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Growth analysis of the lower layer trees in forest stands under conversion in the Starohorské vrchy Mts.: A case study

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Abstract: The case study analyses the structure and dynamics of the diameter growth on the example of two fir-spruce forest stands under conversion to a selection forest. In a series of 51 circular research plots (size 500 m^2), the biometric characteristics (tree species, diameter at breast height, height) of all the stems with a diameter above 8 cm were registered. From the selected stems, we collected 51 cross-sections and 178 tree cores in total and performed age and growth analyses. In addition, for the lower layer trees, we assessed the competition by the neighbouring stand quantified by the competition index. The results confirmed the differences in the age structure, despite the similar diameter distributions in the investigated stands, as well as the differences in the growth dynamics of the spruce and fir in the lower tree layer. Nevertheless, the competition of the neighbouring stand was not proven as a significant factor for the diameter growth of the lower layer trees.

Keywords: competition; diameter increment; fir; selection forest; spruce; transformation

The tendencies directed towards the maintenance and higher stability of endangered forest ecosystems in Europe require significant changes in the applied concepts of their management. The even-aged spruce stands managed by traditional methods especially represent unstable forest ecosystems that are susceptible to negative impacts of wind, insects, changes in the nutrient regime, soil acidification and currently also climate change (Schütz et al. 2006; Boden et al. 2014; Mezei et al. 2014). The high risk of stand damage together with the prospective orientation of European forestry to close-to-nature silviculture evoke the need of converting these forests to uneven-aged stands with an admixture of other native tree species (Gamborg, Larsen 2003; Bauhus et al. 2013). Generally, in comparison with even-aged pure stands, structured mixed forests are characterised by higher resilience when exposed to stress or sudden disturbances (Brang et al. 2014; Hanewinkel et al. 2014). Therefore, the gradual differentiation of the stand structure in spruce forests and the increased proportion of original site-adapted tree species is the most effective way how to reduce the risk of their disintegration. On the sites

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where the natural tree species composition is dominated by shade-tolerant conifers, the conversion to a selection forest is considered as the optimal approach (Korpeľ, Saniga 1994; Saniga, Dendys 2015).

The conversion of a stand to a selection forest is a long-term process that consists of progressive steps oriented to the forming of a stand structure towards the target state (Lüpke et al. 2004). The self-regulation in converted stands starts to function only after a relatively long period. For this process, the permanent ingrowth of natural regeneration individuals into the lowest diameter classes is crucial. The time needed to establish the lower tree layer is the key parameter for the duration of the conversion process and represents the initial point for the ingrowth of trees into the middle and upper stand layer (Schütz 2001a, 2006). Nevertheless, so far, only limited attention has been paid to the exact time quantification of this important phase in the converted stands (e.g. Schütz 2001b).

The dynamics of diameter growth in multi-layered stands differs from that in an even-aged forest. Young trees in even-aged stands in the initial period of their development are not exposed to such strong competition regarding the light, therefore, the diameter increment already culminates at a diameter of 25–30 cm and then decreases significantly. On the contrary, in structurally differentiated stands, trees of low diameters grow in strong shade which has a negative impact on their diameter growth (Schütz 2002). The increment of such trees is characterised by significant variation due to the large heterogeneity of ecophysiological conditions (Schütz 1989; Reininger 2000). During their development, trees gradually receive more light and the increment slowly increases with the growing diameter. From a certain diameter, the increment remains equal or progressively decreases (Schütz 1989; Korpeľ, Saniga 1993). The trees have enough time to adapt to the new environmental conditions and this is reflected in their longer crowns, lower values of height-to-diameter ratio and better root system stability in comparison with the stems in even-aged forest (Burschel, Huss 1997; Schütz 2001a; Röhrig et al. 2006).

Recently, decreasing resistance of even-aged spruce forests has been observed in forest stands of Slovakia as well as other European countries. Therefore, the need to change their management is increasing and the detailed studying of the growth processes in converted stands is gaining importance. The aim of this case study from two mixed stands under conversion to a selection forest was (*i*) to analyse their age structure according to the particular tree layers, (*ii*) to quantify the diameter increments of the trees with different height positions, and (*iii*) to evaluate the impact of the competition by the neighbouring stand on the diameter growth in the lower layer.

MATERIAL AND METHODS

Description of research objects. The research was conducted in two fir-spruce stands (compartments 1631 and 1632c) under conversion to a single-tree selection forest. The investigated stands are the part of the demonstration object Pro Silva Donovaly-Mistríky with an area of 50.3 ha that is located in the south-eastern region of the Starohorské vrchy Mountains in Slovakia (48°52'N; 19°14'E). The mean annual temperature reaches 4.2–4.8 °C and the mean annual precipitation is 950–1 100 mm. The stands are situated at an altitude 900–950 m a.s.l. on a bedrock formed by granite and phyllite. Compartment 1631 is growing on cambisol on a mild slope with a north-western aspect and has a dominant production function. Compartment 1632c is located on a steep slope with an 85% grade with a northern aspect on a shallow, nutrient-poor ranker soil with a high skeleton content and, therefore, belongs to the category of protection forests (Saniga, Vencurik 2007). The most common forest communities are represented by *Fagetum abietino-piceosum* and *Piceetum abietinum*, with Norway spruce [*Picea abies* (L.) Karst.] and silver fir (*Abies alba* Mill.) as the dominant tree species. The admixed tree species European larch (*Larix decidua* Mill.), European beech (*Fagus sylvatica* L.) and rowan (*Sorbus aucuparia* L.) also grow in the stands.

Field measurements and data analysis. The field data needed for the analysis of the stand structure were collected on a series of 51 circular research plots that were systematically distributed across the investigated stands in a network measuring 35 m × 35 m. In the circles with a radius of 12.6 m (500 m^2 in size), we registered the tree species, the diameter at breast height (*DBH*) and the height of all the trees with a *DBH* > 8 cm. The stem volume was calculated according to the two-parameter (*DBH*, height) equations by Petráš and Pajtík (1991).

In the surveyed stands, we also studied the age and diameter increment of the Norway spruce and silver

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fir in the lower (8.1 cm < *DBH* ≤ 12.0 cm), middle (*DBH* 12.1–36.0 cm) and upper tree layer (*DBH* > 36 cm) in detail. For this analysis, we collected the cross-sections (1.3 m from the stem base) of 51 lower layer trees (24 Norway spruces, 27 silver firs) as well as the cores (two perpendicular directions at a height of 1.3 m) of 56 middle layer (27 Norway spruces, 29 silver firs) and 33 upper layer stems (17 Norway spruces, 16 silver firs) randomly distributed across the investigated stands. The samples were tagged, transported to the laboratory and prepared according to the standard methodology (Stokes, Smiley 1996). Subsequently, they were digitised by an Epson Expression 10000XL scanner (Seiko Epson Corp., Japan) at a resolution of 1 200 dpi and analysed using the WinDendro 2009b software (Version Reg, 2009), with the output containing the counts and widths of the year rings. As the cross-sections and cores were taken at a height of 1.3 m, to assess the tree age, it was necessary to add the time needed to reach this height. This period was quantified according to the fitted growth curves of the lower layer trees derived by Vencurik et al. (2019) and represented 18 years for the spruce and 16 years for the fir trees. Based on the year ring widths from the collected cores of the spruce and fir trees, the mean annual diameter increment for the period of the last 5 years Δ*d* (diameter increment) was calculated according to the Equation (1):

$$\Delta d = \frac{d_n - d_{n-5}}{5} \quad (1)$$

where:
Δd – diameter increment;
d_n – diameter in the current year;
d_{n-5} – diameter 5 years ago.

For the selected lower layer trees, we also quantified the competition of the neighbouring trees. As the competitors were considered all trees with a *DBH* > 5 cm (1/2 of the average *DBH* of the lower layer trees) that were located in the circular area of 300 m^2 around the selected tree (i.e. at a distance less than 9.8 m). For all the analysed lower layer trees, as well as their competitors, we also registered the height, vertical crown projection, tree species and the distance between the lower layer tree and the competitor besides the *DBH*. The competition rate was expressed by the competition indices from Hegyi (1974), Biging and Dobbertin (1995) and Elliot and Vose (1995). The suitability of these indices not only for the mature, but also for the young stands, was experimentally verified by Ammer et al. (2005). For the detailed analysis presented in this study, we selected the index from Biging and Dobbertin (1995) that was calculated as follows [Equation (2)]:

$$CI_i = \sum_{j=1}^{n} \frac{cc_j}{cc_i \times \left(dist_{ij} + 1\right)} \quad (2)$$

where:
CI_i – competition index of the tree *i*;
cc_j – crown projection area of the competitor tree *j*;
cc_i – crown projection area of the selected lower layer tree *i*;
$dist_{ij}$ – distance of the selected lower layer tree *i* to the competitor *j*.

All the statistical analyses were performed in the software STATISTICA (Version 10.0, 2010). The differences in the diameter increment (Δ*d*) between the tree species (spruce, fir) and the tree layers were tested by a two-way analysis of variance and the post-hoc Duncan test (Zar 1999). Multiple linear regression was used to analyse the effect of the competition index and the height of the lower layer trees on their diameter increment. The tree height instead of the *DBH* was chosen as a factor due to the high variability in this characteristic in the lower layer.

RESULTS AND DISCUSSION

In the investigated 1631 and 1632c stands, the density of the stems with a *DBH* > 8 cm reached 622 ± 38 stems·ha^{-1} (mean ± SE) and 649 ± 58 stems·ha^{-1}, with the growing stock of 470 ± 29 m^3·ha^{-1} and 438 ± 23 m^3·ha^{-1}, respectively. The dominant tree species was the Norway spruce with the proportion 57% and 81% of the stem number or 63% and 86% of the growing stock, which was followed by the silver fir. The European beech, European larch and rowan occurred only as a single admixture. The diameter distributions in both stands were characterised by a decreasing shape, with a moderate deficit of stems in the middle layer (diameter class of 18–34 cm) and the slightly overrepresented upper layer (Figure 1).

Despite the similar shapes of the diameter distributions (Figure 1), the studied stands distinctively represented different types of age structure (Figure 2). While the mean age of the trees in the middle and upper layer varied in a relatively narrow range in stand 1631 (from 107 ± 7 years for

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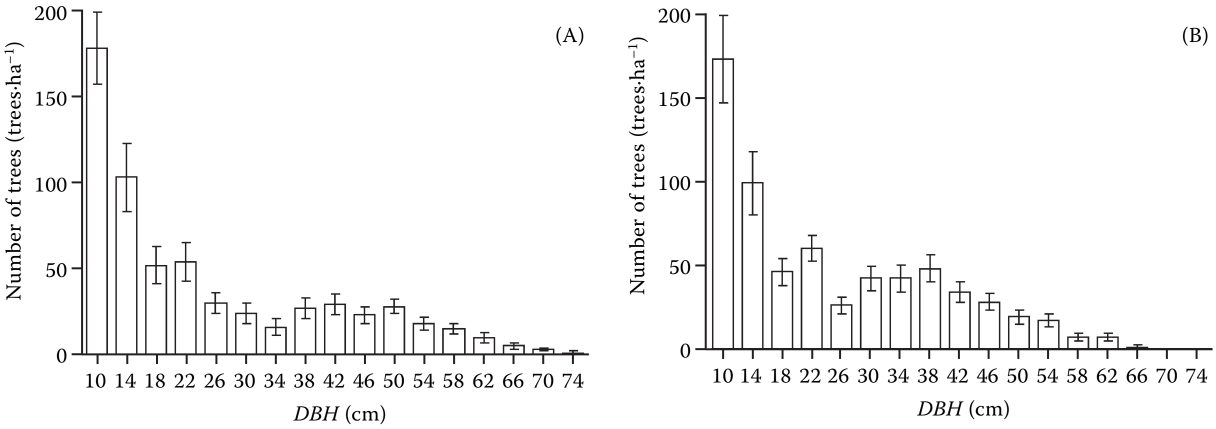

Figure 1. Diameter structure in forest stands (A) 1631 and (B) 1632c (error bars represent standard error)

the spruce in the middle layer to 127 ± 3 years for the fir in the upper layer), the spruce stems forming the upper layer in stand 1632c reached a significantly higher mean age (193 ± 13 years) in comparison with the trees in the middle layer (102 ± 19 years for the spruce and 98 ± 11 years for the fir). The presence of a relatively compact middle layer in stand 1631 is, therefore, much more likely the expression of the strong competition between the upper layer stems of a similar age than the result of the gradual emergence and development of trees under the canopy of the parent stand over the long-term period. This finding also confirms the fact that significant age differences between the stems with a similar diameter usually exist in a selection forest. In the planning and application of management in multi-layered stands, it makes, therefore, much more sense to rely on the dimensions of the trees than on their physical age (Schütz 1969, 1989).

The age of the trees in the lower layer usually varied between 30 and 60 years (Figure 2). This result corresponds to the finding of Schütz (2001b) who, based on the example of 100-year-old spruce-dominated stands after the successful conversion to irregular structures in the Swiss Jura (La Joux Pélichet), estimates that. to achieve a reasonable structural differentiation, it requires at least a period of 60–70 years. In the lower layer of the investigated forest stands in our study, slow-growing spruces with an age significantly exceeding 60 years also rarely occurred. Such trees can grow in shaded conditions even for several decades while they still represent a potential reserve for the ingrowth into the middle layer. After the opening of the growth space, they are able, regardless of their age, to reach dimensions comparable to the trees with an average growth intensity (Schütz 1969; Szymura 2005; Lundqvist, Nilson 2007; Lin et al. 2012).

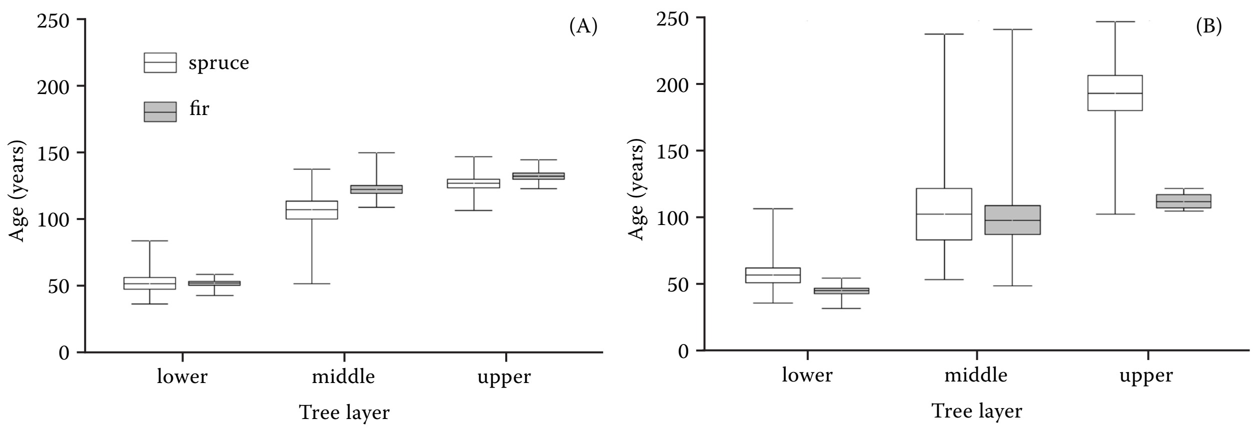

Figure 2. Age of trees according to tree species and forest stand layers in compartments (A) 1631 and (B) 1632c (box represents mean ± standard error, whiskers represent minimum and maximum values)

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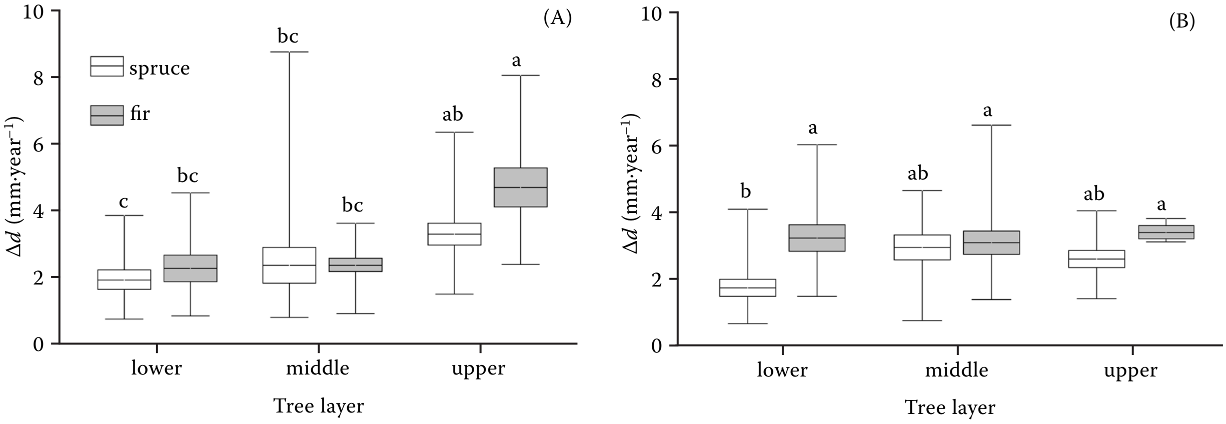

Figure 3. Diameter increment (Δ*d*) according to tree species and forest stand layers in compartments (A) 1631 and (B) 1632c (box represents mean ± standard error, whiskers represent minimum and maximum values)

Despite the extreme site conditions in stand 1632c, the ages of the lower layer trees were similar to those in stand 1631. This fact suggests the comparable growth rhythm of the lower layer trees in the previous period. In the case of the fir trees in the protection forest (stand 1632c), the diameter increment during the last 5 years even was significantly higher than that registered for the fir trees in the stand with the production function (Figure 3). This can be the consequence of lower growing stock as well as the more favourable microclimatic conditions related to the northern aspect and the steep slope in stand 1632c, especially considering their mitigation effect on the negative impact of the ongoing climate change (Campioli et al. 2012; Nothdurft et al. 2012). Nevertheless, the influence of other factors (e.g. differences in the stand structure, inter- and intraspecific competition, etc.) can also play an important role.

The diameter increment (Δ*d*) values in the analysed stands ranged from 0.7 mm·year^{-1} to 8.8 mm·year^{-1} for the spruce and from 0.9 mm·year^{-1} to 8.1 mm·year^{-1} for the fir (Figure 3). In stand 1631, a typical significant increase in the diameter increment values in the higher stand layers was confirmed (Table 1, Figure 3). However, this trend was not observed in the protection stand 1632c. The reason for the relatively low diameter increment of the spruce in the upper layer of this stand was probably the high physical age of the trees (Figure 2). In the case of the fir trees, most of the trees in the upper layer were still only near its lower limit due to the ongoing conversion.

Significant differences in the diameter growth between the spruce and fir trees were confirmed only in the lower layer of forest stand 1632c. The average value of the diameter increment for the fir (3.2 mm·year^{-1}) in comparison with the spruce (1.7 mm·year^{-1}) was nearly twofold higher (Table 1, Figure 3). A similar, although not significant, difference between the spruce and fir was also registered in the lower layer of stand 1631. The differentiated

Table 1. Results of two-way analysis of variance for diameter increment (**Δ***d*)

Stand	Source of variance	*SS*	*df* effect	*MS* effect	*F*	*P*-level
1631	species	5.97	1	5.97	3.09	0.083
	layer	45.36	2	22.68	11.76	0.001
	species × layer	5.93	2	2.96	1.54	0.223
	error	127.29	66	1.93	–	–
1632c	species	6.09	1	6.09	4.04	0.048
	layer	4.13	2	2.07	1.37	0.261
	species × layer	6.63	2	3.32	2.20	0.119
	error	97.98	65	1.51	–	–

SS – sum of squares; *MS* – mean square; *F* – *F*-ratio

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Table 2. Parameters of multiple linear regression for diameter increment (Δd) of lower layer trees

Stand	Species	Factor	a	b	Beta	R^2	Standard error
1631	spruce	competition index	0.181^{NS}	–0.049	$–0.246^{NS}$	0.226^{NS}	0.279
		tree height	–	0.071	0.487^{NS}	–	–
	fir	competition index	$–0.371^{NS}$	–0.115	$–0.440^{NS}$	0.209^{NS}	0.595
		tree height	–	0.136	0.303^{NS}	–	–
1632c	spruce	competition index	2.126*	–0.201	$–0.467^{NS}$	0.216^{NS}	0.389
		tree height	–	–0.002	$–0.005^{NS}$	–	–
	fir	competition index	2.517*	–0.049	$–0.136^{NS}$	0.119^{NS}	0.564
		tree height	–	–0.074	$–0.252^{NS}$	–	–

*$P < 0.05$; NS – not significant; a – intercept; b – regression coefficient

structure of the selection forest and the related decrease in the diffuse radiation intensity towards the ground created more favourable ecological conditions for the fir trees in the lower layer. The better utilisation of diffuse light by the fir results in its faster growth and, therefore, in the higher competitive ability in comparison with the spruce (Grassi, Giannini 2005; Dănescu et al. 2018; Vencurik et al. 2019). The deliberate regulation of the light conditions in the lower layer can, thus, to a certain extent affect the changes not only in the structure, but also in the tree species composition of a forest stand (Smith et al. 1997; Diaci 2002; Robakowski et al. 2004).

According to the results of multiple linear regression, the diameter increment of the spruce and fir trees in the lower layer was neither significantly affected by the height of the analysed tree nor by the competition of the neighbouring stand (coefficients of determination 0.119–0.226; Table 2). This finding was also confirmed by the additional analyses, where an alternative size of the circular area around the selected lower layer tree (100 m^2 and 200 m^2) was applied for the calculation of the competition index. Based on the results of several studies (Givinish 1988; Stancioiu, O'Hara 2006; Gspaltl et al. 2013), we can assume that one of the most important factors affecting the diameter growth of the lower layer trees is the light intensity, which need not necessarily be strongly correlated with the applied competition index. Moreover, in the case of the lateral competition, the impact on the growth of the lower layer trees was found to be significant only when the light levels exceed the threshold of 25% of the full light. (Parent, Messier 1995; Duchesneau et al. 2001). However, in the lower layer of structurally differentiated forest stands, such high solar radiation values are relatively rare (Boncina et al. 2002; Diaci, Firm 2011; Vencurik et al. 2016).

CONCLUSION

The results of this study confirmed that, in the stands under conversion to a selection forest, similar diameter structures can show different age patterns. Besides being the consequence of the multi-aged structure, the difference between the middle and upper layer can also result from the competition within the trees of similar age. Therefore, for the practical management of forest stands under conversion, the dimensions of the trees are better suitable than their physical age. In the lower layer of the converted stands, the fir trees usually reached a higher diameter increment than the spruce trees, which suggests that they have a better competitive ability under the ongoing climate change conditions. In general, the competition of the neighbouring stand was found to have no significant impact on the diameter increment of the trees in the lower layer.

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