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Crown development of beech crop trees under different thinning regimes

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Abstract

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Crop trees are the main bearers of qualitative and value production of the stands. Although the number and production of the mentioned trees are affected by various factors, crown development by means of the thinning regime can be considered as very significant. The paper aims at the comparison of crop trees in homogeneous beech (*Fagus sylvatica* Linnaeus) stands, which were managed by three different management or thinning regimes for a long period (ca. 50 years): (*i*) heavy thinning from below (C grade according to the German forest research institutes released in 1902), (*ii*) Štefančík's free crown thinning, (*iii*) without interventions (control). Selection of crop trees was carried out at the beginning of research using the best stem quality, diameter and height dimension and regular spacing). In this paper only the last assessment of crop trees aged from 83 to 105 years including 23 subplots established across the Slovakian territory was analysed. The highest number of crop trees has been reached in forests where Štefančík's free crown thinning was applied. The proportion of these trees on subplots with the mentioned type of crown thinning was 61% out of the basal area at stand age of 100 years. A much lower proportion was found on subplots managed by thinning from below (32%) and on control ones (20%). Crown parameters (crown width, crown ratio, crown projection area, crown surface area and volume) showed the most appropriate values on subplots where Štefančík's free crown thinning was used. It was: 8.36 m (crown width), 0.50 (crown ratio), 56.84 m^2 (crown projection area), 289.56 m^2 (crown surface area), and 481.75 m^3 (volume). Based on the results obtained after almost 50 years of systematic investigations, the mentioned thinning method was recommended for beech forests.

Keywords: target trees; crown parameters; *Fagus sylvatica* Linnaeus; tending

The tree crown is a bearer of assimilatory organs determining the growth processes of each individual through photosynthesis. Crown size, being closely related to the photosynthetic capacity of a tree, is an important parameter in studies of the growth of individual trees (Hemery et al. 2005; Pretzsch 2009). Therefore, it is considered as one of the most important traits that affect tree radial growth (Assmann 1968), but it remains unclear how (anthropogenic) disturbance intensity affects crown size-radial growth relationships (Pretzsch 2009; Fichtner et al. 2013). Hence, measurement of the crown dimensions is often done for understanding and quantification of the tree growth (Korhonen et al. 2006). Moreover, the utilization of growing (available) space in a stand depends on the crown size (dimensions) and its increment (Utschig 2002; Vacek et al. 2013). Consequently, the competitive environment of a tree strongly affects its crown dimensions and architecture (Schröter et al. 2012).

Crown size depends on many stand factors affecting it (tree species, age, site, species composition, competition, management system, etc.).

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Schröter et al. (2012) concluded that crowns of older beech trees have a high ability to plastically respond to changes in the local canopy conditions, enabling very effective exploitation of canopy space. Beech crowns are able to promptly react to changes in light conditions and environment (Pretzsch, Schütze 2009). On the contrary, Longuetaud et al. (2013) found that *Fagus sylvatica* Linnaeus showed indicating low plasticity and suggesting a strong competitive ability. Schröter et al. (2012) also demonstrated that the position and distance of neighbouring trees were more important than the neighbouring tree size. Current tree crowns are a result of past interactions and long-term response to neighbour competition (Oliver, Larson 1996; Pretzsch 2009; Thorpe et al. 2010; Sharma et al. 2016).

The crowns of beech trees showed strong morphological plasticity in seedlings (Barbeito et al. 2014) and also in old-growth forest (Schröter et al. 2012; Vacek et al. 2013). Consequently, a higher phenotypic plasticity than in other tree species (Pretzsch, Schütze 2005, 2009; Vincent, Harja 2007) was found. However, the plasticity of beech can also be affected by genotype (Gömöry et al. 1998; Schröter et al. 2012) or by abiotic conditions (Lang et al. 2010). Morphological beech plasticity in pure and mixed-species stands was also studied by Woodcock et al. (1995), Dieler and Pretzsch (2013) and by Sharma et al. (2016) for various stand structures. Pretzsch (2014) reviewed how crown morphology and canopy structure in mixed stands can differ from pure stands and how this depends on the selection of tree species and interactions between them.

Different crown parameters (crown width and length, crown surface area, crown volume, crown projection area, crown index, etc.) and their relation to other tree parameters such as DBH or radial increment (Chroust 1972; Suri 1975; Poleno 1984; Hemery et al. 2005), basal area increment (Bartelink 1997; Fichtner et al. 2013), volume increment (Grossmann 1963; Chroust 1972), amount of foliage (Burger 1940), density and tree proportion (Barbeito et al. 2014), production of stemwood (Kuuluvainen 1988), and also to assessment of mortality (Monserud, Sterba 1999), wind firmness (Peltola et al. 2000) and growing space (Utschig 2002) were most frequently analysed. To sum up, crown parameters affected the mentioned tree and stand characteristics. However, Magin (1959) made a sceptical statement about crown's influence on tree increment. This author stated that it is only around 50% and thus the increment prognosis by crown's external characteristics is a mere speculation.

As the crown size strongly correlates with the tree growth, crown projection measurements are often used for model development (Hasenauer, Monserud 1996; Korhonen et al. 2006; Sharma et al. 2016). These models serve as an important tool for forestry decision-making (Pretzsch 2009). An individual-tree growth model was built by Pouderoux et al. (2001), using ecophysiological assumptions, not only stem and crown parameters. At the same time, the authors analysed crown efficiency, which was considered as a macroscopic parameter obtained as a combination of several elementary ecophysiological parameters (photosynthetic efficiency, respiration coefficients etc.). The developed model was applied in a thinning experiment and it was found out that thinning directly increases crown efficiency; canopy closure and climatic fluctuations lead to a large difference in crown efficiency between successive periods.

All the works investigated different crown parameters (crown width, crown length, crown area surface, crown volume etc.) in certain stand parts or selected individuals. Only few works analysed crop tree crowns for a longer period and in a detail. Therefore, in this study, I focus on an analysis of the crown of crop trees in pure beech stands, which were managed by different thinning methods during a long period (over 50 years). The objective of this paper was to compare selected crown parameters of crop trees in the stands managed by different thinning regimes during a long period. It was hypothesized that stands with different long-term thinning regimes are characterized by different crown development of crop trees.

MATERIAL AND METHODS

Site description. The study was conducted in European beech stands in the Western Carpathian Mountains situated in the Central and Eastern part of the Slovak Republic. The beech stands originated from natural regeneration. No tending interventions were performed in the forests until the beginning of research. The research sites lie mostly in a submountain vegetation belt in an elevation range from 250 to 700 m a.s.l. The growing season ranges from 130 to 165 days and snow cover from 60 to 100 days. Andesite parent rock and flysch sandstone are dominant. The study area comprises pure beech forests characterized by *Fagetum pauper*, *Fagetum*

Table 1. Site characteristics of long-term research plots in beech stands included in the analysis

Long-term research plot/subplot	Number of measurements	First/last measurement	Age span (yr)	Geographic position		Elevation (m a.s.l.)	Mean annual temperature (°C)	Mean annual precipitation (mm)	Soil unit
				north latitude	east longitude				
Jalna/C, H, 0	12	1959/2012	36–89	48°33'	18°57'	610	6.2	800	Eutric Cambisol
Konus/C, H, 0	12	1961/2014	30–83	48°47'	22°18'	510	6.5	900	
Kalsa/C, H, 0	12	1961/2014	37–90	48°35'	21°29'	520	6.0	790	Stagni-Eutric Cambisol
Kalsa/H2	10	1969/2014	45–90	48°35'	21°29'	520	6.0	790	
Zalobin/C, H, 0	12	1962/2015	39–92	48°59'	21°44'	250	7.9	660	
Zlata Idka/C,H,0	12	1960/2013	40–93	48°44'	21°01'	700	6.7	780	Haplic Cambisol (Dystric)
Ciganka/C, H, H2, 0	10	1967/2012	60–105	48°46'	20°05'	560	5.5	918	
Lukov/H, 0	11	1962/2011	45–94	49°17'	21°06'	550	5.5	690	
Lukov/C	10	1966/2011	49–94	49°17'	21°06'	550	5.5	690	

C – heavy thinning from below (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, 0 – control plot (no thinning)

typicum, *Fageto-abietinum*, and *Querceto-Fagetum* forest type groups (Zlatník 1976).

Sampling and measurements. Twenty-three long-term research subplots (LTRPs) at seven localities (called hereinafter as "series" of subplots) across Slovakia were established by Prof. Dr. L. Štefančík in 1959–1969. These subplots represented homogeneous (even-aged) naturally regenerated beech forests in Slovakia. At the time of their establishment, the forests were in the growth stage from small pole to pole timber. Table 1 shows basic LTRPs site characteristics and their location in Slovakia (Fig. 1).

The above-mentioned series of LTRPs consisted of 3 to 5 subplots (mostly three), 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 DBH ≥ 3.6 cm and/or trees which reached this threshold during the measurements were numbered on all subplots.

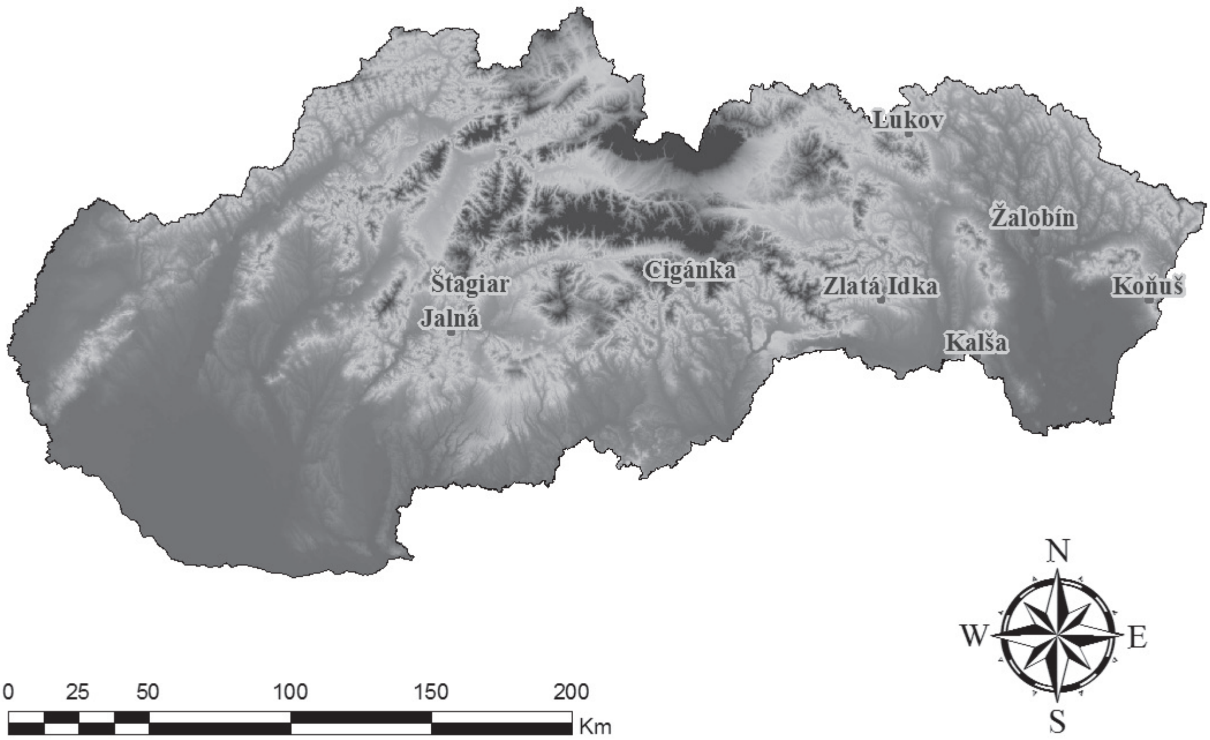

Fig. 1. Location of the series of long-term research plots in pure beech stands in Slovakia

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

Apart from DBH measurement, tree height, crown base and crown radius (four radius readings taken in the northern, eastern, southern and western directions) were measured in crop trees.

However, crop trees were usually dominant or co-dominant trees in the canopy layer – classes 1 and 2 according to Kraft (1884). These trees were selected at the first measurement and re-assessed every 4–5 years according to the same mentioned criteria on each subplot. When the crop tree lost the above-mentioned position or presented criteria, hence it was cancelled. Competing trees (on tended subplots only) were marked and cut in the same years. Totally, from 10 to 12 measurements and crop tree re-assessments have been performed up to now.

Data processing and statistical analyses. Only the last assessment of crop trees aged from 83 to 105 years was analysed. Crown width, crown length, slenderness quotient, crown ratio (crown length to tree height), crown projection area and crown surface area (hereafter crown area), crown volume and basal area were derived. Based on four crown radii, the crown width (CW) was calculated (Eq. 1):

$$CW = \frac{\sum CR_{1-4}}{2} \quad (1)$$

where:
CR – crown radius.

Crown length was defined as the vertical distance from the crown base to the top of the crown. Slenderness quotient represents tree height and DBH ratio. The hundred largest trees (with the largest DBH) per hectare were selected to calculate slenderness quotient (*h*/DBH ratio). Crown projection area (using the formula for a circle) and crown surface area (CA) were calculated as Eq. 2 (Kramer 1988; Fichtner et al. 2013):

$$CA = \pi CR / 6CL^2 \left[\left(4CL^2 - CR^2 \right)^{3/2} - CR^3 \right] \quad (2)$$

where:
CL – crown length.

Crown volume (CV) was calculated as Eq. 3 (Assmann 1968) for broadleaved tree species:

$$CV = \pi / 12 \left(CW^2 CL \right) \quad (3)$$

where:
CW – crown width.

To make it simpler for further statistical analyses, for the type "crown thinning" we grouped the subplots with 5- or 10-year thinning interval into 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 3.1, 2008) (Kupka 2008) was used.

RESULTS

The measured and derived growth characteristics of crop trees (Table 2) showed the most appropriate values for stands managed by crown thinning. The proportion of these trees on subplots with the above-mentioned type of thinning was 61% out of the basal area at stand age of 100 years. A much lower proportion was found on subplots managed by thinning from below (32%) and on control ones (20%). Consequently, crown parameters (crown width, crown ratio, crown projection area, crown surface and volume) also showed the best values on the subplots with crown thinning.

Fig. 2a illustrates the relationship between DBH and crop tree crown width. The narrowest linear regression was found on control subplots (r^2 = 0.737) and the lowest on subplots with crown thinning (r^2 = 0.574). Crown width increased with the increasing DBH. The highest values of crown width for all the crop tree diameters were recorded on subplots with crown thinning. The control and the subplots with thinning from below actually showed the same linear dependence, but their crown width was always smaller in comparison with crown thinning.

A much weaker dependence was manifested between DBH and crop tree crown length (Fig. 2b). The coefficient of determination (r^2) varied from 0.274 to 0.359. The longest crowns of crop trees occurred on the subplot with thinning from below.

Table 2. Characteristics of crop trees after long-term (45–53 years) investigation

Characteristic	Statistics [mean (coefficient of variation)]		
	control	thinning	
		crown	low
No. of sample crop trees	133	284	155
No. of sample crop trees per plot	19 (43.85)	41 (37.24)	23 (42.53)
No. of crop trees per hectare (stems·ha^{-1})	79 (43.18)	133 (27.65)	92 (40.66)
Basal area per hectare (m^2·ha^{-1})	9.23 (45.58)	20.50 (21.15)	12.66 (23.84)
Tree age (yr)	92.77 (7.55)	93.52 (7.64)	91.81 (6.68)
DBH (cm)	37.74 (18.11)	44.37 (14.63)	41.06 (17.27)
Height (m)	32.44 (9.90)	33.10 (9.06)	34.04 (10.75)
Stem slenderness	0.88 (12.23)	0.76 (11.42)	0.84 (13.06)
Crown width (m)	6.29 (24.10)	8.36 (19.02)	7.06 (23.57)
Crown length (m)	15.32 (18.17)	16.47 (16.38)	16.48 (18.91)
Crown ratio	0.47 (14.32)	0.50 (12.97)	0.48 (15.64)
Crown surface area (m^2)	203.24 (34.83)	289.56 (30.46)	245.03 (35.85)
Crown projection area (m^2)	32.84 (50.11)	56.84 (38.77)	41.28 (48.54)
Crown volume (m^3)	260.28 (59.52)	481.75 (48.97)	351.04 (60.00)

The values of crop tree crown length on control subplots were higher than the values on subplots with crown thinning up to the DBH of 55 cm.

The curve of the linear relationship between DBH and slenderness quotient (h/DBH ratio) confirmed the most favourable values for crown thinning (Fig. 2c). At the same time, this dependence was tightest on control subplots again (r^2 = 0.677). The least favourable values for all DBH were found at thinning from below. It is interesting that the values of slenderness quotient on control subplots decreased with the increasing tree diameter up to $d_{1,3}$ = 58 cm, when they were balanced with crown thinning (0.61).

The weakest relationship was revealed between DBH and crown ratio (Fig. 2d). Here, the smallest differences in comparison with tending and/or management systems were found. From the DBH of 45 cm, the crown constituted at least half of the tree height, regardless of the management system.

On the contrary, one of the strongest linear dependences was found out between DBH and crop tree crown surface area (Fig. 2e). Again, the coefficient of determination was highest on control subplots (r^2 = 0.750) and lowest on subplots with crown thinning (r^2 = 0.631). Up to the DBH of 30 cm, the crown surface area of crop trees was practically the same for all management systems. Later, from that diameter, the differences commenced to show in favour of subplots with crown thinning. This thinning method was also the best from the aspect of the relationship between DBH and crown projection area (Fig. 2f), or DBH and crown volume (Fig. 2g). Here, more distinctive differences started to be evident from the DBH of 34 cm. The coefficient of determination was always highest on control subplots (r^2 = 0.726 and 0.758) and lowest on subplots with crown thinning (r^2 = 0.552 and 0.613).

DISCUSSION

A relationship between DBH and crown size is the most frequently investigated dependence (Hemery et al. 2005; Sharma et al. 2016), and at the same time it is affected by many factors. Besides the neighbourhood competition (Pretzsch 2009; Thorpe et al. 2010; Sharma et al. 2016), crown shape and the area of assimilatory organs also matter (Poleno 1984). Within our experiment dissimilarity in the studied regimes became evident also for these parameters. Crop trees were selected according to strictly defined criteria at the age between 40 to 60 years, (after two or three interventions; except for the control subplot) and those published by Štefančík (1984) – stem quality, stem and crown dimension and spacing. Regarding the crown shape, trees with the continuous type of crown were selected as these are the most suitable from the morphological point of view (Vacek 1987; Woodcock et al. 1995; Dassot et al. 2015). When conducting thinning from below, the crown level remained unaffected. Thus crop tree crowns developed without any intentional assistance. On the contrary, crowns on subplots with crown thinning were regularly liberated. Subsequently, crown plasticity enabled the canopy to occupy a higher space and to reduce overlaps between neighbouring crowns (Longuetaud et al. 2013). It was a positive crown level intervention with the aim to eliminate the competitive trees. Consequently, the highest values of investigated crown parameters (crown width, crown surface area, crown projection area and crown volume) were found at crown thinning. At the same time, the values of DBH and basal area increment were the highest by application of this method (Štefančík 2015).

Most authors investigated the significant dependence between DBH and crown size (Hemery et al. 2005; Pretzsch 2009; Sharma et al. 2016). It is necessary to point out that the crown size must be optimal as Guericke (2002) confirmed. He stated that beeches with medium-sized crowns showed more efficient productivity than trees with extremely large crowns. According to Sterba (1999),

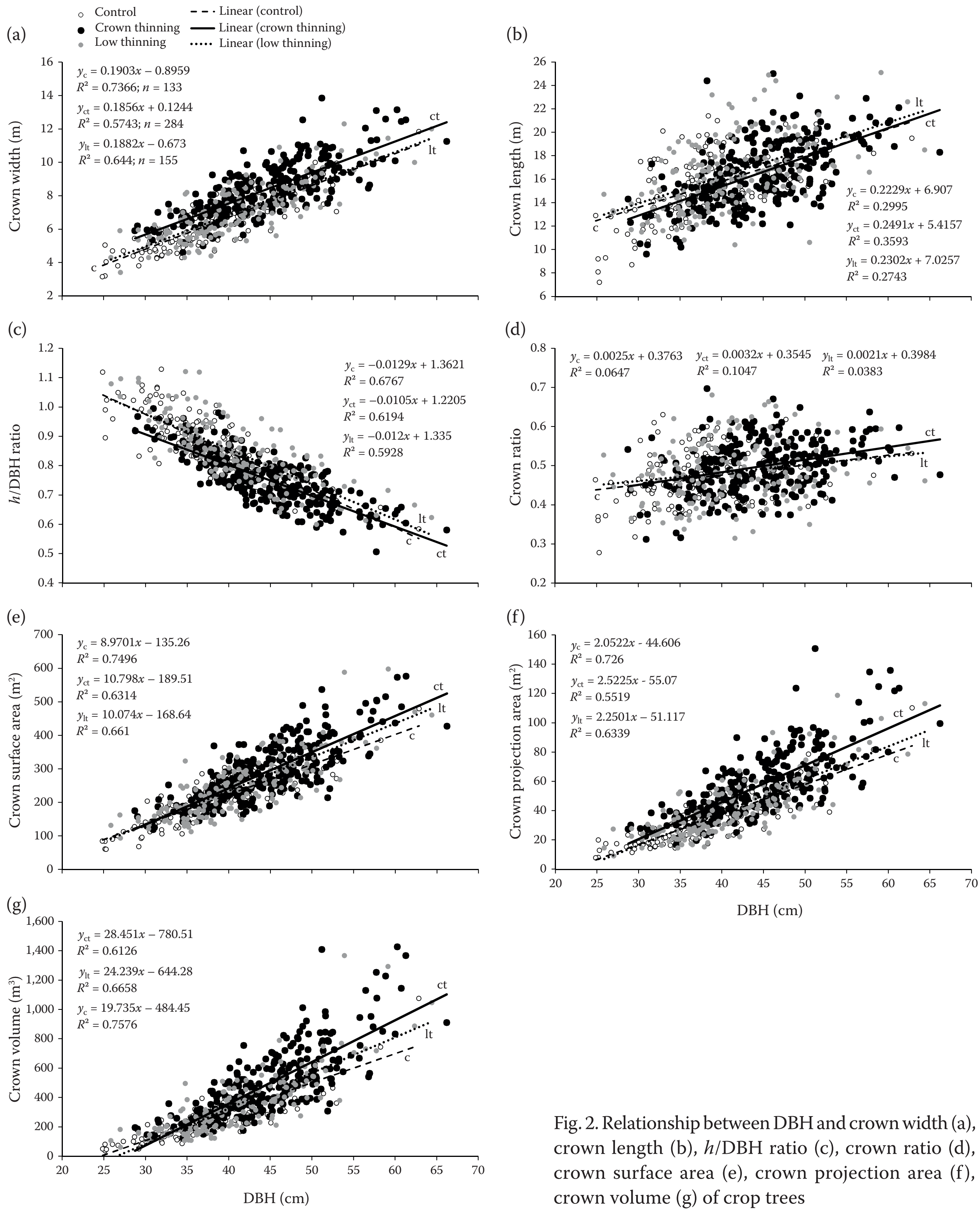

Fig. 2. Relationship between DBH and crown width (a), crown length (b), *h*/DBH ratio (c), crown ratio (d), crown surface area (e), crown projection area (f), crown volume (g) of crop trees

small trees with long crowns were able to occupy relatively more space in the period after thinning than taller trees with smaller crowns.

A weak regression dependence was ascertained between DBH and crown length and crown ratio. It is connected with the vertical stand structure, which fundamentally differentiates. Contrary to our results, Bartelink (1997) found that crown length appeared to be strongly correlated with stem basal area (r^2 = 0.89). In our experiment controls and subplots with crown thinning have similar structure regarding the proportion of suppressed individuals (Štefančík 2015). These individuals, however, are completely absent on subplots with thinning from below, where the lowest number of trees was found (Bosela et al. 2016). Light conditions inside the crown level (Pretzsch 2009), which are probably the best on subplots with thinning from below, relate to the previous fact. The highest values of crown lengths prove this statement for this tending method. In contrast, crown length and crown ratio were most sensitive to disturbance intensity with significantly lower values in unmanaged stands, even after short-term abandonment of forest management (Fichtner et al. 2013).

Podlaski (2006) investigated the relationship between crown characteristics and the radial increment of beech in a national park in Poland. The radial increment of beech increases as the degree of liberation of the light-exposed part of the crown from neighbouring trees increases. And the increase in the relative crown length causes a significant increase in the radial increment. Most of the best growing beech trees are characterized by the light part of the crown confined in an area of up to about 55%, and the relative crown length spanning the range from 55 (trees 61 to 80 years) to 76% (trees 21 to 40 years).

Crop trees also create a skeleton of the static stability of each stand. Within our experiment, it is supported by their parameters, namely by their slenderness quotient (*h*/DBH ratio). Trees with the higher above-mentioned quotient are more prone to external damage (snow and wind) than trees with the lower slenderness quotient (Slodičák, Novák 2006; Sharma et al. 2016). The influence of *h*/DBH ratio on tree stability is expected to be lower for broadleaved tree species as compared to conifers (Vospernik et al. 2010). Simultaneously, trees with the lower value of this ratio are expected to have a larger crown size (Sharma et al. 2016). It was also confirmed by our experiment, when crown width, crown volume and crown surface area in stands with crown thinning were higher compared to those with crown thinning, as well as to the control. The value of slenderness quotient was 0.7 at the DBH of 50 cm on subplots with crown level tending. Favourable values of slenderness quotient were also achieved by other management systems. It is in compliance with findings by Dudzinska and Tomusiak (2000). These authors analysed 560 beeches at the age from 36 to 134 years and average values varied from 0.70 to 1.27. Much larger experimental material consisting of 4,854 beech trees was analysed by Sharma et al. (2016) with the mean value of height to DBH ratio 0.8. However, to ensure the stability, the number of crop trees per hectare is also important and their more or less regular spacing. The highest number of crop trees was recorded at the crown thinning system (on average 133 trees per hectare) and the lowest on control plots (79 trees per hectare). If we consider the triangular arrangement (Assmann 1968), crop tree average spacing would be 9.3 and/or 12.1 m on the control subplot. The average crown width (radial distance between stems) was 8.4 m on subplots with crown thinning, whereas only 6.3 m on control subplots. It follows that crop tree crowns would create a complete crown canopy only on a subplot managed by crown thinning. For comparison, Schröter et al. (2012) presented the mean value of crown radii 5.5 m, i.e. 11 m of crown width. These values are higher in comparison with results of our experiment due to the much older beech stand at the age from 180 to 240 years. It was proved that crown size and/or crown plasticity is predominantly influenced by competition (Dieler, Pretzsch 2013; Longuetaud et al. 2013; Barbeito et al. 2014).

The age at which the above-mentioned parameters are achievable should be considered as another important factor. It is known that older beech stands (over 100 years) suffer from false heart more intensively (Račko, Čunderlík 2011). It considerably decreases their value production. To avoid this, an effort to shorten a rotation period is necessary (Dhôte 1997). Besides the stem quality, the stem dimension is also decisive for achieving the highest value production. According to the Slovak Technical Standard (STN 48 0056) "Qualitative Assortment of Hardwood Timber" effective in Slovakia, the minimum stem diameter is 45 cm. This is possible to achieve at the stand age of 90 to 95 years (Štefančík 2015) on subplots with long-term and systematic tending by the crown thinning method.

If we assume that the annual radial increment is 0.5 mm, the stem dimension of 60 cm would be achieved not later than within 120 to 125 years. In the case of higher increment, it would be earlier (less than 100 years), which corresponds with our assumptions (Štefančík 2015). It is much earlier than Utschig and Küsters (2003) stated that it is nearly impossible to reach the crop diameter of 60 cm within a rotation time of 140 years.

CONCLUSIONS

It was hypothesized that stands with different long-term thinning regimes are characterized by different crown development of crop trees. After a long-term investigation (more than 45 years), the analysis of the results of crop tree crown development (at the age from 83 to 105 years) confirmed differences. The strongest dependence was found between DBH and crown width (r^2 = 0.574 to 0.737), slenderness quotient (r^2 = 0.593 to 0.677), crown surface area (r^2 = 0.631 to 0.750), crown projection area (r^2 = 0.552 to 0.726) and crown volume (r^2 = 0.613 to 0.758). A weak relationship was found out between DBH and crown length (r^2 = 0.274 to 0.359) and/or DBH and crown ratio (0.038 to 0.105). A comparison of the investigated parameters of crop tree crowns showed the most favourable values for crown thinning management compared to heavy thinning from below or without interventions. The above-mentioned method of thinning is recommended to the practice for management of pure beech stand. Apart from the best quality of stems which should be ensured by crop tree selection, a given dimension of 45 to 50 cm at the thicker end of the trunk is desirable. Based on our results, it can be stated that the above-mentioned dimension of crop beech trees is achievable in a shorter rotation period than 110 to 130 years, which is actually recommended under Slovak conditions. It can also be useful for the wood industry in order to decrease the risk of heart rot occurrence.

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