgium was evaluated in a study by Henin et al. (2018).

Wood density represents an important physical property. Its importance and factors affecting its variability were demonstrated in many studies. Tumenjargal et al. (2018) studied the variability within a stem for *Larix sibirica* or Zhang et al. (2021) for *Picea mariana*. It can serve as an excellent predictor of the wood's strength, stiffness or hardness. It is also an essential indicator for paper yield and paper making (Tsoumis, 1991; Acuna, 2006; Ivković et al., 2009; Tumenjargal et al., 2018). Dimensional changes associated with shrinkage significantly impact wood products (Shmulsky and Jones, 2011). Generally, the lower the shrinkage values, the better the quality of the wood. Density dependence is also assumed for shrinkage, meaning that the higher the density values, the higher the wood shrinkage (Tsoumis, 1991; Tumenjargal et al., 2020; Zhang et al., 2021). Although this issue is more complex, some authors attributed the changes to other factors (Leonardon et al., 2010) as the dependence on density was not confirmed.

It is also crucial for wood and wood products to resist various kinds of loading. Compression strength represents a vital parameter of wood in terms of products for structural applications (Shmulsky and Jones, 2011). It is also related to other mechanical properties (Green et al., 2008; Tumenjargal et al., 2020). However, wood properties are subject to considerable variability, unlike other conventional materials. They depend on age and site conditions, geographic variation and vary according to the stem's position (Zobel and Buijtenen, 1989; Gartner et al., 2002; González-Rodrigo et al., 2013; Tumenjargal et al., 2020; Sarkhad et al., 2021; Wieruszewski and Mydlarz, 2021).

The studies mentioned above, evaluating Douglas-fir wood properties and comparing them to other softwoods, only compare the results with the literature. Such comparisons are not sufficiently meaningful as they do not consider the influence of the habitat, silvicultural measures or the possible effect of tree age. In this article, we compare the wood properties of Douglas-fir trees with selected European conifers that grew together within one stand. Thus, each studied stand always included individuals of the same age, developing under the same growth conditions. We examined Douglas-fir wood from various sites and sample trees of different ages. We primarily focused on comparison with spruce, pine, and possibly larch. The main studied properties were wood density, shrinkage and compression strength. We also evaluated the variability of these properties within the stem and the effect of density on strength. This study aimed to provide a real comparison of Douglas-fir wood properties with selected European coniferous species, thereby providing relevant information about possible Douglas-fir wood utilisation in non-native areas.

2. Materials and methods

2.1. Materials

The results presented in this article are part of an extensive project focused on evaluating the Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) in terms of ecological demands, production and wood quality in the Czech Republic. Although it was not the primary focus of the project, we took advantage of the Douglas-fir growing in stands together with Norway spruce (*Picea abies* (L.) Karst.), Scots pine (*Pinus sylvestris* L.) or, in one case, with the European larch (*Larix decidua* Mill). Thus, the compared tree species within the given stand were always characterised by the same age, site conditions and silvicultural history.

We had a total of four stands, referred to in this article as localities (LOCs), where the Douglas-fir has consistently grown together, at least with one of the native coniferous species. A more detailed description of the evaluated localities in terms of the location and site conditions is given in Table 1.

The representation of individual tree species differed depending on the locality. Douglas-fir occurred at LOC1, LOC 2 and LOC 3 together with spruce. In contrast, Douglas-fir was accompanied by Scots pine at LOC 2 and LOC 4. Furthermore, it was also possible to compare European larch at LOC 3.

For this study, 16 Douglas-fir, 12 Norway spruce, 10 Scots pine and 4 European larch sample trees were taken for wood property tests. As stated in the forest management plan, the tree's average age, diameter and height are presented in Table 2.

2.2. Methods

The different diameters of the trees, depending on the age, are the primary reason why the method of collecting test material differed depending on the location. After the sample tree felling, a section (log) about 1.5 m long, representing the stem base, was always taken from the stem. In addition, sections representing different vertical stem positions were taken at 20%, 40% and 60% of the stem height at LOC 1 and LOC 2 because older stands attained sufficient stem diameters for the analysis within the stem profile. Therefore, it was possible to assess the effect of height on the distribution of properties in the stem of individual tree species. A central board was employed to produce test specimens cut out of the section using a band saw (Fig. 1). The central plank allows

Table 1
Main characteristics of the studied localities.

	Local name	Latitude, Longitude	Altitude (m a.s.l.)	Soil type	Site description
LOC 1	Kostelec n. Č. l.	50.0072625 N 14.8537100 E	350	Luvisol	*Querceto-Fagetum oligo-mesotrophicum* Nutrient-medium Oak-Beech
LOC 2	Krymlov	49.9460656 N 14.9257086 E	430	Luvic gley	*Querceto-Abietum variohumidum oligotrophicum* Seasonally waterlogged poor oak-fir
LOC 3	Opočno	50.2489386 N 16.1185581 E	343	Cambisol	*Querceto-Fagetum illimerosum mesotrophicum* Medium rich loamy oak-beech
LOC 4	Polánky	50.2060317 N 16.0288061 E	261	Cambisol arenosum	*Pineto-Quercetum oligotrophicum (arenosum)* Nutrient-very poor Pine-Oak

Table 2
Species characteristics according to the forest management plan. DBH – diameter at the breast height; H – tree height.

	Species	Number of trees	Average age	DBH (cm)	H (m)
LOC 1	Douglas-fir	4	70	37	30
	Norway spruce	4		26	26
LOC 2	Douglas-fir	4		27	24
	Norway spruce	4	50	23	22
	Scots pine	4		24	23
LOC 3	Douglas-fir	3		22	20
	Norway spruce	4	40	21	19
	European larch	4		17	16
LOC 4	Douglas-fir	5	25	10	11
	Scots pine	6		12	10

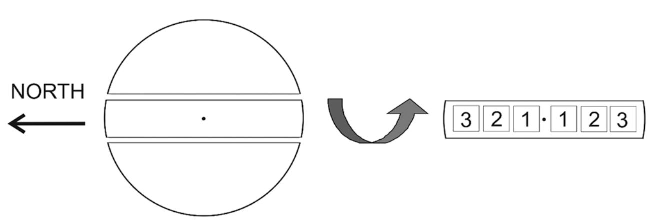

Fig. 1. Section sampling – the position of the central board concerning cardinal point and position of the test specimens to the pith.

determining the relative position of the test specimen concerning the position of the pith (in the presented graphs, the number 1 indicates the position closest to the pith, whilst the highest number signifies the position most approaching to the bark). Therefore, we also evaluated the distribution of the investigated properties within the stem in the radial direction for individual tree species. Test specimens with 20 × 20 × 30 mm (tangential × radial × longitudinal) were used for all wood properties tests.

The test specimens were divided into two sets. The first set of these specimens was used to determine the compression strength along the fibres and simultaneously determine the density at a given moisture content. Thus, it was also possible to assess the compression strength dependence on density in the evaluated tree species. The test specimens were air-conditioned until the equilibrium moisture content of the wood was stabilized in a controlled environment with an air temperature of 20 ± 2 °C and an air relative humidity of 65 ± 5% and finally evaluated for moisture content following standard ČSN 49 0103. After reaching the equilibrium moisture content of the wood (about 12%), the density and compression strength along the fibres were measured. Rectangular test specimens 20 × 20 × 30 mm (tangential x radial x longitudinal) were used. Density for 12% wood moisture content was set as a ratio of weight and volume of those specimens following ČSN 49 0108. The testing machine Tira 50 kN was used to determine compression strength along fibres using the standardized procedure (ČSN 49 0110). The second series of test specimens (20 × 20 × 30 mm) was employed to determine basic wood density and volumetric shrinkage. The basic wood density was determined as the wood dry mass weight (oven-dry) and the wood volume above the fibre saturation point (FSP) ratio. Volumetric shrinkage was calculated as the difference between the volume of wood with moisture content above FSP and oven-dry wood. All these tests were performed according to standards ČSN 49 0108 and ČSN 49 0128. The number of specimens differed according to the locality, depending on the age and diameter of the trees (Table 3). The detailed description of the applied test was given by Schönfelder et al. (2018, 2019).

Data analysis.

The statistical parameters were calculated using STATISTICA software (version 13.4.0.14, TIBCO Software Inc., CA, USA). We used ANOVA and Tukey's multiple range test to assess the difference between tree species and sites and evaluate the effect of the position within the stem on the properties being assessed. We also tried to answer how much density is a reliable predictor of mechanical properties. We applied the standard linear regression model to explain the relationship between variables. Correlation coefficients were also determined between mechanical properties and wood density to assess a dependence between these quantities.

3. Results

The Douglas-fir exceeded both spruce and pine wood in all evaluated localities with its density, basic wood density and compression strength. The main descriptive statistics for the localities and the tested species are presented in Table 3. The difference between Douglas-fir and spruce wood density is statistically significant ($P < 0.001$). The difference between the numerical values is considerable (above 100 kg.m^{-3}) and, therefore, entirely fundamental in terms of wood processing and use. The Douglas-fir density demonstrably exceeds pines (LOC 2 $P < 0.01$, LOC 4 $P < 0.001$). At LOC 4, similarly to spruce, there is a marked difference in numerical values. A similar trend applies to basic wood density and compression strength. A statistically significant difference was confirmed ($P < 0.001$). The differences in the values are apparent and impact the manufacturing industry and the following applications. The only tree species whose density and compression strength parameters that the Douglas-fir does not achieve is larch ($P < 0.001$). There are no fundamental differences in the wood shrinkage between the evaluated species. Although the numerical values of shrinkage are the lowest or comparable for Douglas-fir in some localities, the differences are not relevant in terms of wood processing and use. Statistically significant differences between tree species within the stand were only confirmed at LOC 1 and LOC 2 ($P < 0.001$). At LOC 3 only compared to larch ($P < 0.01$), the Douglas-fir indicates lower shrinkage values than larch.

If we look at the values of individual Douglas-fir wood properties across localities, we encounter the obvious pitfall of only comparing the achieved results with the literature. The values differ depending on the investigated properties and locality, often statistically significantly. The climatic conditions, the stand, silvicultural measures or other factors can

Table 3
Wood properties by localities and species – mean values and their variability (SD – standard deviation, N – number of specimens).

		Density (kg.m^{-3})			Basic density (kg.m^{-3})			Compression strength (MPa)			Volumetric shrinkage (%)		
		Mean	SD	N	Mean	SD	N	Mean	SD	N	Mean	SD	N
LOC 1	Douglas-fir	**561**	92	379	**460**	75	608	**48.4**	14.4	379	**11.9**	2.3	608
	Norway spruce	**444**	59	83	**356**	49	209	**36.1**	6.1	83	**11.3**	2.0	209
LOC 2	Douglas-fir	**540**	68	164	**480**	50	207	**39.7**	11.2	164	**10.9**	2.2	207
	Norway spruce	**438**	45	131	**369**	40	258	**31.0**	5.5	131	**12.5**	1.7	258
	Scots pine	**517**	69	130	**426**	54	141	**33.3**	8.9	130	**12.7**	2.1	141
LOC 3	Douglas-fir	**533**	56	212	**446**	46	200	**41.8**	5.8	212	**11.7**	1.4	200
	Norway spruce	**423**	52	228	**349**	40	219	**34.7**	6.4	228	**11.7**	2.3	219
	European larch	**591**	83	243	**485**	66	227	**45.8**	8.4	243	**12.5**	2.5	227
LOC 4	Douglas-fir	**562**	48	132	**470**	39	134	**44.0**	6.2	132	**10.9**	2.0	134
	Scots pine	**441**	37	156	**361**	31	159	**30.0**	4.6	156	**11.1**	11.4	159

influence the resulting properties. No trend could be found, nor was it the subject of this study. In any case, it may not be true that older trees must always provide wood with higher strength or wood density (see the results for LOC 4).

The properties distribution within the stem in the radial direction reflects the age effect and provides an idea of the impact of the position on the evaluated properties and usability of individual stem zones. In our case, it turned out to be very similar for all studied tree species. The density showed an increasing trend from the stem centre to the bark. The lowest values are reached at the pith and the highest in the tight bark vicinity (Fig. 2). The difference is especially noticeable for Douglas-fir at LOC 1, where more horizontal positions were available for the sample trees. Adversely, this trend was not confirmed for Douglas-fir as the only tree species at LOC 3. Spruce is also noticeable with its gradual increase in values, where the differences between individual positions were not statistically significant in most cases. Basic wood density also showed a

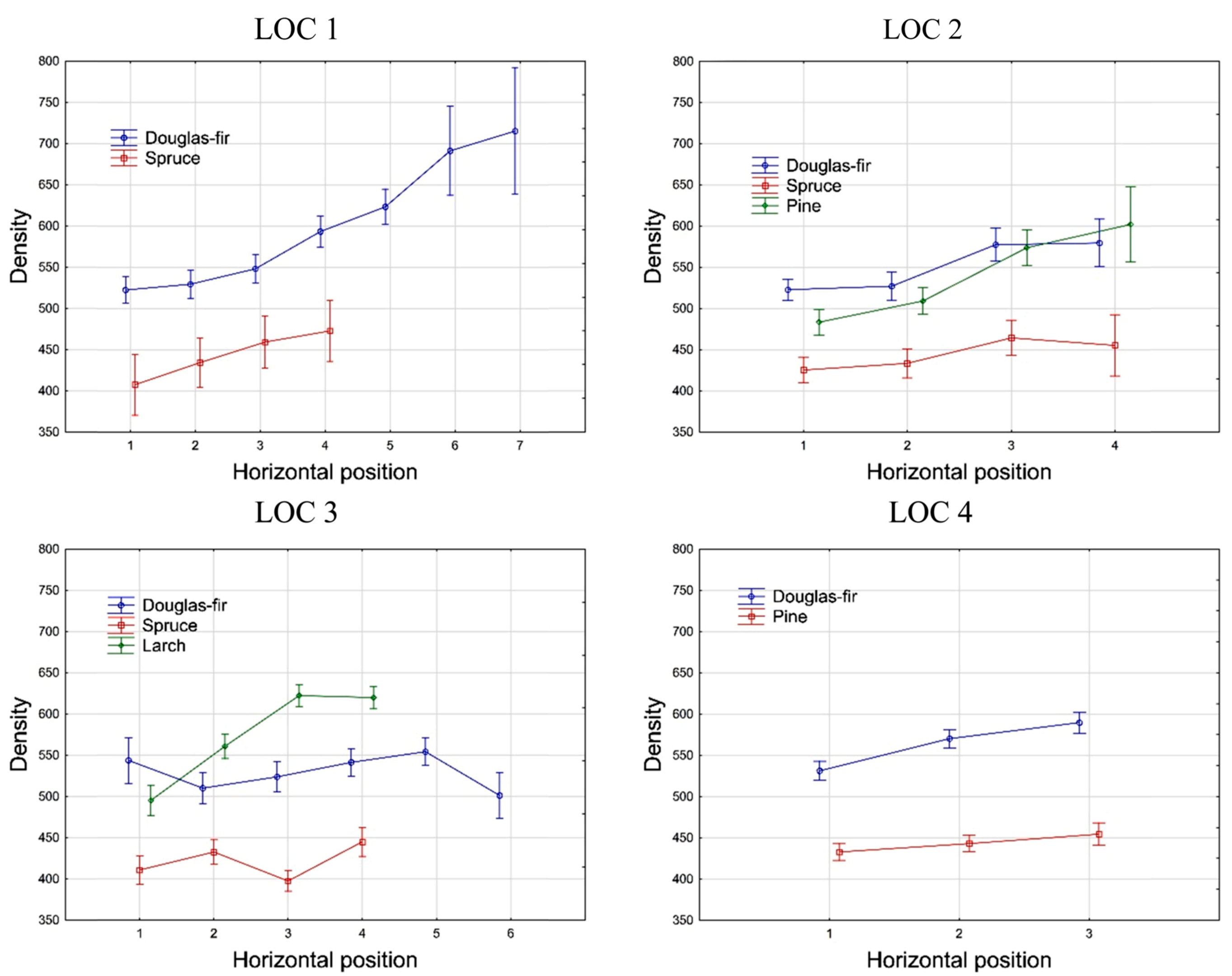

Fig. 2. Wood density (kg.m^{-3}) pattern along stem radius (x-axis: 1 represents the stem centre, whereas the highest figure depicts the outer stem part) at the studied localities.

similar trend.

The course of compression strength in the horizontal plane corresponds to the close correlation between density and mechanical properties. Thus, the distribution of values largely copies the density course in the radial direction. Regardless of the tree species and location, the compression strength increases towards the bark (Fig. 3). Spruce is again characterized by a slight increase in values, which were usually not statistically different from each other. Statistical analyses also did not confirm a difference between the individual positions for Douglas-fir at LOC 3 and pine at LOC 4 (where only a few positions were available).

The effect of the position in the stem on volume shrinkage of Douglas-fir wood is demonstrable mainly at LOC 1 and LOC 2. As in the case of density and compression, shrinkage increases with increasing distance from the pith for all tree species at the relevant site (Fig. 4). The influence of the position proved to be ambiguous at the remaining localities.

The vertical course of properties within the stem could only be evaluated at LOC 1 and LOC 2, where the trees were older with larger stem diameters. The effect of height within the stem was demonstrated only for the Douglas-fir and only at LOC 1. Density and compression strength values decreased with increasing height (Fig. 5). No trend depending on the vertical position was demonstrated for spruce growing in this locality. No height-related trend could be detected at LOC 2 for all evaluated tree species. No clear trend for volumetric shrinkage was confirmed concerning the stem height for either locality.

Our study also evaluated the extent to which wood density (as a physical property and a primary qualitative indicator) affected compression strength (i.e., the mechanical wood property; Fig. 6). Density was a good predictor of compression strength, regardless of the tree species. Correlation coefficients fluctuated in the range of 0.80–0.53, 0.80–0.47, 0.71–0.69 for the Douglas-fir, spruce and pine, respectively. For larch, it reached 0.77. The highest correlation coefficient was achieved for LOC 1, where the oldest individuals occurred. In both cases (Douglas-fir and spruce), the correlation coefficients were the same (0.80; Table 4).

We also evaluated the relationship between shrinkage and density. Although the literature shows a linear relationship between these characteristics, wood density cannot be used as a suitable indicator of volume shrinkage based on our results. The achieved results were quite inconsistent. The differences between tree species were considerable, depending on the locality. The coefficients ́values were mainly low or did not even confirm a positive correlation between the properties. For Douglas-fir, it ranged from 0.71 at LOC 1–0.37 at LOC 3. For spruce, it ranged from – 0.38 (negative correlation) at LOC 2–0.36.at LOC 3.

4. Discussion

This study ́s Douglas-fir wood density values ranged from 533 to

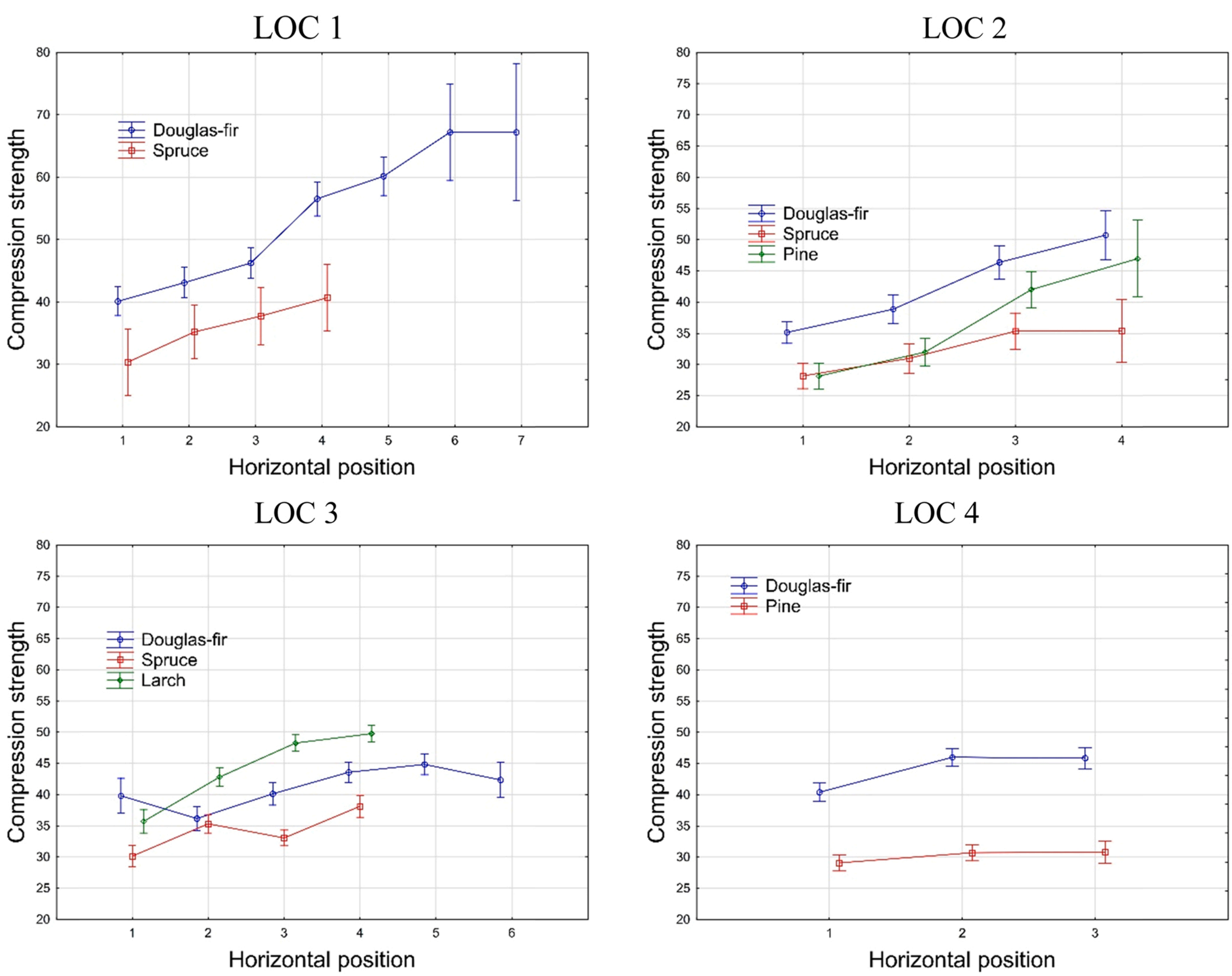

Fig. 3. Compression strength (MPa) pattern along stem radius (x-axis: 1 represents the stem centre, while the highest figure depicts the outer stem part) at the studied localities.

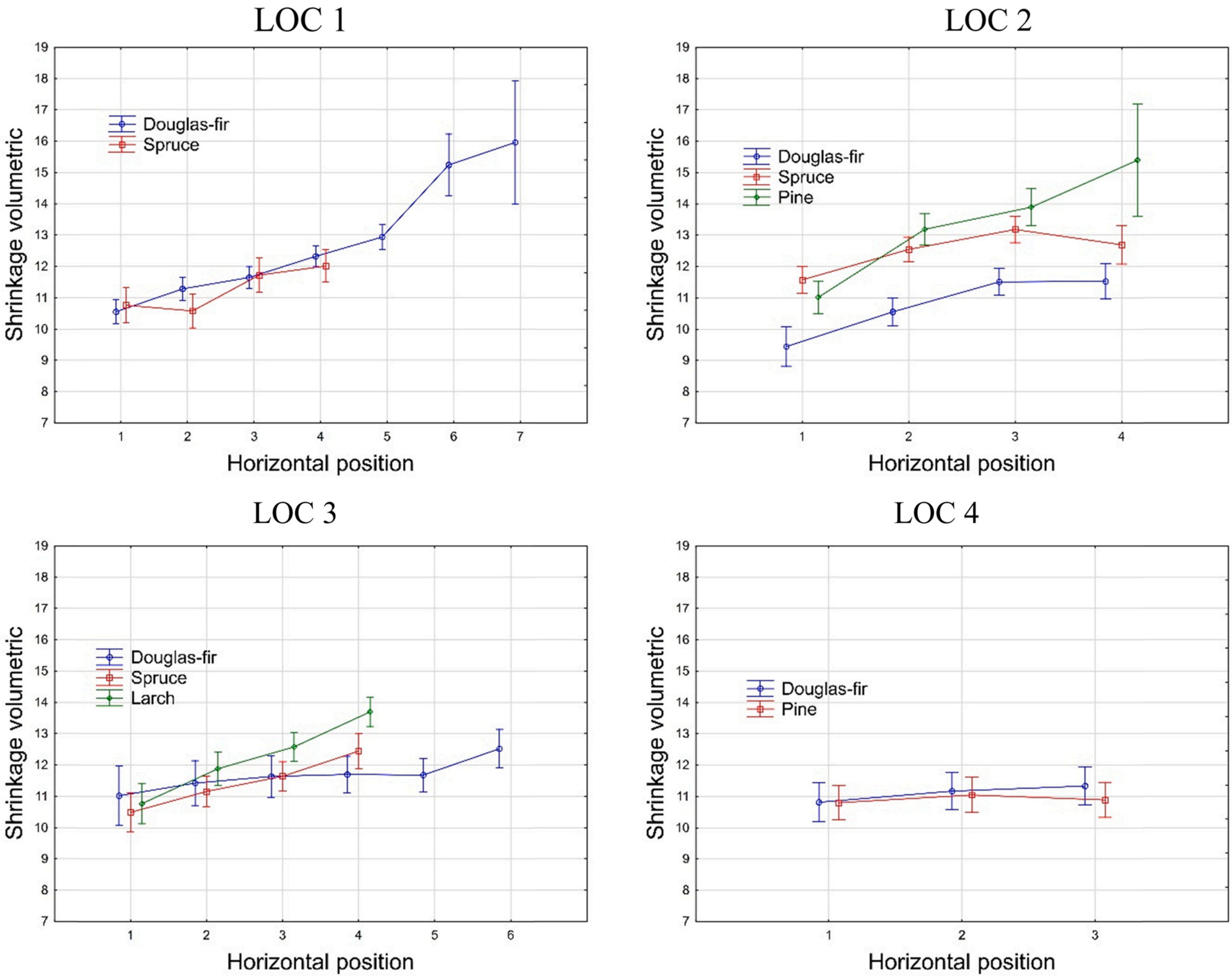

Fig. 4. Volumetric shrinkage (%) pattern along stem radius (x-axis: 1 represents the centre trunk part, the highest figure signifies the outer trunk part) at the studied localities.

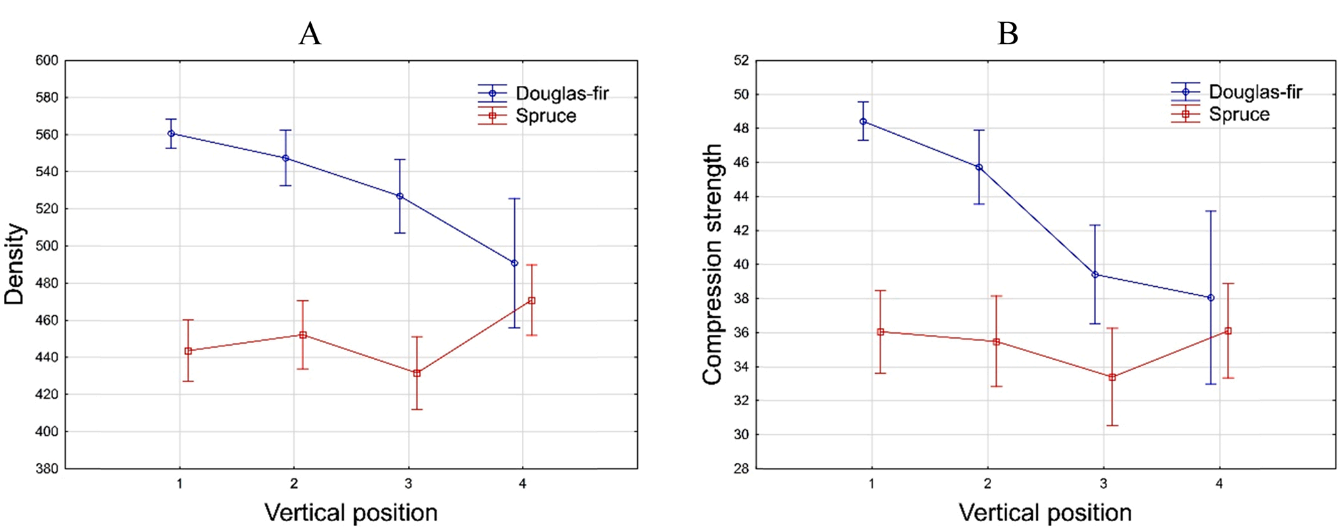

Fig. 5. Effect of vertical position on the density (A) and the compression strength (B) distribution within a stem for LOC 1 (1 – basal part, 2 – 20%, 3 – 40%, 4 – 60% stem height).

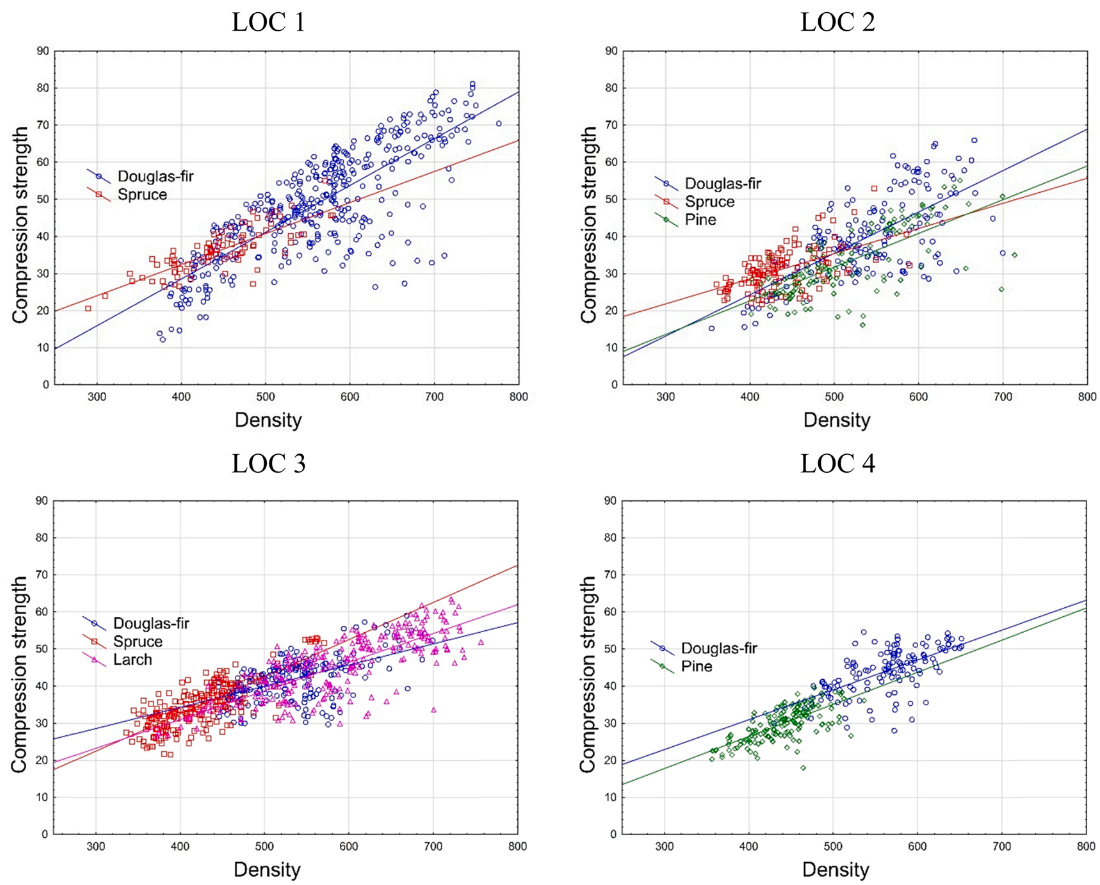

Fig. 6. Correlation between density and compression strength for individual species and localities.

Table 4
Equations of regression, coefficient of correlation and significance from models of the relationship between density and compression strength.

	Regression model	Correlation coefficient	Determination coefficient	P-value
LOC 1				
Douglas-fir	y = −21.8868 + 0.1261 *x	r = 0.80	$r^2 = 0.64$	0.001
Spruce	y = −1.1061 + 0.0838 *x	r = 0.80	$r^2 = 0.64$	0.001
LOC 2				
Douglas-fir	y = −19.1008 + 0.109 *x	r = 0.66	$r^2 = 0.44$	0.001
Spruce	y = 5.8076 + 0.0576 *x	r = 0.47	$r^2 = 0.22$	0.001
Pine	y = −13.6852 + 0.0909 *x	r = 0.71	$r^2 = 0.50$	0.001
LOC 3				
Douglas-fir	y = 12.2396 + 0.0553 *x	r = 0.53	$r^2 = 0.28$	0.001
Spruce	y = −2.5368 + 0.088 *x	r = 0.71	$r^2 = 0.51$	0.001
Larch	y = 0.0567 + 0.0773 *x	r = 0.77	$r^2 = 0.60$	0.001
LOC 4				
Douglas-fir	y = −1.1824 + 0.0804 *x	r = 0.62	$r^2 = 0.39$	0.001
Pine	y = −8.1231 + 0.0865 *x	r = 0.69	$r^2 = 0.48$	0.001

562 kg.m^{-3}. The Douglas-fir achieves relatively high values in the original areas in only one region (Table 5). These are even higher values in some of our localities than those stated in the literature. The qualitatively evaluated Douglas-fir trees provide comparable or even better wood than native areas. On the other hand, compared to pressure, our samples achieved lower values (39.7 – 48.4 MPa), and only the values achieved in the stand with the oldest trees were comparable with the domestic localities. We did not anticipate a fundamental difference in wood shrinkage. In general, there are no significant differences between commercial conifer species (Kollmann and Côté, 1968). Compared to the domestic localities of Douglas-fir, it is evident that these are relatively lower values (10.9 – 11.9%), which is undoubtedly more favourable in terms of wood processing and use. Todaro and Macchioni (2011) achieved similar shrinkage values. Lower volume shrinkage compared to spruce and larch was reported by Pollet et al. (2017).

Based on the values specified in the literature (Table 5), it could be assumed that the difference between spruce and Douglas-fir is not significant (depending on the area of origin). For pine wood, it could be concluded that in terms of density, it is comparable to Douglas-fir (again, according to the area of origin). Regarding compression strength, spruce reaches comparable values. From a literary comparison, pine, in fact, comes off better. However, our study did not confirm this, which compared sample trees from the same stand. In all cases, the spruce wood lagged behind the Douglas-fir wood, concerning density by more than 100 kg.m^{-3} (i.e., in some localities by more than a quarter). In terms of compression strength, Douglas-fir exceeded spruce by 7.1–12.3 MPa depending on the locality, which is a difference of up to 34%. Pine wood density values were highly variable depending on the locality. In both cases, the values for the Douglas-fir were always significantly higher than for pine. For LOC 2, the difference was even higher than 120 kg.m^{-3} (above 27%). Compressive strength was exceeded for pine by 6.4–14 MPa, which is more than 46%. Based on literature values, the only fact that can be accepted is the higher values of wood density and compression strength for larch wood (Pollet et al., 2017). The shrinkage values correspond to the data in the literature. It is evident that there are no significant differences between coniferous tree species in terms of shrinkage (Wagenführ, 2007).

In comparing the Douglas-fir with European conifers in the Central European region, based exclusively on literature, Giagli et al. (2019) found a higher density value for Douglas-fir wood than the tabular

Table 5
Overview of properties reported in the literature for native areas of Douglas-fir and European coniferous tree species.

	Douglas-fir (Alden, 1997)	Wood Handbook (Ross, 2010)	Norway spruce (Wagenführ, 2007)	Scots pine (Wagenführ, 2007)	European larch (Wagenführ, 2007)
Density at 12% MC (kg.m^{-3})	480[a]/500[b]/ 540[c]		470	510	590
Compression strength at 12% MC (MPa)	47.6[a]/51.2[b]/ 49.8[c]	47.6[a]/ 51.2[b]/ 49.9[c]/ 43.0[d]	50	55	55
Volumetric shrinkage (%)	10.7[a]/11.8[b]/ 12.4[c]		11.6 – 12.0	11.2 – 12.4	11.4 – 15.0

[a] Interior North
[b] Interior West
[c] Coast
[d] Interior South

values for spruce and pine. However, the Douglas-fir did not achieve the values of larch. Based on our results, we can accept this general statement. In the mentioned study, the Douglas-fir achieved the highest compression strength values (including larch) and high shrinkage values (12.7%). It was not confirmed in our study.

On the other hand, Remeš and Zeidler (2014) point to comparable spruce, pine and Douglas-fir wood values. The marked difference in Douglas-fir and Norway spruce density is confirmed by Krajnc et al. (2019) from the western Ireland region. Similar to our study, the difference exceeded 100 kg.m^{-3} in some cases. However, these were trees from the same geographical area, not the same stand. Moreover, Drewett (2015) achieved a Douglas-fir wood density value of 455 kg.m^{-3}, which is lower than the value reported for Norway spruce by literature. It clearly points to the difficulty of comparison with tabular data and the results of other authors.

The distribution of physical and mechanical properties in the tree stem, especially in conifers, has been examined by many authors (e.g., Alteyrac et al., 2005; Kimberley et al., 2017; Langum et al., 2009; González-Rodrigo et al., 2013; Tumenjargal et al., 2018; Sarkhad et al., 2021). The course of density (and other related properties) in the stem in the radial direction, or depending on height, are the result of the anatomical wood structure (in particular the presence of juvenile wood) and the nature of conifer growth (Jozsa and Kellogg, 1989; Zobel and Sprague, 1998; Barnett and Jeronimidis, 2003). It is characterized by a horizontal trend, where the density reaches the lowest values in the middle stem part and increases towards the bark. The increase in this direction was confirmed for Douglas-fir wood density by Lausberg et al. (1995), Gartner et al. (2002), Drewett (2015), Giagli et al. (2019). This trend was also confirmed for the Douglas-fir in our case. The course was similar for compression strength, given by the dependence on density. The lowest mean results were obtained for the position nearest the pith by Bawcombe (2012). Lower values of density and compression strength are shown by the central stem zone for Douglas-fir, according to Pollet (2017). The same properties distribution is confirmed for compression and shrinkage by Giagli et al. (2019). The consistent effect of the distance to the pith on mechanical properties is mentioned by Rais et al. (2014). It is worth noting that the remaining species of conifers behaved similarly. Some of the authors first reported a decrease in density from the pith to the cambium to a certain distance, and only then an increase (Jozsa and Middleton, 1994; Langum et al., 2009; Bawcombe, 2012). This trend only occurred for the Douglas-fir at LOC 3 and is not statistically significant.

The effect of the vertical position on properties is not too obvious (practically none in the case of spruce). In this case, a negative correlation between density and height is assumed (Johnson and Gartner, 2006; Langum et al., 2009). In our study, the highest density and compression strength value was achieved at the bottom part of the stem (and decreased towards the crown) only at one locality. The effect of height was not confirmed in the remaining localities. Other authors also agree with such conclusions for the Douglas-fir. Only minor differences for wood density related to stem height were noted by Bawcombe (2012). The same author did not find any significant difference between the vertical positions in compression strength. The ambiguous effect of the longitudinal position on density is confirmed by Krajnc et al. (2019). Acuna (2006) reports only a slightly decreasing density trend with increasing tree height. Nevertheless, the author states limited predictive capability.

Wood density is widely used as an explanatory factor in evaluating mechanical properties (Bodig and Jayne, 1982; Dinwoodie, 2000; Ivković et al., 2009). Usability has also been confirmed for Douglas-fir wood. Todaro and Macchioni (2011) state a robust positive correlation between wood density and compression strength for the Douglas-fir and consider wood density a good predictor of wood mechanical properties. Statistical analyses confirmed the close relationship between density and compression strength as was stated in the case of Pollet et al. (2017) or Tumenjargal et al. (2020).

We also tested how much shrinkage is affected by density and whether density can indicate dimensional changes. Shrinkage of wood is affected by many factors. The first of them and often reported is wood density (Tumenjargal et al., 2020). It is supposed that the magnitude of shrinkage is higher with higher density, i.e. timbers with higher density shrink more (Tsoumis, 1991; Shmulsky and Jones, 2011; Pollet et al., 2017). Effect of cell-wall substance and so proportionality between density and shrinkage was also reported by Siau (1984). It can be even described by a mathematical formula. The differences in shrinkage among species cannot be attributed just to density. One theory explaining the differences between softwoods and hardwoods is a difference in chemical composition, namely lignin content. Other reason is occurrence of exclusively uniseriate rays in softwoods in contrast to hardwoods. Difference between early-wood and latewood in softwoods, cell-wall structure (microfibril angle) is another factor playing a role in dimensional changes related to moisture changes below fibre saturation point (Tsoumis, 1991). Influence of earlywood and latewood tracheids mentioned Dinwoodie (2000) or Skaar (1988) for Douglas-fir. Although some authors reported the relationship between shrinkage and density, the effect of density was not manifested in our case, which is more favourable in the use of Douglas-fir wood. Weak correlation was reported by Ivković et al. (2009) for radiate pine. Although Douglas-fir has a significantly higher density than spruce, its shrinkage values do not differ considerably from spruce. Nevertheless, it is a positive finding, as shrinkage is regarded as a negative wood property and wood with lower values has greater preconditions for use in industry.

5. Conclusions

The Douglas-fir represents an important non-native tree species in many European countries. Based on climate scenarios, it is assumed that it will mainly replace spruce or pine stands suffered by ongoing global climate change. The processing industry also expects the substitution of domestic conifers wood by Douglas-fir. Based on our experiments, we can say that Douglas-fir wood significantly exceeds spruce wood in its density and strength, regardless of the stand type at which the tree species is found. Even the age of the studied tree species was not reflected in this huge difference. In terms of wood shrinkage, both tree species are comparable and usable for the same purposes. Moreover, in our comparison, Douglas-fir also surpassed pine wood in its density and strength, which is often described in the literature as equivalent or even better in some characteristics. For shrinkage, as in the case of spruce, there are no significant differences between these species. Only larch surpassed Douglas-fir in all analysed properties. It also includes shrinkage, where higher strength and density are redeemed by higher values in dimensional changes related to changes in moisture content. Depending on the position in the stem, the variability of the evaluated properties corresponded to the general trends reported for softwoods, or no trend could be demonstrated. Density can be a good predictor of the Douglas-fir wood mechanical properties, whilst the wood shrinkage has proven not overly dependent on density.

CRediT authorship contribution statement

Aleš Zeidler: Conceptualization, Methodology, Supervision, Writing – review & editing. **Vlastimil Borůvka**: Data curation, Software, Writing – original draft. **Jakub Černý**: Resources, Writing – review & editing. **Martin Baláš**: Data curation, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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