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Evaluation of the effect of different thinning types on dendrometric parameters and subsequent spontaneous growth in a beech-oak-linden stand

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Abstract: Due to an increasing risk of further damage to forests, forest managers are considering introducing an alternative direction for their future development – via the cultivation of mixed forests. At middle altitudes in the Czech Republic, an oak-beech-linden stand is the most natural type, and we tried to answer three main questions: (*i*) How the various thinning types affect dendrometric parameters and quality of the stand; (*ii*) How long thinning works on this stand until it loses its effect; (*iii*) How the stand develops spontaneously after abandonment. This experiment was conducted at the Training Forest Enterprise in the Czech Republic in Drahanská vrchovina (highlands in central Moravia). In 1988, four plots were established in a 49-year-old stand where, in three of the plots, different types of thinning (crown, low and heavy crown) were performed, leaving one (reference plot) to develop naturally. The height, the height of the crown base and diameter at breast height (*DBH*) were measured, and the shape and quality of the trunk and crown were estimated on each tree. Measurements were carried out in 1989, 1994, 1999, 2005, 2010, 2015, and 2020. In the first 10 years, the *DBH* and height of the crown base did not show any differences, and the linden at the heavy crown plot outgrew the linden trees at the other plots in height. After these 10 years, the thickest linden, the tallest beech and linden, and the greatest height of the crown base of beech and linden were all found at the heavy crown plot. The shape and quality of the trunks and crowns of beech, oak and linden were similar in all plots (including the reference plot) during the entire experiment. After thinning, the plots were left to grow spontaneously. The heavy crown thinning removed a greater number of thicker trees at the middle level, thus supporting the trees growing in the lower part of the middle level and in the below level (i.e. the beech and linden). These trees then grew more quickly compared to the others, but their quality decreased, as did that of the others. Therefore, a forest left to grow and develop spontaneously is practically unusable for commercial purposes.

Keywords: abandonment forest; diameter at breast height; *Fagus sylvatica*; height; mixed forest; quality of stem and crown; *Quercus petraea*; *Tilia cordata*

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Climate change brings a rapid increase in temperature and a very uneven distribution of precipitation throughout the year in the form of alternating torrential rain and long periods of drought. At present, these side effects are already visible and will undoubtedly be more significant in the future. However, forests (especially monocultures) cannot adapt quickly enough in such a short time, during which these side effects become worse, thus causing more suffering to the forest. Due to an increased frequency of damage observed and an increasing risk of further damage to the forest complex (Seidl et al. 2014), forest managers are considering introducing an alternative direction for the future development of the forests – via cultivation of mixed forests (Millar et al. 2007). There are many studies that support the idea that mixed forests prosper because they are more stable, resistant, and diverse, they provide better aesthetic values and opportunities for recreation, and last but not least they are more productive, compared to monocultures (Gamfeldt et al. 2013; Felton et al. 2016; Metz et al. 2016; Bauhus et al. 2017; Jactel et al. 2018; Heinrichs et al. 2019). Vertical and horizontal distribution of roots and crowns of individual species and the dynamics of their growth presumably decrease competitive pressure in water, nutrients and light in mixed stands (Lindén 2003; Hooper et al. 2005; Brooker et al. 2008). An insight into the spatial structure and mechanisms in mixed stands is offered in older studies (e.g. Kelty 1992; Olsthoorn et al. 1999), as well as in more recent ones (e.g. Liang et al. 2016; Pretzsch et al. 2017; Bravo-Oviedo et al. 2018).

Thinning is the most important operation of forest management for future development (Daume, Robertson 2000). The primary consequence of thinning is a drop in the number of trees in the stand (i.e. its density), due to which the subsequent growth of the remaining trees is affected (Tullus 2002; Zeide 2004). A decrease in the number of trees also occurs during spontaneous development of abandoned forests (Šebková et al. 2011; Badraghi et al. 2023). The main difference between spontaneous development of a forest and the development of a forest through targeted thinning is in the secondary consequence, i.e. the quality of a stand which is affected during thinning in two ways – by the elimination of: (*i*) qualitatively unsuitable trees; (*ii*) surrounding trees, which can negatively affect the growth of the target tree (Polanský 1955; Vyskot 1978).

The tree composition in a mixed forest can be influenced by thinning and, as a result, achieve the target composition (Pretzsch et al. 2021). There are dozens of types of thinning – differing in their intensity, purpose, position in the vertical profile of a stand, and the species for which they were intended. The main approach to sorting is low thinning, crown thinning and their combination (Kerr, Haufe 2011), and each type can have various intensities – light, medium and heavy (Tesař 1996). Almost all types of thinning were invented for monocultures (Polanský 1955; Vyskot 1962; Vyskot 1978), however, there are practically no general regulations for how to perform thinning in a mixed stand (Pretzsch et al. 2021). The reason is the difficulty of generalising the influence of thinning on individual species in a stand (Juodvalkis et al. 2005). In monoculture, only intraspecific competition takes place and, based on the knowledge of the influence of thinning on monoculture from the past few hundred years, the effect of thinning can be estimated. On the other hand, trees in a mixed forest are affected by interspecific competition (in addition to intraspecific), and therefore, the result of thinning can be completely different from the same one performed in a monoculture. Moreover, knowledge gained from thinning in mixed stands in past centuries is either limited or vaguely formulated. Thinning, which is carried out in mixed forests, is often derived according to the most frequently occurring (one) species in the stand and insufficiently takes into consideration the demands of others (Forrester 2014), like various demands on silvicultural space, growth periods, the required density, etc. (Mitscherlich 1970; Ammer 2008; Ducey et al. 2017; Juchheim et al. 2017).

However, thinning does not have a permanent effect. According to Juodvalkis et al. (2005), the first changes in dendrometric parameters do not become visible until one year after thinning, the peak of growth occurs after approx. 2–3 years, and the increments 7–8 years after thinning are as great as they would be in an un-thinned forest. Assmann (1961) already describes not only an intensive increase in the thickness within a short time after thinning, but also a gradual slowdown of growth because the trees are not able to maintain accelerated growth long-term. The reason for

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this phenomenon is an increase in the availability of light, water and nutrients immediately after thinning, and their reduction again by subsequent filling of the above-ground and below-ground layers by the remaining trees (Meinzer et al. 2011; Usta et al. 2019).

At first, the managed forests that were abandoned (intentionally or unintentionally) for decades are called 'secondary old-growth' (Piovesan et al. 2008; Ziaco et al. 2012), and are characterised by large quantities of dead wood and a frequent occurrence of large old trees – especially after many decades of spontaneous growth (Burrascano et al. 2013). It is generally believed that the natural mortality of trees is based mainly on competitive interactions that are related to stand density in unmanaged forests (Westoby 1984), and also on external factors, such as windstorms, biotic pests, fires, etc. (Vygodskaya et al. 2002). The thickness distribution in a natural forest has a typical inverse J-shaped curve, first described by DeLiocourt (1898), through mortality rates among diameter classes across the entire range of diameters (Hough 1932; Meyer 1952; Leak 1996; Cancino, Gadow 2002). However, in some cases, the thickness distribution can also have a normal distribution, which is typical for even-age stands (Vandekerkhove et al. 2005).

Regarding the cultivation of an oak-beech-linden stand, which is a type of mixed forest that seems to be the most natural at middle altitudes in the Czech Republic (CZ), we tried to answer three main questions: (*i*) How do the various thinning types affect dendrometric parameters and quality of the stand?; (*ii*) How long does thinning work on this stand until it loses its effect?; and (*iii*) How does the stand develop spontaneously after abandonment?

MATERIAL AND METHODS

Description of the research plot. This experiment was carried out at the University Forest Enterprise 'Masaryk Forest' in Křtiny (entire name abbreviated to UFE; 49°17'48.9"N, 16°44'30.2"E; Figure 1), which met the location criteria.

The study took place at an altitude of around 420 m a.s.l. The soil of the stand (established in 1940, 6.19 ha in size) was Cambisol, according to IUSS Working Group WRB (2015). The climate was humid continental (Köppen 1936), with a mean annual air temperature of 9.4 °C and a precipitation of 613 mm, according to the long-term normal between the years 1981–2010 (CHMI 2023). Characteristic parameters of the stand are entered in Table 1.

Description of the planting and cultivation method. The 6.17 ha stand was established in 1940. There were two-year-old saplings (all from UFE) planted in individual mixing (to achieve the best possible mixing). In this stand, the research plot was established in 1988 and divided into five sections, with 20-metre buffer zones (Figure 2; Table 2) around each section. The same thinning method (as inside the section) was applied, leaving the trees unmeasured. The buffer zone minimised the effect of external factors. For example, the total area (with

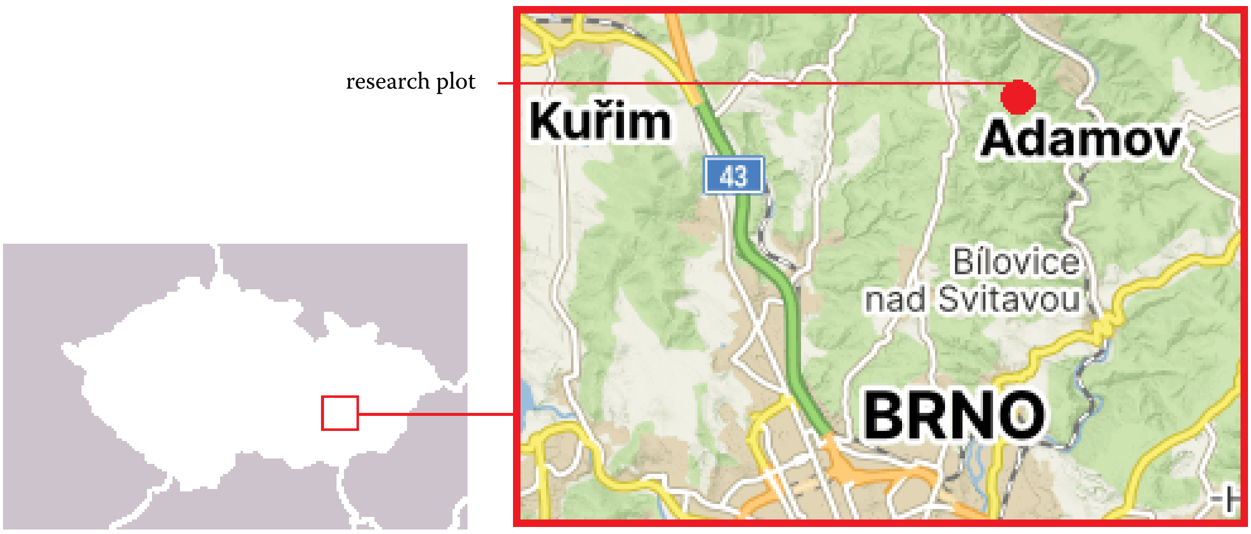

Figure 1. The location of the research plot

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Table 1. Characteristic parameters of the 80-year-old stand

Species	Species composition (%)	Mean *DBH* ± SD (cm)	Mean height ± SD (m)
Fagus sylvatica	50	17.8 ± 9.0	18.5 ± 9.4
Quercus petraea	40	21.8 ± 5.5	22.6 ± 10.4
Tilia cordata	10	15.9 ± 8.8	15.9 ± 6.4

DBH – diameter at breast height; SD – standard deviation

the buffer zone) of heavy crown plots was 0.36 ha; however, in order to reduce the risk of being influenced by external factors, the area on which trees were measured was reduced to 0.16 ha. In each section, the heights (*H*) and diameter at breast height (*DBH*) of all trees were measured, and individual types of thinning were carried out in the 1988–1989 winter, based on their histograms. Each of the remaining trees was marked with a unique number and a dot (1.3 m above ground). After thinning, this research plot was left abandoned for more than 35 years.

The crown thinning (CT) is carried out at the middle level and removes co-dominant trees (Figure 3; Polanský 1955; Vyskot 1962; Vyskot 1978). It was introduced for deciduous (mainly beech and oak) stands (Polanský 1955). The objective is to increase the production value of pre-selected target trees and the stability of each one (Vyskot 1962; Vyskot 1978). This is performed in such a way that one or two secondary trees at middle level (usually of low quality or insufficient thickness and height) are removed to favour target trees (i.e. thick trees at middle level with excellent down to good quality; Polanský 1955).

In low thinning (LT), the thinning intervention progresses from the lowest trees at below level up towards the middle level (Figure 3; Vyskot 1962), i.e. all suppressed, dying, dead and clearly overshadowed trees, and trees that push their tops into the middle level but cannot grow into it due to a lack of space (Polanský 1955). This improves the composition of the stand immediately after the intervention, it does not threaten the production of the stand, it does not actively interfere mainly in the middle level, and it releases the canopy, thus lengthening the crowns of level trees (Vyskot 1962). The outcome is usually a stand structure with only one homogeneous middle level (Vyskot 1962). The trees are then evenly distributed, they have a normally developed crown and a straight trunk (Polanský 1955).

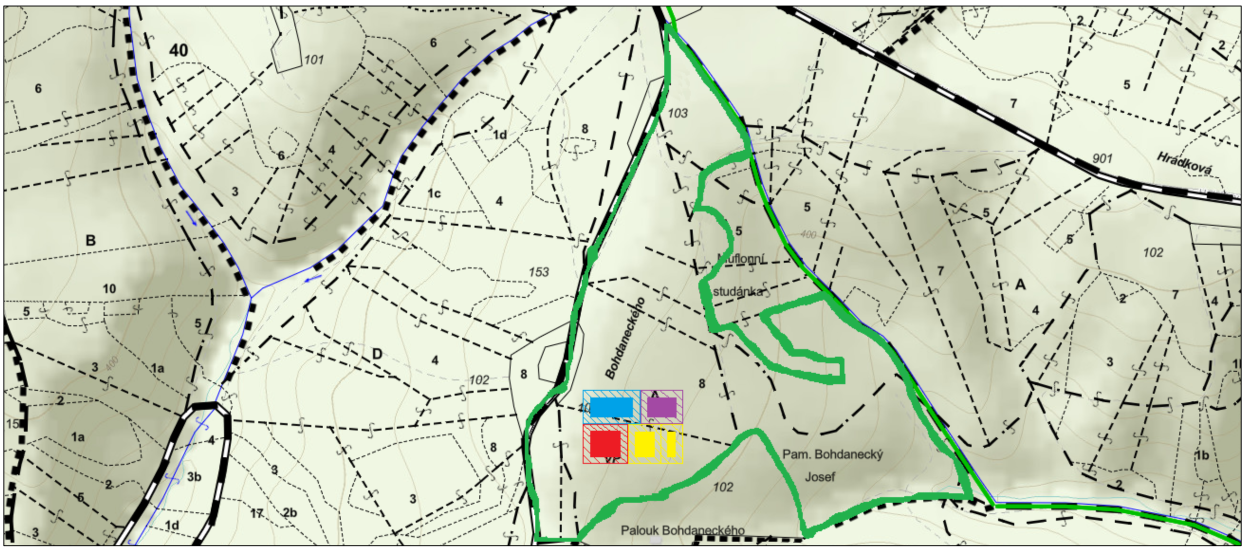

Figure 2. The location of the research plot in the stand

Green – border of the stand; red – low thinning; blue – crown thinning; yellow – reference plot; purple – heavy crown thinning; hatched – buffer zones

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Table 2. Characteristic parameters of the sections

Section	Thinning	Area (ha)	Area with buffer zone (ha)	Thinning intensity (%)
1st	crown thinning	0.22	0.46	26
2nd	low thinning	0.22	0.45	16
3rd	heavy crown thinning	0.16	0.36	34
4th	reference plot	0.25	0.64	0
5th	reference plot			

The thinning intensity was calculated based on the basal area before and after thinning

Heavy crown thinning (HCT) is heavy crown thinning conducted via negative selection in beech stands (Figure 3; Vyskot 1962). The objective of this type of thinning is to create suitable conditions for accelerating the growth of the remaining trees by removing the thickest trees in the stand (Tesař 1996). It is based on the methods proposed by Voropanov and Borggreve, who focused on supporting secondary trees growing at middle level but reaching smaller dimensions (Polanský 1955). According to Borggreve, all trees at above level should be removed and all the stronger (even those of a very high quality) trees at middle level should be harvested, provided that ingrowing and secondary trees replace those removed (Vyskot 1962). Voropanov proposed a method that works on the assumption that light is the only factor that can be regulated by logging and that the conditions of tree growth (i.e. moisture, heat and microbiology of the soil) can be changed at the same time (Polanský 1955). According to Voropanov, all strong trees at the middle and above level are removed, provided that ingrowing or shaded trees follow – according to light foci (Vyskot 1962). Vyskot defined heavy crown thinning (also named Voropanov-Borggreve thinning) by combining the Voropanov and Borggreve methods, in which the strongest level trees and all above level trees are removed, in order to provide more light to the secondary level, or even shaded or ingrown trees located in the below level, thereby accelerating their growth (Vyskot 1962).

The reference plot (RP) was left to grow freely, in order to have a comparison with the three types of thinning above (Figure 3).

Method of measurement. The measurement of *H*, the height of the crown base (*HCB*), the *DBH*, and selected parameters of Polanský's classification of tree classes (PC) was conducted on all trees in the plots in the autumn of 1989, 1994, 1999, 2005, 2010, 2015, and 2020. We calculated the tree composition of each plot according to the number of trees per plot and their basal area (taken from *DBH*). The cumulative height increment (*CHI*) and cumulative thickness increment (*CTI*)

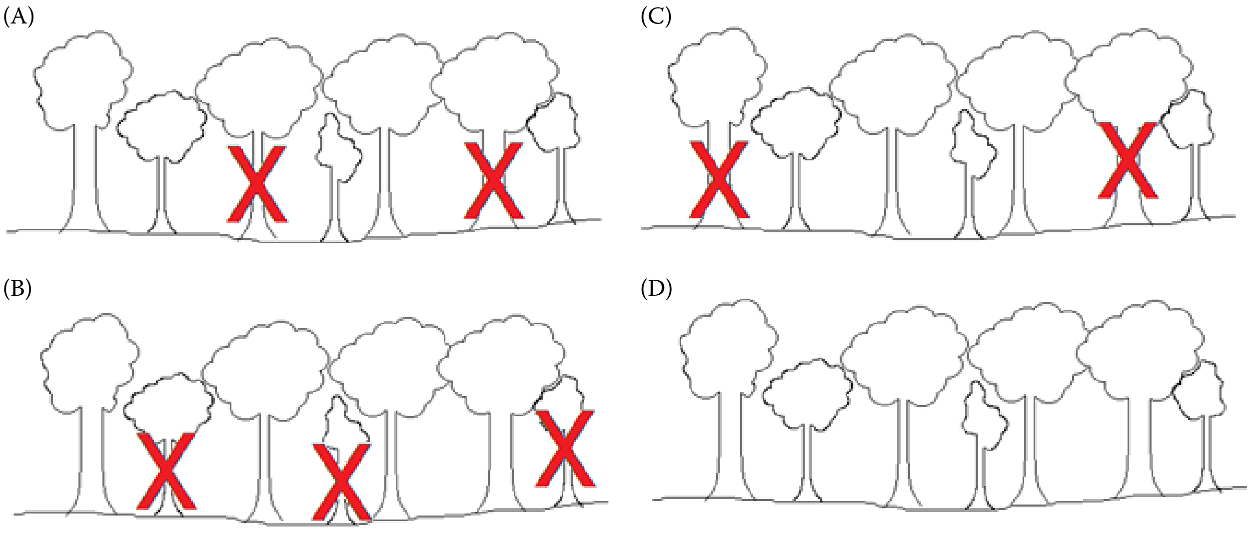

Figure 3. Types of thinning: (A) crown thinning; (B) low thinning; (C) heavy crown thinning; (D) reference plot

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Table 3. Polanský's classification

Quality class	SQ_T	SQ_C
1	straight, cylindrical, no knots	symmetrical, appropriate size (neither big nor small)
2	mostly straight, some knots	appropriate size, partly deformed
3	curved, numerous knots	visibly below-average size, asymmetrical
4	strongly curved, numerous knots, very low-grade tree	inappropriate size (too small or big), asymmetrical

SQ_T – shape and quality of trunk; SQ_C – shape and quality of crown

were calculated as a percentage increase in height or thickness in the year of measurement, relative to that in the year the thinning was performed.

DBH was measured using a calliper (accurate to 0.1 cm). The *H* and *HCB* (accurate to 0.1 m) were measured using a Blume Leiss altimeter (Carl Leiss, Germany), a Vertex V ultrasonic hypsometer (Haglöf, Sweden), or a height measuring rod (based on trigonometry). PC is a system for classifying trees according to their *H*, *DBH*, shape, and quality of stem and crown (Table 3). We focused on the estimation of only the shape and quality of the trunk (SQ_T) and crown (SQ_C) because we had already measured the *H* and *DBH* parameters.

Statistical analysis. In the first year of the measurement (i.e. 1989 after thinning), at least 400 trees were measured; after 10 years, almost 300 trees; and during the last measurement (i.e. 2020), at least 200 trees. These numbers of trees or the size of the research area should be sufficient for statistical evaluation, and, thanks to buffer zones, the risk of external influences has been reduced. Smaller numbers of trees (or smaller research areas) have been used in many scientific works (Baterlink 1997; Collet et al. 2001; Gömöry, Paule 2011; Vacek et al. 2017). Statistical analysis of the data was performed using TIBCO Statistica™ (Version 13.3.0, 2017) with a confidence interval of 95%. Normality of the data distribution was examined before the main analysis. The main effects were analysed using analysis of variance (ANOVA), after which Fisher's least significant difference (LSD) test was applied, in order to identify differences among the main effects and interactions.

RESULTS

Development of the number of trees in individual plots. Initially, all plots had a similar number of trees – around 4 000 pcs·ha^{-1} – with a Gaussian distribution (Figures 4 and 5). After thinning, HCT had the lowest density (2 622 pcs·ha^{-1}) and a positive skew, then CT (2 592 pcs·ha^{-1}) with a positive skew, LT (2 785 pcs·ha^{-1}) with a negative skew of distribution, and RP had the highest density (3 998 pcs·ha^{-1}) and the same distribution because thinning had not been performed. The subsequent decrease in the number of trees throughout the experiment was only natural development at the stand (Figure 5). After the first five years, we noticed a natural decrease in the number of trees on all plots – the smallest at CT (12%) and the greatest at RP (20%). Ten years after thinning, the smallest spontaneous loss occurred at CT (22%), and at the other plots it was in the range of 27% (HCT) to 31% (RP). It is possible to see the decline in the development curves throughout the entire measurement. The steepest curves of spontaneous mortality during the entire experiment (where the total decrease was almost 70%) were recorded at LT and RP, and the least steep curves (with a cumulative decrease of almost 60%) at HCT and CT. During the last measurement, the numbers of trees were similar at all plots, regardless of the very different numbers of trees immediately after thinning.

Height. There was no statistically significant difference in the height of oak during the entire experiment (Figure 6A). However, according to the acceleration of the cumulative height increment, there was a noticeable difference between the plots (Figure 6D). Oak trees at HCT and RP had an accelerated cumulative height increment (compared to that of the other plots) and, from the second measurement on, they were statistically significantly different from those of the other plots (always $P = 0.0001$). During the last measurement, we found a greater cumulative increment (of up to about 40%) at HCT and RP than at LT and CT.

In the case of beech, we found a statistically significant difference only during the last two meas-

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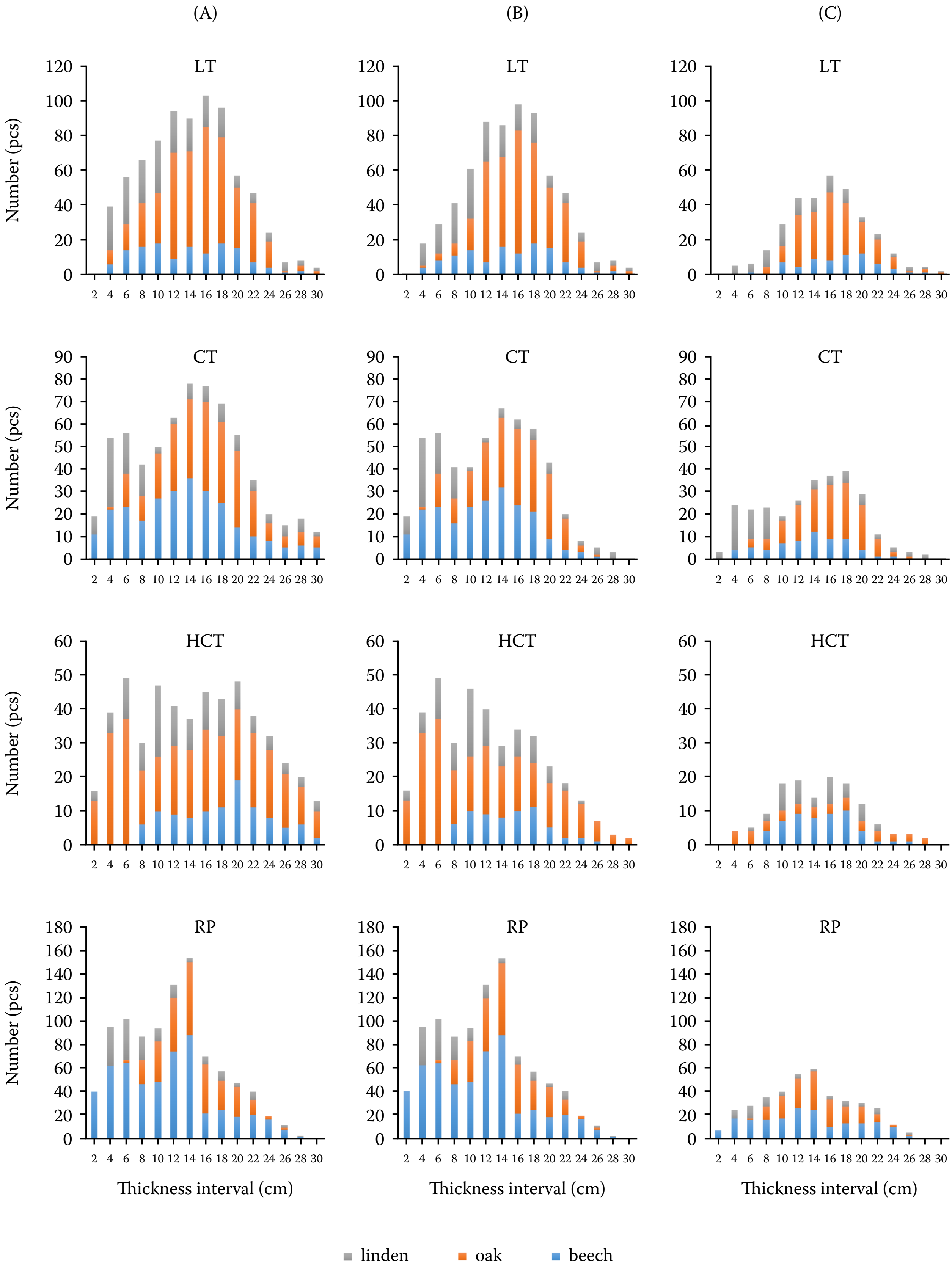

Figure 4. Thickness structures of plots: (A) before thinning; (B) after thinning; (C) at the end of the experiment

LT – low thinning; CT – crown thinning; HCT – heavy crown thinning; RP – reference plot

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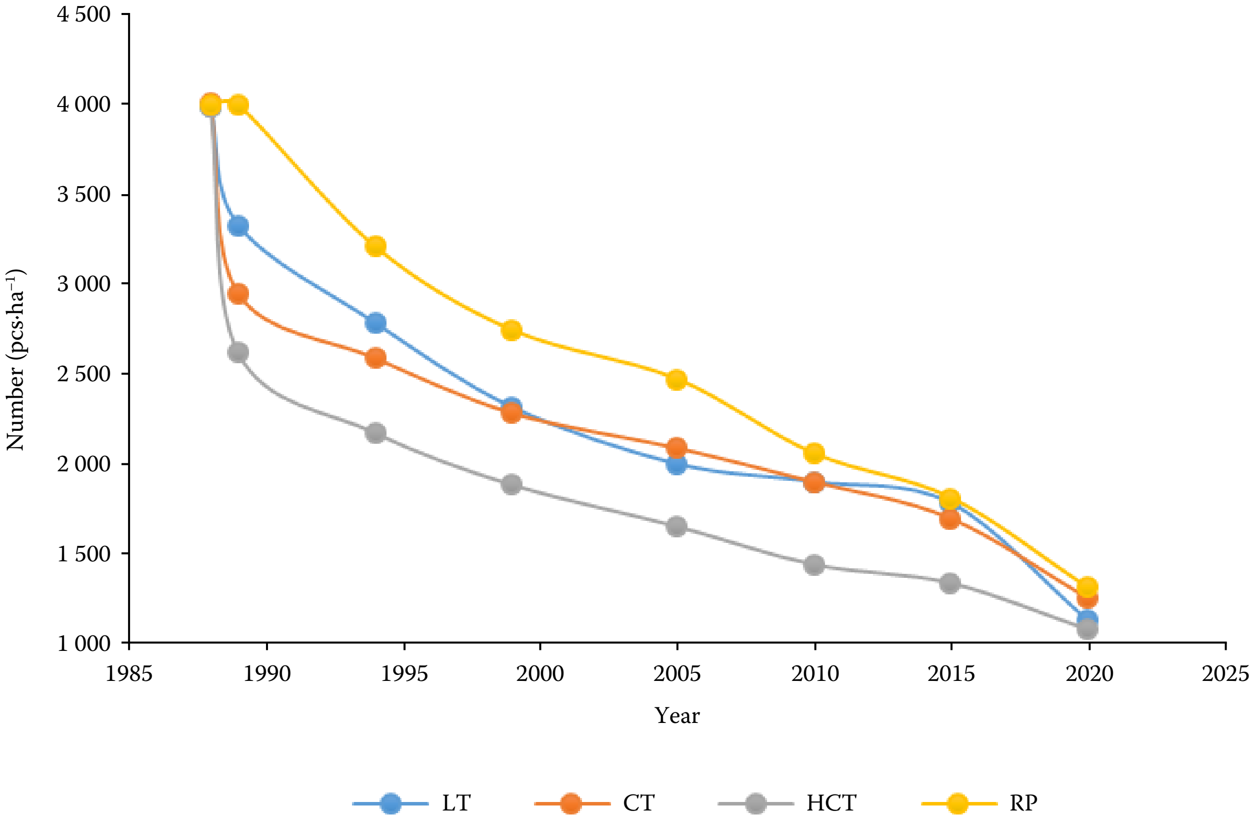

Figure 5. Development of the number of trees at individual plots

LT – low thinning; CT – crown thinning; HCT – heavy crown thinning; RP – reference plot

urements between the mean tallest tree at HCT and the lowest at LT and RP (Figure 6B). The cumulative height increment showed an accelerated height increase at HCT (compared to the others) from the third measurement on (Figure 6E), which was statistically significantly different from those at the other plots (always P = 0.0001). During the last measurement, we found a difference (of about 60%) between the smallest cumulative increment at LT and the greatest at HCT.

From the third measurement on, the mean height of linden was different between HCT and the other plots (1999: P = 0.0264; 2005: P = 0.0106; other years: P = 0.0001; Figure 6C). Also, the cumulative height increment at HCT was greater than at the other plots (always P = 0.0001), but already from the first measurement (Figure 6F).

Diameter at breast height. The mean *DBH*s of oak at the individual plots were very similar throughout the entire measurement period (Figure 7A). However, the cumulative thickness increments were different during the first measurement (Figure 7D). The greatest increment was found at LT (P = 0.0001), but in other years the cumulative thickness increments were similar and without statistical difference.

During the measurements, the mean *DBH*s of beech at the individual plots differed only slightly (Figure 7B). After five years, the cumulative thickness increment at LT reached the highest value (P = 0.0001), but during subsequent measurements there was a decrease in the rate of the increment and no difference was found in comparison with the others (Figure 7E). On the other hand, 15 years from the thinning until the end of the measurement, the increment was greatest at RP (2005: P = 0.0412; 2010: P = 0.0134; other years P = 0.0001).

The mean *DBH*s of linden were not statistically significantly different among the plots during the first ten years (Figure 7C), but then the difference between the mean *DBH* at HCT and at RP became statistically significant (1999: P = 0.0378; from 2005: P = 0.0001), and from 2005 on the *DBH* at HCT was also different from that of the other plots (P-values were in the range

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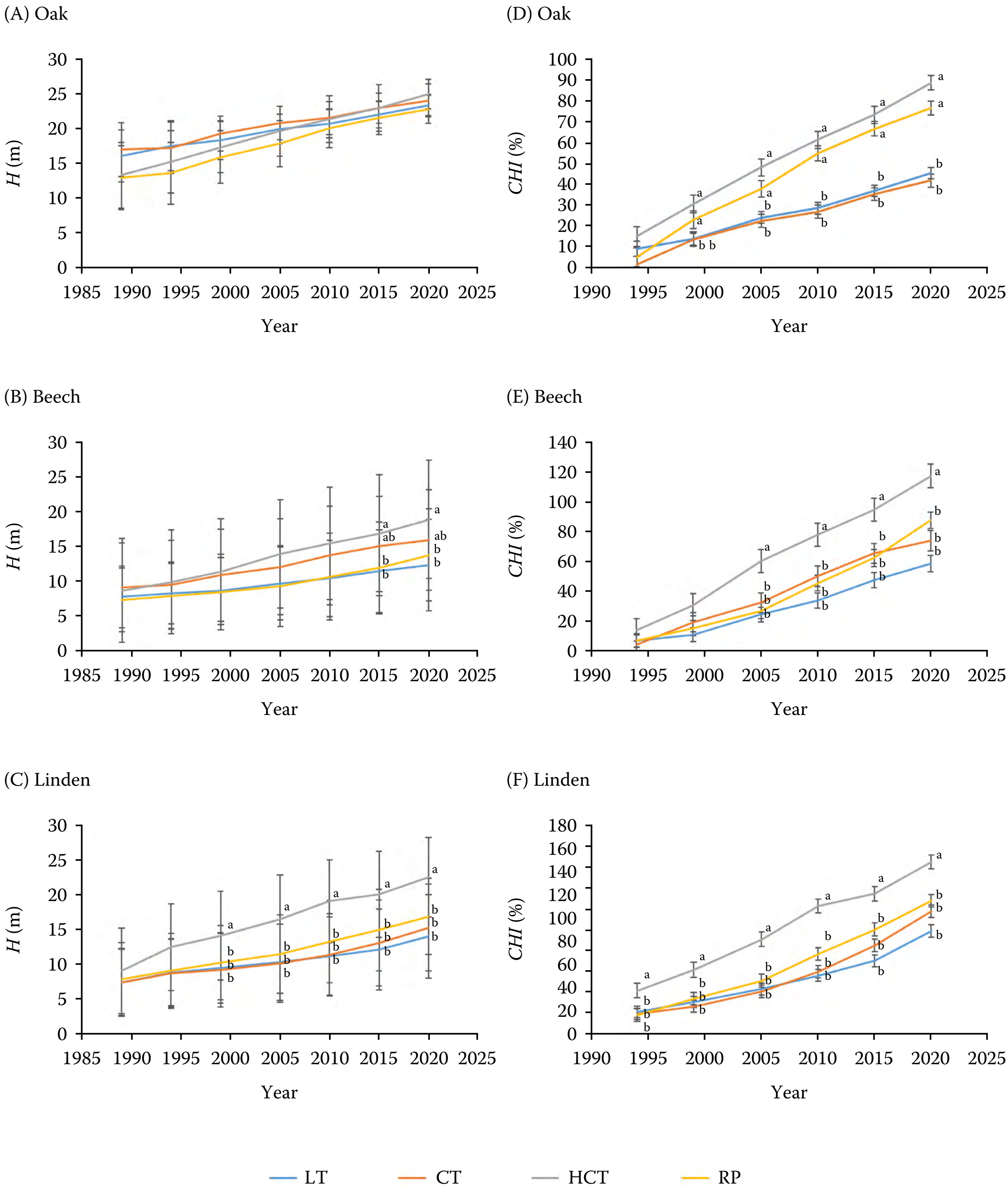

Figure 6. (A–C) Height (*H*) and (D–F) cumulative height increment (*CHI*)

LT – low thinning; CT – crown thinning; HCT – heavy crown thinning; RP – reference plot; a, b – homogeneous groups of the mean *H* (*CHI*) at the plots (with a confidence interval of 0.95); whiskers – standard deviations

of 0.0274–0.0426). The cumulative thickness increments among individual plots were different from the second measurement on (Figure 7F). We found the greatest cumulative increment at HCT and the smallest at RP (always $P = 0.0001$), where the difference between the cumulative

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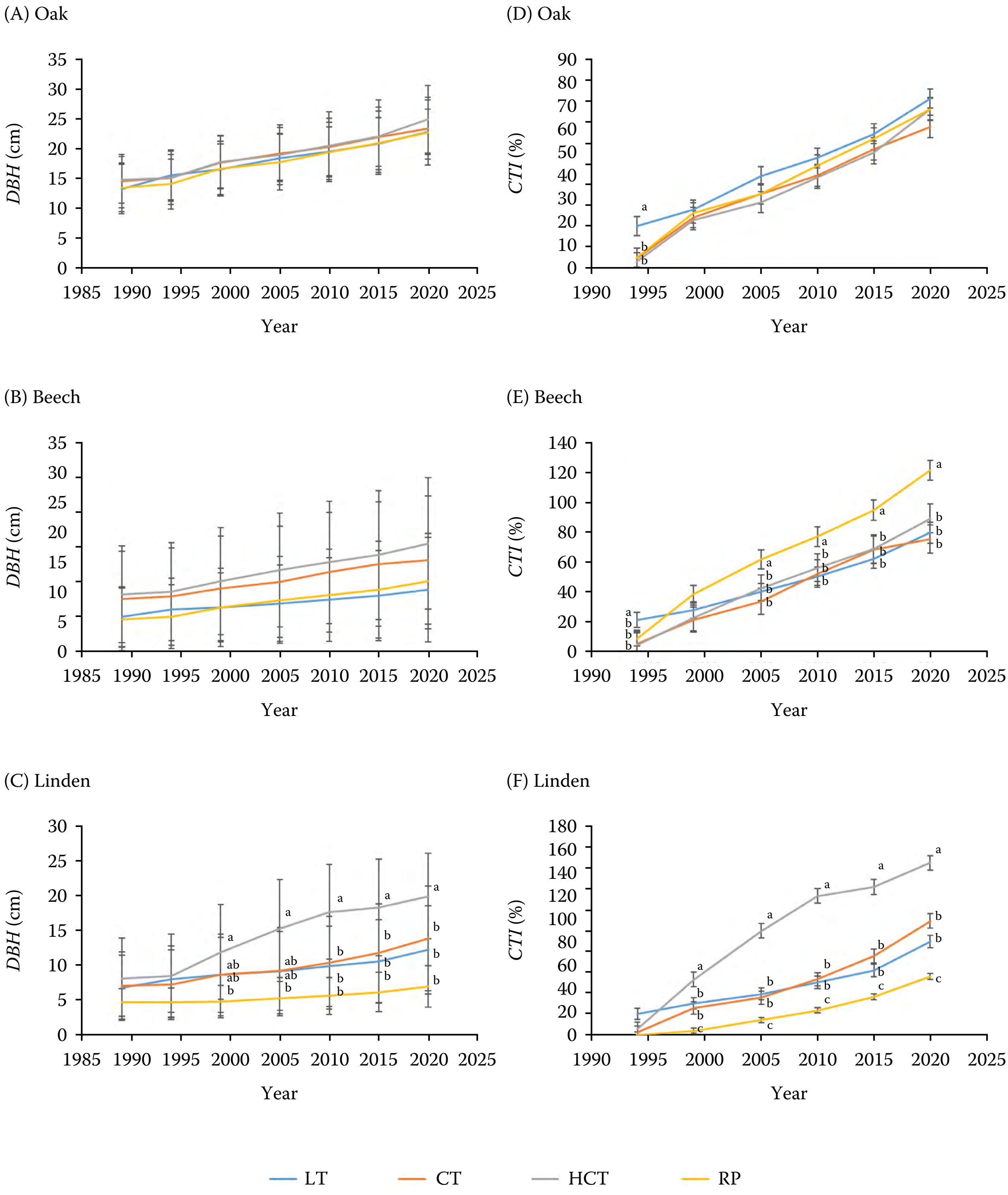

Figure 7. (A–C) Diameter at breast height (*DBH*) and (D–F) cumulative thickness increment (*CTI*)

LT – low thinning; CT – crown thinning; HCT – heavy crown thinning; RP – reference plot; a, b, c – homogeneous groups of the mean *DBH* (*CTI*) at the plots (with a confidence interval of 0.95); whiskers –standard deviations

thickness increments at these two plots was almost 100% during the last measurement. Also, the cumulative increments at LT and CT were greater than that at RP and smaller than that at HCT from the second measurement on (always $P = 0.0001$).

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Height of the crown base. The *HCB*s of oak did not differ from one measurement to the next (Table 4). In the case of beech (Table 4), only during the last three measurements, we noted statistically significant differences between the highest and lowest values, where the trees had the highest *HCB* at HCT and the lowest at LT (*P*-values were in the range of 0.0006–0.0176). The *HCB*s of linden were different only during the last four measurements (Table 4), where there was a difference between the highest *HCB* at HCT and the others (*P*-values were in the range of 0.0001–0.0394).

Shape and quality of the trunk. After thinning, the SQ_T values at the individual plots were similar for each species. The SQ_T of oak (Table 5) at the individual plots gradually worsened towards the end of the experiment (except that at CT, which remained more or less the same the whole time). However, the decrease in quality of each plot was no more than by one class, meaning that no statistical differences were detected (Table 5). The SQ_T of beech at the individual plots also gradually worsened towards the end of the experiment; however, the differences were no greater than one class, thus worsening at a similar rate. At HCT and CT, the values of SQ_T of linden were fairly constant during the entire experiment, while those at LT and RP declined only slightly (Table 5). However, the decrease in quality of each plot was no more than by one class, meaning that no statistical differences were detected.

Shape and quality of the crown. The SQ_C of oak was lowest at CT after thinning (Table 5). At the other plots, the values of SQ_C were higher by no more than one class. During the measurement, the SQ_C at RP, HCT, and LT increased gradually, but the SQ_C at CT greatly and, as a result, the SQ_C at CT achieved similar values to those of the other plots during the last measurement at the end of the experiment. In the cases of beech and linden (Table 5), the SQ_C slowly increased during each measurement (by about half a class) at all plots.

Table 4. Height of the crown base (*HCB*) in m (± SD)

Species	Year						
	1989	1994	1999	2005	2010	2015	2020
				LT			
Beech	2.59 (± 2.43)	2.63 (± 2.36)	2.89 (± 1.94)	3.93 (± 2.47)	4.65 (± 2.88)^{b}	5.35 (± 3.27)^{b}	6.26 (± 3.67)^{b}
Oak	9.22 (± 3.14)	10.37 (± 3.02)	10.9 (± 2.65)	13.05 (± 2.07)	14.05 (± 1.96)	15.2 (± 1.91)	16.39 (± 1.74)
Linden	3.25 (± 2.22)	3.88 (± 2.32)	4.48 (± 2.68)	5.78 (± 3.35)^{b}	6.68 (± 3.75)^{b}	7.66 (± 4.11)^{b}	9.1 (± 4.38)^{b}
				CT			
Beech	3.55 (± 3.24)	3.92 (± 3.19)	4.39 (± 2.86)	5.84 (± 3.39)	7.15 (± 4.04)^{ab}	8.42 (± 4.37)^{ab}	9.13 (± 4.52)^{ab}
Oak	9.26 (± 2.88)	10.42 (± 2.74)	11.30 (± 2.30)	13.32 (± 2.19)	14.50 (± 2.10)	15.62 (± 1.93)	16.37 (± 2.00)
Linden	3.38 (± 2.51)	4.14 (± 2.60)	4.51 (± 2.93)	5.84 (± 3.49)^{b}	6.94 (± 3.98)^{b}	8.21 (± 4.33)^{b}	9.96 (± 4.77)^{b}
				HCT			
Beech	3.95 (± 3.67)	5.37 (± 3.83)	5.90 (± 4.46)	8.01 (± 5.03)	9.5 (± 5.42)^{a}	10.56 (± 5.73)^{a}	12.16 (± 5.92)^{a}
Oak	8.75 (± 3.66)	11.26 (± 3.58)	12.03 (± 3.11)	13.74 (± 3.18)	15.05 (± 3.18)	16.03 (± 3.33)	17.9 (± 2.01)
Linden	5.89 (± 3.67)	7.74 (± 3.69)	8.73 (± 4.07)	11.04 (± 4.40)^{a}	13.46 (± 4.11)^{a}	14.41 (± 4.26)^{a}	16.15 (± 3.97)^{a}
				RP			
Beech	2.23 (± 1.95)	2.93 (± 1.98)	3.34 (± 2.50)	4.31 (± 2.96)	5.39 (± 3.38)^{ab}	6.38 (± 3.75)^{ab}	7.65 (± 3.92)^{ab}
Oak	7.60 (± 3.00)	9.80 (± 2.87)	10.07 (± 2.39)	11.55 (± 2.48)	13.19 (± 2.26)	14.38 (± 2.08)	15.3 (± 1.92)
Linden	3.92 (± 2.83)	4.88 (± 2.78)	5.10 (± 2.55)	6.37 (± 3.13)^{b}	7.97 (± 3.63)^{b}	9.57 (± 3.90)^{b}	11.29 (± 3.90)^{b}

SD – standard deviation; LT – low thinning; CT – crown thinning; HCT – heavy crown thinning; RP – reference plot; letters in the superscript denote homogeneous groups of the mean *DBH* (*CTI*) at the plots (with a confidence interval of 0.95)

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Table 5. Shape and quality of the trunk (SQ_T) and shape and quality of the crown (SQ_C) in m (± SD)

Species	1989	1994	1999	2005	2010	2015	2020
SQ_T							
				LT			
Beech	2.11 (± 0.77)	2.12 (± 0.75)	2.25 (± 0.60)	2.17 (± 0.73)	2.35 (± 0.87)	2.57 (± 0.50)	3.37 (± 0.72)
Oak	2.19 (± 0.56)	2.19 (± 0.59)	2.21 (± 0.72)	2.15 (± 0.75)	2.25 (± 0.88)	2.28 (± 0.51)	2.78 (± 0.75)
Linden	2.55 (± 0.48)	2.57 (± 0.48)	2.63 (± 0.45)	2.88 (± 0.49)	2.91 (± 0.86)	3.25 (± 0.61)	3.41 (± 2.46)
				CT			
Beech	2.11 (± 0.68)	2.13 (± 0.66)	2.26 (± 0.45)	2.17 (± 0.51)	2.32 (± 0.45)	2.58 (± 0.65)	3.04 (± 1.13)
Oak	2.13 (± 0.65)	2.15 (± 0.68)	2.24 (± 0.74)	2.23 (± 0.67)	2.36 (± 0.54)	2.23 (± 0.59)	2.33 (± 1.02)
Linden	2.17 (± 0.87)	2.17 (± 0.84)	2.16 (± 0.56)	2.29 (± 0.48)	2.18 (± 0.56)	2.09 (± 0.64)	2.51 (± 1.14)
				HCT			
Beech	2.15 (± 0.49)	2.16 (± 0.49)	2.28 (± 0.46)	2.29 (± 0.74)	2.38 (± 0.83)	2.44 (± 0.59)	2.95 (± 1.10)
Oak	2.27 (± 0.79)	2.26 (± 0.75)	2.25 (± 0.53)	2.36 (± 0.76)	2.12 (± 0.65)	2.39 (± 0.56)	2.63 (± 1.35)
Linden	2.12 (± 0.49)	2.13 (± 0.53)	2.19 (± 0.68)	2.18 (± 0.75)	2.30 (± 0.82)	2.00 (± 0.51)	2.25 (± 1.16)
				RP			
Beech	2.32 (± 0.59)	2.34 (± 0.60)	2.40 (± 0.73)	2.56 (± 0.45)	2.65 (± 0.81)	2.77 (± 0.55)	3.27 (± 0.78)
Oak	2.49 (± 0.88)	2.48 (± 0.86)	2.45 (± 0.64)	2.57 (± 0.54)	2.56 (± 0.75)	2.64 (± 0.54)	2.84 (± 0.79)
Linden	2.44 (± 0.89)	2.45 (± 0.88)	2.59 (± 0.84)	2.90 (± 0.53)	2.99 (± 0.83)	3.05 (± 0.66)	3.35 (± 0.77)
SQ_C							
				LT			
Beech	2.48 (± 0.76)	2.60 (± 0.69)	2.70 (± 0.62)	2.59 (± 0.57)	2.89 (± 0.76)	3.11 (± 0.72)	3.53 (± 0.73)
Oak	2.26 (± 0.68)	2.30 (± 0.68)	2.33 (± 0.67)	2.44 (± 0.42)	2.34 (± 0.53)	2.56 (± 0.72)	2.79 (± 0.80)
Linden	2.37 (± 0.68)	2.49 (± 0.56)	2.55 (± 0.48)	2.70 (± 0.49)	2.84 (± 0.75)	2.97 (± 0.66)	3.47 (± 0.87)
				CT			
Beech	2.27 (± 0.54)	2.33 (± 0.55)	2.44 (± 0.56)	2.73 (± 0.79)	2.97 (± 0.86)	2.95 (± 0.67)	3.33 (± 1.06)
Oak	1.25 (± 0.74)	1.35 (± 0.66)	1.43 (± 0.55)	1.63 (± 0.89)	1.79 (± 0.57)	1.88 (± 0.84)	2.34 (± 1.10)
Linden	2.39 (± 0.82)	2.49 (± 0.68)	2.56 (± 0.43)	2.65 (± 0.63)	2.85 (± 0.84)	2.92 (± 0.66)	3.00 (± 1.25)
				HCT			
Beech	2.32 (± 0.69)	2.43 (± 0.71)	2.55 (± 0.74)	2.70 (± 0.57)	2.88 (± 0.79)	3.03 (± 0.85)	3.45 (± 1.15)
Oak	2.14 (± 0.52)	2.20 (± 0.63)	2.27 (± 0.79)	2.38 (± 0.45)	2.32 (± 0.64)	2.31 (± 0.75)	2.54 (± 1.22)
Linden	2.39 (± 0.65)	2.45 (± 0.67)	2.57 (± 0.70)	2.79 (± 0.49)	2.83 (± 0.45)	3.00 (± 0.79)	3.25 (± 0.94)
				RP			
Beech	2.32 (± 0.80)	2.42 (± 0.77)	2.52 (± 0.74)	2.59 (± 0.81)	2.89 (± 0.59)	3.11 (± 0.70)	3.43 (± 0.94)
Oak	2.38 (± 0.67)	2.38 (± 0.77)	2.38 (± 0.84)	2.45 (± 0.42)	2.55 (± 0.48)	2.57 (± 0.71)	2.72 (± 0.96)
Linden	2.37 (± 0.80)	2.50 (± 0.76)	2.70 (± 0.73)	2.82 (± 0.42)	2.95 (± 0.45)	3.25 (± 0.88)	3.43 (± 0.75)

SD – standard deviation; LT – low thinning; CT – crown thinning; HCT – heavy crown thinning; RP – reference plot

DISCUSSION

A certain disadvantage or limitation of the described experiment is, of course, the lack of repetitions, which are desirable for experimental work to completely avoid the influence of uncontrolled factors that may disturb the experimental results (Zar 2010), however, there are almost no scientific works dealing with the loss of the effect of thinning on stands and their subsequent natural growth, especially in mixed forests where various types of thinning had been carried out. In addi-

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tion, we had to compare our results with those of the studies that deal with the effect of thinning on stands (i.e. the results from the first ten years), and subsequently with those of the studies on natural old-growth forests or abandoned forests.

After we conducted the three types of thinning (see above), there was no statistically significant effect on the thickness growth, even five years after thinning (only the *DBH* of linden at the plot with the heaviest thinning was greater than that of the others, but this was after the first 10 years). Also, all thickness increments were similar – except for oak and beech, where these increments were greatest at LT after 5 years (in subsequent years there was no statistical significance), and for linden, where the increment was greater at HCT from 10 years after thinning until the end of the measurement. These results are different from those in the works of Hibbs et al. (1989), Mayor and Rodà (1993), Nowak (1996), Oliver and Larson (1996), Miller (1997), Medhurst et al. (2001) and Juodvalkis et al. (2005). Also, Štefančík and Štefančík (2001) or Boncina et al. (2007) recorded a great increase in thickness. In Slovakia, Štefančík and Štefančík (2001) found that thinning achieved a great annual increment in beech stands, in which periodic thinning was conducted. Boncina et al. (2007) carried out an experiment with periodic thinning in which the thicknesses of the mature beech trees in the thinned plot were compared to those at the reference plot. There, the thickness of beech growing at the plot that was being thinned was greater than that at the reference plot after 10 years. On the other hand, in early Danish studies, oak showed only a very small thickness increment and beech showed a moderate increment after thinning (Moller 1947).

Various reactions to the thinning performed were observed by Usta et al. (2019), who conducted three types of thinning in two young beech stands, and from their results, it is obvious that there were very different thickness responses. At the first stand, the plot with heavy thinning had a similar thickness to that of the reference plot, and at the plots with light and medium thinning, the thicknesses were even smaller than at the reference plot. At the second stand, the thickness of the beech in the plot with heavy thinning was smaller than that in the reference plot; there was no difference in the thickness between the reference plot and the one with light thinning; the thickness in the plot with the medium thinning increased, compared to that in the reference plot (Usta et al. 2019). Juodvalkis et al. (2005) state that the thickness after thinning in deciduous trees does not increase in comparison with the trees in the reference plots if thinning is very heavy. This applies to the oak and beech in our case, but not to linden. Linden trees were located mainly at the below level during thinning. Thinning (mainly at the middle level, i.e. crown thinning and heavy crown thinning) helped them to receive more light, water, and nutrients, so that the trees were able to grow. Our results show that the heavier the thinning in the stand, the greater the thickness increment of linden that was mostly located in the below level. Similar results (from dominant and co-dominant linden trees) are stated in the study by Šušić et al. (2022), who wrote that larger increments were achieved after heavy thinning carried out at the middle level.

According to Juodvalkis et al. (2005), the increase in the thickness increment in oak and beech stands occurs one year after thinning and reaches its maximum after 2–3 years. In addition, Cañellas et al. (2004) describe that the thickness increase is positively correlated with the thinning intensity at one 30-year-old stand. After 5 years, we measured differences in the increments of beech and oak between the light thinning and the other types. The light thinning was performed with the lightest (16%) intensity, and the intervention was conducted at below level. Seven or eight years after thinning, the thickness increment decreased to that of the reference plot, but the total thickness was greater than that in the reference plot due to the increase in the thickness increment in previous years (Juodvalkis et al. 2005). Assmann (1961) also describes an intensive thickness increase after thinning and adds that the trees are not able to maintain this rate for a longer period of time. These claims are not exact because our results show that the increments at different plots had different curves. Five to ten years after thinning, the LT (i.e. the lightest thinning) increment curves were less steep than the others. The reason for the accelerated thickness increment of the remaining trees should be the greater availability of light, water and nutrients (Usta et al. 2019). As the trees grow and fill the above-ground and below-ground layers, the availability of light, water and nutrients decreases, and therefore the thickness increment decreases again (Meinzer et al. 2011).

The abandonment of forestry activities has a very strong impact on the subsequent charac-

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ter of stands (Gondard 2001; Bürgi, Russell 2001). We found a considerable decrease in the number of trees per ha at all our plots during the spontaneous development of the forest (which lasted 30 years). A large spontaneous reduction in the number of trees in the unmanaged forest was also found by Badraghi et al. (2023).

In scientific works, the effect of thinning on the height of oak, beech or linden is seldom described and the results contained in the few available works differ. For example, at one beech stand, there was a positive reaction of the trees after medium and heavy thinning, and at the other, there was none (Usta et al. 2019). Ciancio et al. (2006) also describe a positive effect of thinning on the height of beech trees. Cañellas et al. (1998) and Cañellas et al. (2004) reported an increase in the heights of oaks after thinning. When comparing the heights at our plots, we found a different thinning effect on each species. In the case of beech, there was no visible effect on the height or height increment while thinning. In the case of oak, there was no noticeable increase in height, but the cumulative height increments showed a statistically significant increase at HCT, compared to the others after 10 years. Linden trees had similar results, as did oak trees; however, a statistically significant increase in the height increment at HCT, compared to the others, occurred already after 5 years.

The values of the trunk shape of beech and oak were in the range of 2 to 2.5 at all of the thinned plots, which means that the trunk is quite knotty and not very straight. However, the trunk shapes of beech and oak at the reference plot showed similar values. This fact does not correspond with studies which state that thinning is carried out with the view of improvement of quality of the trunk (Hibbs et al. 1989; Cameron et al. 1995; Oliver, Larson 1996; Medhurst et al. 2001; Rytter, Werner 2007). It can, therefore, be concluded that all trees in our plots had low-placed crowns before thinning. In 1989, the mean heights of oak, beech and linden were 15 m, 7 m, and 7 m, respectively. Based on these values, it is obvious that the tops of oak crowns reached the upper part of the middle level, whereas the ones of beech and linden reached only the lower part of the middle level or the below level. In 1989, the mean crown base heights of oak, beech and linden were 7 m, 3 m, and 4 m, respectively. According to the models of thinning described by Slodičák and Novák (2007), there should be 5 000 beech trees or 2 000 oak trees per hectare (no model of thinning of linden was given), however, at our plots, there were always around 4 000 trees per hectare, which is not the number of trees recommended by these models. Oak is a species very susceptible to phototropism (Sternberg 2013). We assume that a greater number of trees per hectare brings about accelerated height growth of oak towards sunlight, in which case the trees do not grow vertically but search for maximum sunlight. Shapelessness of the trunk of oak, due to phototropism, was also mentioned by Kučeravá and Remeš (2014). Beech needs more trees per hectare than we had at our plots and does not suffer from phototropism as much as oak. However, due to more light and space, it does not grow very tall but wider, with its greater number of thicker branches, growing above its shorter, straight and thicker trunk. Slodičák and Novák (2007) described that (fewer than recommended) target trees of beech have patulous branches because a small number of nurse individuals allows them to become patulous. Moreover, Kučeravá and Remeš (2014) state that beech has a genetic predisposition to dichotomy, which is mainly created through great spacing (i.e. with more free space around the tree, and more light). Linden is a species that needs strict thinning interventions and support of forest management. When this is not met, it often stays in the below level as a curved, knotty and dichotomous tree (Vyskot 1978).

The values of the trunk shape of beech, oak, and linden were slightly below 2.5 (except that of oak at CT, where the value was below 1.5), which means a partly deformed below-average-size crown. Ten years after thinning, these values slightly worsened, as if the crowns stayed partly deformed and of below-average size, and there was no increase in the crown projection. These reasons did not correspond to those by Juodvalkis et al. (2005), who showed that oak increased the increment of the crown more than twice after thinning, or Eule (1959), Kennel (1966), Pretzsch (1992), and Guericke (2002), who stated an increase in the increment of the crown. Moreover, Roloff (1985) and Sternberg (2013) claimed that the crown can become less deformed by improving the radiation conditions and crown plasticity after thinning, where the spreading of the crown should last for up to about 7 years (Georgievsky 1957; Buzikhin, Pschenichnikova 1980; Juodvalkis et al. 2005). This,

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however, in our case, was not only not confirmed but created a worse crown.

CONCLUSION

The numbers of trees at the plots were very different after thinning (the number of trees at the heavy crown plot was half that at the reference plot). However, after 30 years of spontaneous growth, all plots (through self-regulation) had a similar number of trees. Moreover, due to the fact that the thinning was performed only once, the shape and quality of the crown and trunk were similar at all plots, and it seems that one thinning did not have an effect on these parameters. Also, the effect of the different types of thinning on height and *DBH* (if they were carried out only once) was, for all species, not significant. However, the cumulative percentage increments of height of all species were greatest at the heavy crown plot during the first 10 years, and those of thickness of all species were significant at the plot with low thinning, but only in the first five years, then they became insignificant. After 30 years, we found differences only in *DBH* and only for linden, where the thickest one was at the heavy crown plot. The spontaneous development of the cumulative percentage thickness increment showed that the greatest was at the heavy crown plot for linden and at the reference plot for beech, while the cumulative percentage height increments were greatest for all species at the heavy crown plot.

We assume that the best type of thinning for similar mixed stands could be heavy crown thinning, although we did not find many significant differences in the *DBH* and height. However, we did find differences in the cumulative increments (both height and *DBH*), where the best values were achieved by beech and linden at the heavy crown plot (there were practically no differences among the oaks growing at different plots). After thinning, many thin trees at below level remained and many thick trees at middle level were removed and, due to this, the initial *DBH*s and heights were slightly lower than at the other plots. On the other hand, the remaining trees, which received more light, and competed less for water and nutrients, should grow faster (which is obvious in their accelerated growth), and, thanks to the accelerated increments, the trees reached the values of the other plots, and even outgrew them. However, it is important to remember that the thinning was performed only once, and the effect may not be so clear-cut.

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