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Long-term tending effect on static stability of pure beech (*Fagus sylvatica* L.) stands

*Igor Štefančík**

Department of Silviculture and Forest Production, National Forest Centre, Zvolen, Slovak Republic

**Corresponding author: igor.stefancik@nlcsk.org*

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Abstract: The production stability together with the provision of required functions are the key requirements for the future existence of stable forest stands. Sufficient mechanic stand stability could be developed by the early and long-term thinning where basic tree characteristics, such as stem and crown parameters play the decisive role. We compared selected parameters of static stability in pure beech stands, which have been exposed to heavy low thinning and free-crown thinning with control stands without interventions. Data from twenty-seven long-term research subplots at eight localities across Slovakia were involved in this study. In total 7 693 trees between 30 and 110 years were analysed. Slenderness (h/d ratio), crown length, crown width and crown ratio proved to be the most explanatory parameters for the defining mechanical stability on subplots with free-crown thinning. We found the least favourable results on control subplots. The differences between the subplots with tending (regardless of the tending method) and the control subplots were statistically significant in all studied parameters ($P < 0.05$).

Keywords: beech; thinning; slenderness ratio; crown width; crown length; crown ratio

The growth and development of forest stands can be affected by various factors (abiotic, biotic, anthropogenic). The endangerment of stands due to the influence of any of these factors depends on their intensity and also on the ability of forest stands to resist (mitigate) their effects or become even more resilient (Brang et al. 2014). With regard to abiotic factors (wind, snow, ice), tending of stands is the most effective measure to increase and strengthen mechanical stability of stands (Slodičák 1987; Slodičák, Novák 2006; Poleno et al. 2009; Štefančík 2012; Bošeľa et al. 2016; Konôpka, Konôpka 2017; Vacek et al. 2019).

The most often aim of tending is to ensure mechanical stability, so the stands can withstand the adverse effects of wind or snow. Early and systematic tending is especially important in spruce (coniferous) stands (Konôpka et al. 1989), which are more affected by abiotic factors, compared to deciduous tree species (Stolina et al. 1985; Vacek et al. 2020). Difference in groups of tree species is supported by the data on salvage cuttings in Slovakia over the last 20 years (Kunca et al. 2019). Mechanic stability can be assessed through various parameters of the crown and tree stem (Sharma et al. 2016, 2017; Konôpka, Konôpka 2019). However,

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it is most often characterised by the value of the slenderness, the quotient between height (*h*) and diameter at breast height (DBH) (Assmann 1968; Slodičák, Novák 2003, 2006; Bošeľa et al. 2014; Sharma et al. 2016b, 2017b).

The method by which required mechanic stand stability can be achieved is an important fact in the tending of stands (Štefančík et al. 2018). In this connection, Slodičák, Novák (2007) evaluated the results of many years of research into the mechanic stability of spruce stands. They monitored and compared the effect of the low thinning with negative selection, crown thinning with positive selection and control plots (without interventions) on the static stability of spruce stands aged between 80 and 94 years.

Similarly, Konôpka and Konôpka (2019) analysed the results from research plots established in the 1970s, where a one-time thinning was performed at the beginning of the research. In addition, in other research plots, which were cultivated by the method of target trees, they monitored the development of selected parameters of static stability. It was about the proportion of the crown length to the total tree height (crown ratio) and the slenderness quotient.

Data from long-term measurements of various static stability parameters (crown length, crown ratio, crown width, slenderness quotient) served as the basis for developing models of target trees of spruce stands (Konôpka 1992) as well as models of multi-layered and mixed stands in Central Europe (Sharma et al. 2019a, 2019b). Considerably fewer contributions were devoted to the static stability of deciduous stands (Dudzinska, Tomusiak 2000; Sharma et al. 2016) and the evaluation of target trees in beech stands (Remeš et al. 2015; Štefančík 2017; Štefančík et al. 2018). There is practically a lack of knowledge about the development of mechanic stability for beech stands.

Our aim was to compare selected parameters of mechanic stability in pure beech stands which were systematically cultivated (35 to 58 years) by two different thinning methods with stands without interventions.

MATERIAL AND METHODS

Site description. The study was conducted in beech (*Fagus sylvatica* L.) stands in the Western Carpathians Mountains situated in Central and Eastern part of the Slovak Republic (Figure 1), which

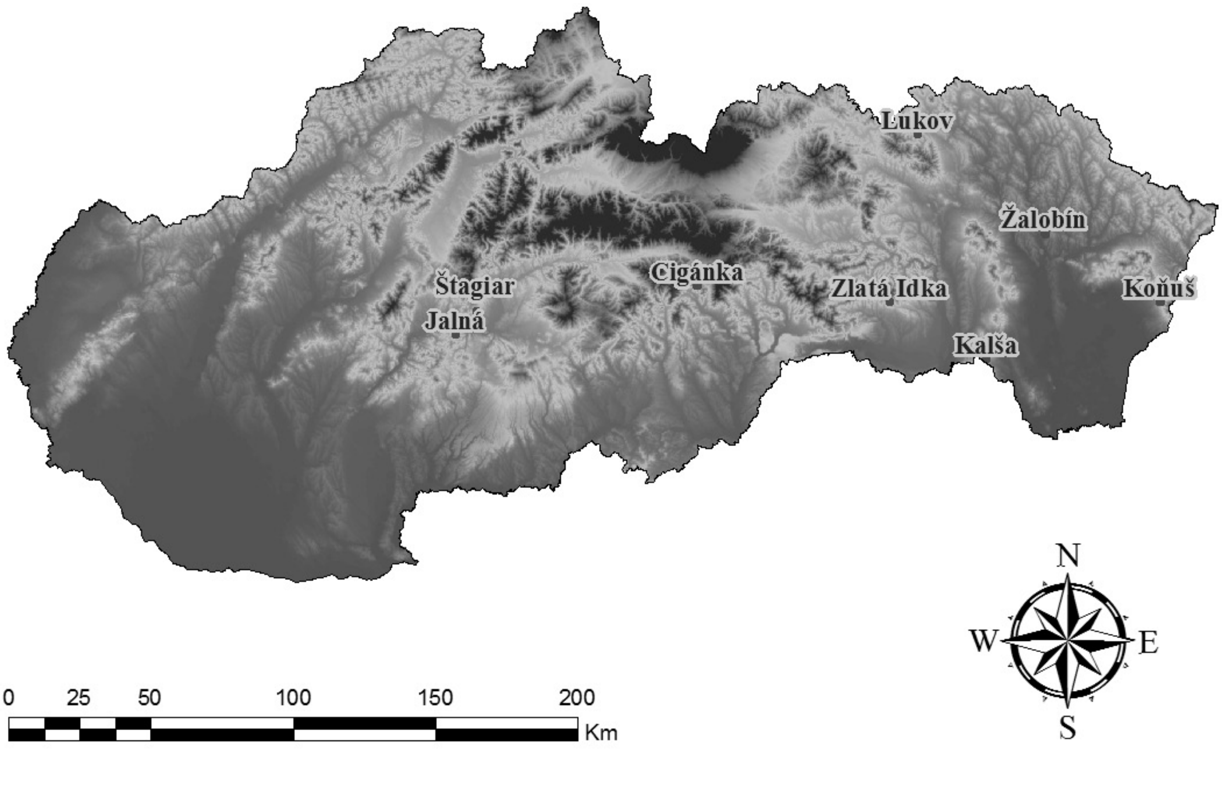

Figure 1. Location of the research plots in pure beech stands, Slovakia

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originated from natural regeneration. No tending interventions were performed in the forests until the beginning of the research. The research sites lie mostly in a sub-mountain vegetation belt in an elevation range from 250 to 700 m a.s.l. and slope of 15–26° with east to north-western exposure. The growing season lasts 130–165 days (Hančinský 1972). The average number of days with snow cover is 40–80 days.

The study area is qualified from warm, dry, with mild winter sub-region [50 or more summer days (SD) annually in average with daily maximum air temperature ≥ 25 °C] to moderately warm (cool), humid, with cool winter (less than 50 SD annually in average with daily maximum air temperature ≥ 25 °C and the July mean temperature 16 °C or more) sub-region (according to Konček 1961–2010; Klimatický atlas Slovenska 2015). Andesite parent rock and flysch sandstone are dominant. The study area comprises pure beech forests characterised by the *Fagetum pauper*, *Fagetum typicum, Fageto-abietinum and Querceto-Fagetum* forest type groups (Zlatník 1976).

Sampling and measurements. Twenty-seven long-term research subplots (LTRPs) at eight localities (called hereinafter as "series" of subplots) across Slovakia were established by the Prof. Dr. Ladislav Štefančík in 1959–1984, representing homogeneous (even-aged) naturally regenerated beech forests in Slovakia. At the time of their establishment, the forests were in a growth stage from small pole to pole timber (Table 1).

The above-mentioned series of LTRPs comprised from 3 to 4 subplots , which were arranged next to each other (along the contour line), and separated from each other by a 15 m wide buffer zone. The area of each subplot was 0.25 ha (50 × 50 m). At the beginning of our research all living trees with the diameter at breast height DBH ≥ 3.6 cm and/or trees which reached this threshold during the measurements were labelled and evidenced on all subplots.

The following thinning types were applied: 1 – "low thinning" – heavy low thinning (C-grade, following the principles defined by German forest research institutes, released in 1902) and 2 – "crown thinning" – free-crown thinning (thinning from above) applied in 5 or 4- and 10-year intervals, respectively, as defined by Štefančík (1984a). The principle of this thinning method is in supporting the selected best-quality trees (so-called target or crop trees) by removing their competitors. An emphasis was given not only to the stem quality (straight high-quality stem without knots, without visible external damage), dimensions (as large as possible diameter and height) and also to the crown shape (continuous stem axis to the tree top) and spacing (more or less regular arrangement) of target trees (Štefančík 1984). One subplot in each series (locality) was left unmanaged as a "control", where no interventions were applied.

A transect of 10 m in width and 50 m in length was established on each subplot. Tree height, crown base and crown width (four radius readings taken in the northern, eastern, southern and western directions) were measured in all trees on the transect, as well as in target (crop) trees at each inventory (measurement) during the study period. In total between 8–13 measurements were performed until now.

Data processing and statistical analyses. Crown width, crown length, slenderness ratio, crown ratio (crown length/tree height), were derived. Based on four crown radii, the crown width (*CW*) was calculated (Equation 1):

$$CW = \Sigma\ CR_{1\text{-}4}/2 \qquad (1)$$

where:
CR – crown radius.

Crown length was defined as the vertical distance from the crown base to the top of the crown. Slenderness represents the quotient between tree height (h) and DBH. The hundred largest trees (with the largest DBH) per hectare were selected to calculate slenderness (h/DBH).

To simplify further statistical analysis, for type "crown thinning" we grouped the subplots with 5 (4) or 10 year thinning interval into the one type. The experimental data were processed by mathematical and statistical evaluation, using Microsoft Excel Standard (Version 2013) as well as the QC Expert software (Version 3.3, 2013) (Kupka 2013).

Correlation analysis was used to indicate relationship between selected parameters ([slenderness h/d ratio], crown length, crown width and crown ratio). Differences between subplots and different management regimes (thinning methods) were tested by one-way analysis of variance (ANOVA), and consequently by Duncan´s tests (QC Expert software).

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Table 1. Site characteristics for long-term beech research plots

Name of plot/ subplot	Number of measurements	First/last measurements	Age span (years)	Geographic position north latitude	Geographic position east longitude	Elevation a. s. l. (m)	Mean annual temperature (°C)	Mean annual precipitation (mm)	Soil unit	Forest site type
Jalna/C, H, 0	13	1959–2017	36–94	48.55	18.95	610	6.2	800	Eutric Cambisol	Fertile oak beechwoods
Konus/C, H, 0	13	1961–2019	30–88	48.78	22.30	510	6.5	900	Eutric Cambisol	Fresh oak beechwoods
Stagiar/I, II, III, IV	8	1984–2019	38–73	48.63	19.04	620	6.6	925	Cambisol	Fresh oak beechwoods
Kalsa/C, H, 0	13	1961–2019	37–95	48.58	21.48	520	6.0	790	Stagni-Eutric Cambisol	Fertile oak beechwoods
Kalsa/H2	11	1969–2019	45–95			520	6.0	790		
Zalobin/C, H, 0	13	1962–2020	39–97	48.98	21.74	250	7.9	660	Stagni-Eutric Cambisol	Fresh oak beechwoods
Zlata Idka/C, H, 0	13	1960–2018	40–98	48.74	21.01	700	6.7	780	Haplic Cambisol (Dystric)	Acid beechwoods
Ciganka/C, H, H2, 0	11	1967–2017	60–110	48.76	20.09	560	5.5	918		
Lukov/H, 0	12	1962–2016	45–99	49.28	21.10	550	5.5	690	Haplic Cambisol (Dystric)	Fertile beechwoods
Lukov/C	11	1966–2016	49–99	49.28	21.10	550	5.5	690		

C – heavy low thinning (C grade according to German forestry research institutes from 1902); H – free crown thinning according to Štefančík (1984) principles, thinning interval of 4 or 5 years; H2 – free crown thinning according to Štefančík (1984) principles, thinning interval of 10 years; I, II, III, IV – free crown thinning according to Štefančík (1984) principles, thinning interval of 5 years; 0 – control plot (no thinning)

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RESULTS

The linear correlation between age and slenderness (*h*/DBH ratio) showed the lowest values for subplots with the crown thinning (Figure 2) applied, where this dependence was also the closest (R = 0.572). Higher values of slenderness (not favourable results) were found for the low thinning and the control subplot. Regardless of the management regime, the values of the slenderness quotient decreased with age, while the differences between the two subplots with different tending and the control were significant ($P < 0.05$).

The relation between age and crown width is presented in Figure 3. We found the closest correlation on subplots with the crown thinning (R = 0.705) and the lowest again on the control subplots (R = 0.432). With increasing age, the crown width also increased. The highest values of the crown width were found in the subplot with crown thinning. The crown width was lower for the subplot with the low thinning applied and the control subplot, in comparison with subplot where crown thinning was applied. The differences between the subplots were significant ($P < 0.05$).

The bigger agreement was found between the stand age and the crown length (Figure 4). The coefficient of determination was (R^2 = 0.406) for the control subplot, (R^2 = 0.515) for the low thinning and (R^2 = 0.547) for the subplot with the crown thinning. The longest crowns occurred in the subplot with the low thinning, or more precisely, the shortest were found on the control subplots. The differences between both were significant ($P < 0.05$).

We found the smallest correlation between age and the crown proportion of the tree height (crown ratio) (Figure 5). There were also the smallest differences between the compared management methods. The differences among the subplots with different thinnings were insignificant ($P > 0.05$), but significant between the control subplot and the subplots with tending ($P < 0.05$). The crown ratio was again the highest in the subplots with the performed crown thinning.

DISCUSSION

When comparing the slenderness values, the lowest were found in the subplot with the crown thinning, from the age of approximately 50 to 60 years, in comparison with the control and/or low thinning subplot. This suggests that the effect of tending manifested with delay, after several interventions. However, it is necessary to take into account that the tending did not begin until the age of

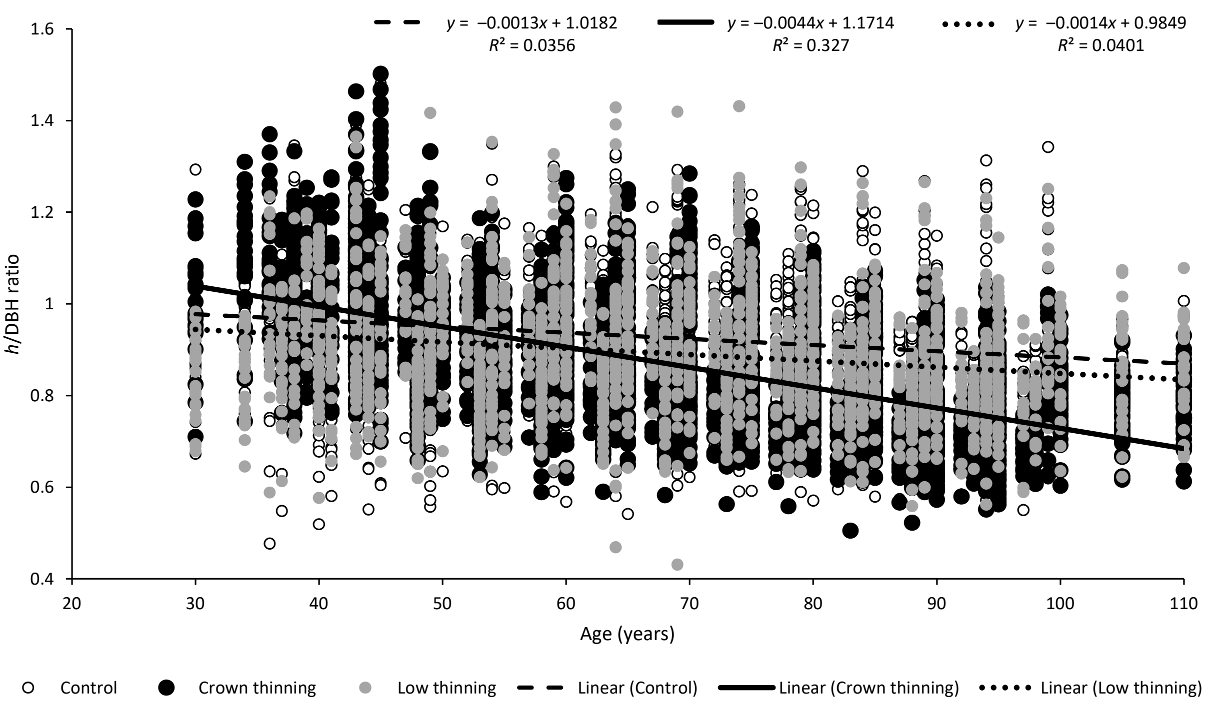

Figure 2. Relationship between stand age and slenderness ratio

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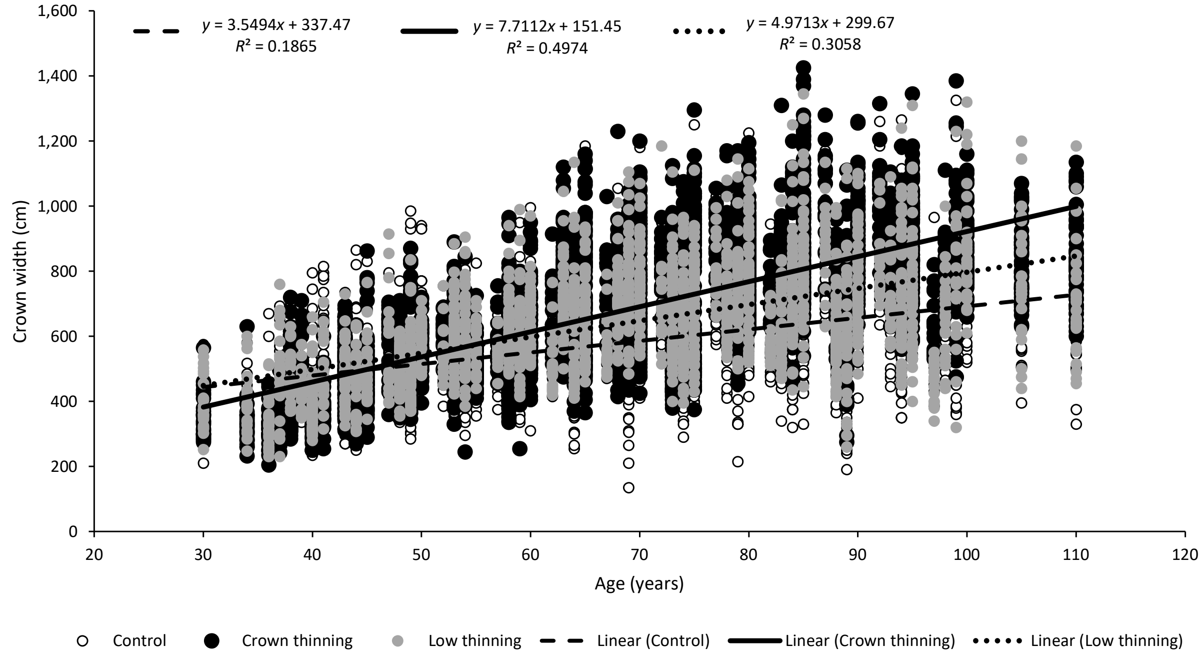

Figure 3. Relationship between stand age and crown width

30–45 years (with the exception for LTRP Ciganka). Until then, no interventions were performed on all subplots. The effect of interventions was positive after approximately 20–30 years of systematic tending. The equations of linear correlation showed that in the assumed rotation age of 100 years, the values of the slenderness quotient in the control subplot would be 0.89, 0.73 in the subplot with crown thinning and 0.84 in the subplot with the low thinning. These values are consistent with the findings of Dudzinska, Tomusiak (2000), who analysed 560 beech trees between 36 and 134 years of age, with average values

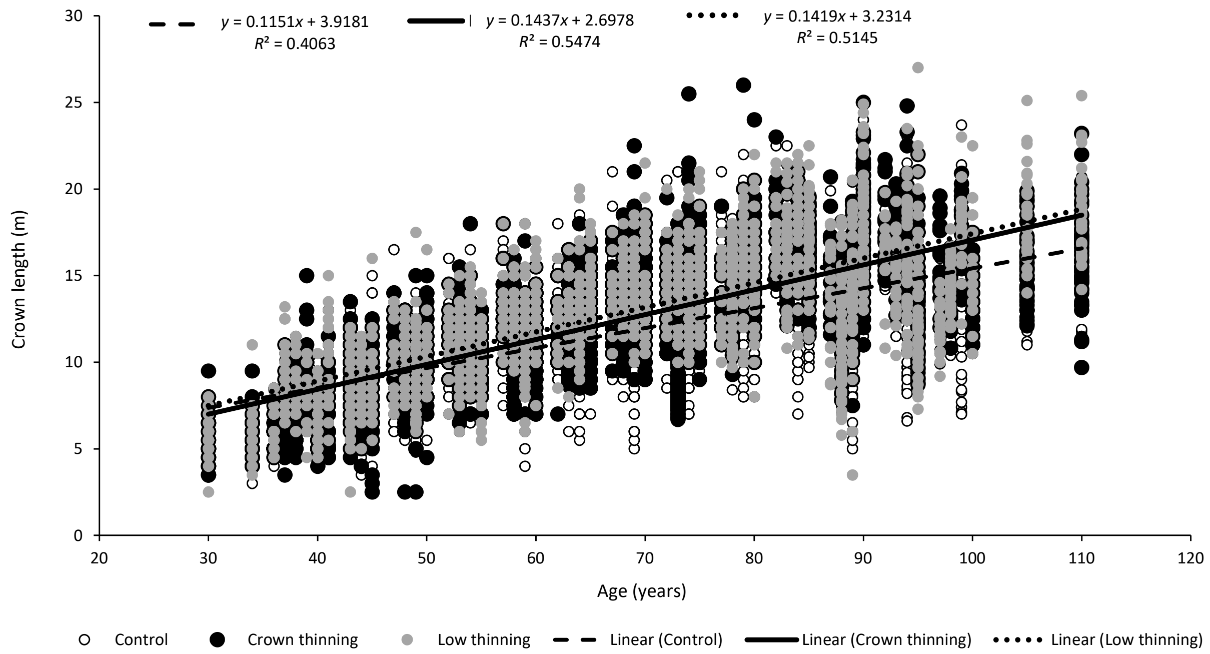

Figure 4. Relationship between stand age and crown length

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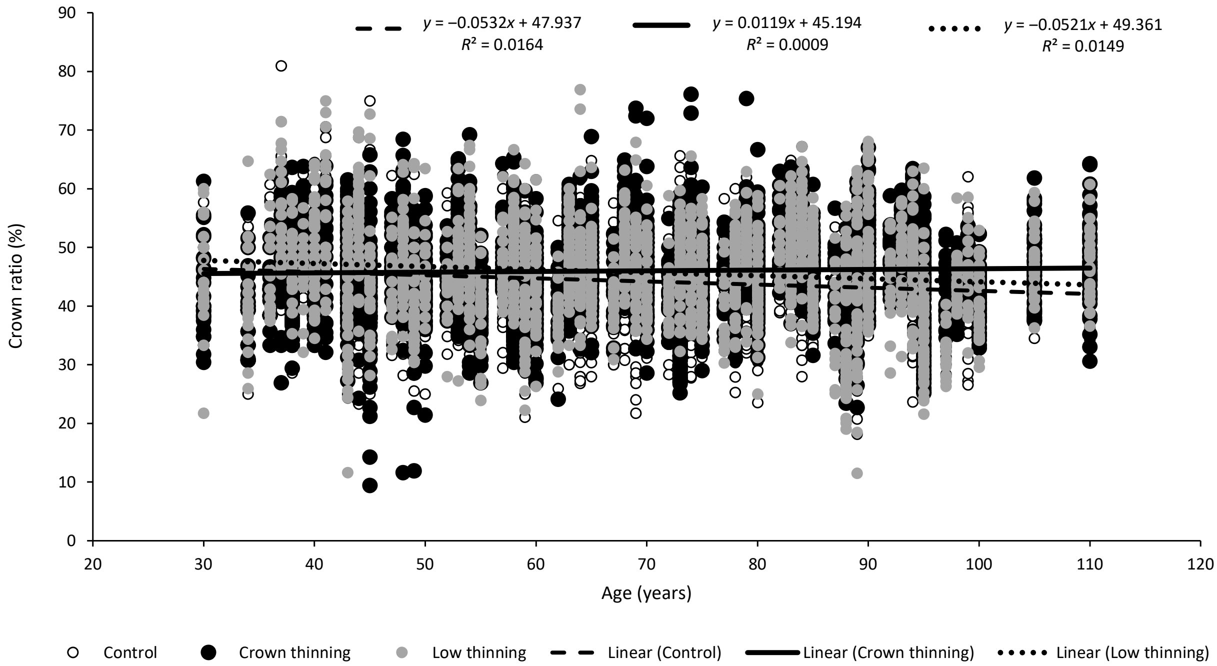

Figure 5. Relationship between stand age and crown ratio

ranging from 0.70 to 1.27. Konôpka et al. (1987) investigated the course of values of the slenderness depending on the stand age and site index. For beech at the age of 100, they state values of 0.88 and 0.94 for the site index 24 and 30, which corresponds to our data for the control subplot.

The mechanic stability of a tree is influenced by several factors such as DBH and crown size (Hemery et al. 2005; Sharma et al. 2016a, 2017a, 2018), stand density and competition of neighbouring trees (Pretzsch 2009; Sharma et al. 2016b, 2019a), as well as crown shape and the area of assimilatory organs (Poleno 1984). Due to decreasing number of trees with increasing age, the tree crowns are growing. As expected, we found the largest width of the crowns on the subplot with the crown thinning. It is related to the method of stand management. Namely, during the low thinning, the crown level of the stand was practically untouched, so that the tree crowns developed without any intentional help. On the contrary, on subplots with the crown thinning, crowns of trees at crown stand level were regularly released by each intervention. It was a positive intervention in the crown level, which removed especially the competitors of the target trees. The equations of linear correlation showed that at the rotation age of 100 years, the crown width would be 6.9 m in the control subplot, and 8.0 meters in the subplot with the low thinning applied. According to the silvicultural models of beech stands developed in Slovakia in the past, and/or at the beginning of the research (Štefančík 1984), the achievement of such crown width was assumed at the age of 110–130 years. However, after about 50 years of research (according to the linear dependence we described), it turned out that the model width of the crown of 8.0 meters can be achieved in the subplot with crown thinning already at the age of 85 years. The reason is systematic and long-term tending through crown thinning. The possibility of shortening the rotation age of beech stands to the age of 80–90 years was also confirmed by the quantitative production (basal area, merchantable volume) of beech stands in the stated age on these research subplots (Štefančík 2015).

The crown length on both subplots with different tending was very similar, but significantly different from the control subplots. The highest crown length in the subplot with low thinning is related to the stand structure, which is levelled in height due to the missing suppressed level of the stand, as well as the lowest number of trees (Pretzsch 2005; Štefančík 2015; Štefančík et al. 2018; Sharma et al. 2019b). This creates sufficient space and light conditions for the length growth of the crown. With crown thinning, especially «free-crown thinning»,

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the suppressed components are also positively supported (Štefančík 1984a), which improves natural pruning of stems, and/or shortens the length of crowns. The smallest crown length found in the control subplot is related both to their smallest size (width), due to the absence of interventions, and also to the highest stand density on control subplots (Assmann 1968; Pretzsch 2005; Štefančík 2015). At the age of 100, the crown length reached 15.4 m on control subplots, while in both subplots with different tending it was about 2 meters more (17.1 and 17.4 m). This corresponds to half the upper height of trees at a given (rotation) age, depending on the site index of the location (Halaj et al. 1987) and also the method of tending (Štefančík 2015). This statement was more or less confirmed by the values of the crown ratio to the height of the tree, which reached 46.4% in the subplot with crown thinning at the age of 100 years.

CONCLUSION

Comparison of selected parameters of mechanic stability of pure beech stands managed by different regimes (aged 30 to 110 years) confirmed the differences after long-term monitoring (35 to 58 years). Out of the monitored parameters, the strongest dependence manifested itself between age and crown parameters (width and length). We found the weakest dependence between age and the crown ratio to the tree height. Comparison of all monitored parameters showed the most favourable values for subplots managed by free-crown thinning, in comparison with heavy low thinning and the subplot without interventions. The differences between the managed subplots (regardless of the method) and the control subplots were always significant ($P < 0.05$). Based on the results as well as the ongoing long-term research of quantitative and qualitative production in these subplots, the best results can be stated for long-term and systematic tending by the crown thinning.

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