Ann. For. Sci. 64 (2007) 47–57
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DOI: 10.1051/forest:2006087

Original article

Effects of selective thinning on growth and development of beech (*Fagus sylvatica* L.) forest stands in south-eastern Slovenia

Andrej BONCINA*, Ales KADUNC, Dusan ROBIC

University of Ljubljana, Biotechnical Faculty, Department of Forestry and Renewable Forest Resources, Vecna pot 83, 1000 Ljubljana, Slovenia

(Received 25 May 2006; accepted 25 August 2006)

Abstract – We studied the effects of two types of selective thinning on beech stands formed by a shelterwood cut in 1910 – with lower number of crop trees and higher thinning intensity (T1) and higher number of crop trees with lower thinning intensity (T2). The stands were thinned in 1980, 1991 and 2001. Despite a lower stand density after thinning, the annual basal area increments of thinned stands in both thinning periods (1980–1991 and 1991–2002) were around 20% higher compared to those of the control (unthinned) stands. The mean annual basal area increment of dominant trees was 30–56% larger in the thinned plots compared to the control plots. Of 176 initial crop trees in the T1, 72% were chosen again during the last thinning. In the T2, 258 crop trees were chosen in the first thinning, and only 62% of these trees were chosen again during the last thinning. Only crown suppression and diameter classes of crop trees significantly influenced their basal area increment when diameter classes, crown size, crown suppression, and social status were tested. In the thinned stands, the dominant trees are more uniformly distributed if compared to the dominant trees in the control plots. Finally, the herbaceous cover and the species diversity were higher in the thinned plots.

thinning / *Fagus sylvatica* / basal area increment / crop tree / stand structure / distribution

Résumé – Effets de l'éclaircie sélective sur la croissance et le développement des peuplements de hêtres dans le sud-est de la Slovénie. Nous avons effectué des recherches sur les effets de deux sortes d'éclaircies sélectives entreprises sur des peuplements de hêtres formés par la coupe d'abri de 1910 : l'une avec un faible nombre d'arbres de place et une grande intensité d'éclaircie (T1), l'autre avec un nombre élevé d'arbres de place et une intensité faible. Ces peuplements ont été éclaircis en 1980, 1991 et 2001. Bien que la surface terrière de ces peuplements ait été réduite, l'accroissement en surface terrière des peuplements éclaircis a été supérieur de 20 % approximativement aux cours des deux périodes séparant les éclaircies (1980–1991 et 1991–2002) à celui des peuplements non éclaircis. L'accroissement moyen en surface terrière des arbres dominants a été de 20 à 56 % supérieur dans les peuplements éclaircis. Soixante-douze % des 176 arbres de place initiaux de la parcelle expérimentale T1, ont de nouveau été désignés lors de la dernière éclaircie. Sur T2, il y avait 258 arbres de place lors de la première éclaircie, et seulement 62 % d'entre eux ont été de nouveau désignés au cours de la dernière éclaircie. Une analyse parallèle de l'influence des classes de diamètre, de la taille et du couvert des houppiers, et du statut social des arbres montre que le couvert et les classes de diamètre des arbres de place exercent une influence marquée sur l'accroissement de leur surface terrière. Dans les peuplements éclaircis, la répartition spatiale des arbres dominants est plus régulière que dans les peuplements non éclaircis.
Le couvert de la strate herbacée et la diversité des espèces sont plus importants dans les peuplements éclaircis.

éclaircie / *Fagus sylvatica* / accroissement en surface terrière / structure de peuplement / répartition spatiale

1. INTRODUCTION

Beech (*Fagus sylvatica* L.) is one of the most widespread tree species in Central Europe [4]. The importance of beech from both an ecological and economic standpoint has been increasing in the last decades in Europe [16, 24, 26, 29, 37]. Consequently, tending in beech forests, especially thinning, is becoming increasingly important. Thinning may have significant effects in beech stands because of the crown plasticity of individual trees, especially with regard to surrounding radiation conditions [41]. The objectives of thinning vary, but typically include increasing the share of large diameter trees, improving timber quality and increasing yield value, shortening the production (rotation) time, improving stand stability, influencing tree species composition, and increasing biodiversity [3, 19, 23, 35, 48, 52].

Classification of thinning methods varies due to different criteria, including the type of thinning, intensity (grade), return interval, and the timing of the first thinning [48]. Two major types of thinning used in forest tending are low (from below) and high (from above) thinning. In low thinning, only suppressed trees are removed, whereas high thinning removes dominant and co-dominant trees in the canopy [30]. Both types of thinning can be carried out with different intensities, which are typically divided into light, moderate, and strong [2, 15].

One type of high thinning, commonly referred to as selective thinning, has been frequently used in Central European forestry. It is based on Schädelin [43] principles. First, positive selection is carried out relatively early in stand development, where crop trees are chosen and competitors are

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* Corresponding author: andrej.boncina@bf.uni-lj.si

removed. Crop trees are selected each time the stand is entered for thinning, and should be distributed as uniformly as possible. Abetz [1] developed a variety of selective thinning methods, where final crop trees are chosen in young stands when the first thinning is carried out. Busse [9] initiated the concept of group selection thinning, which was later developed by Kato [21], where a cluster or small group of future trees is treated as an individual crop tree. Reininger [40] developed structural thinning, which creates fine-structured stands.

Several studies have focused on the effects of thinning on stand parameters, comparing thinned and unthinned (control) stands [8, 17, 47, 48] or stands with different thinning intensities [16, 20, 42, 49]. Similarly, the effects of different thinning regimes on stand value have also been examined [14, 17, 19]. Moreover, the effects of different types of selective thinning have been studied, such as group selective thinning [22], and the consequences of early and late thinning [18, 23].

Classical selective thinning according to Schädelin [43], Leibundgut [31] and Schütz [45] is characterised by repeating the selection of crop trees; their number strongly decreases from the beginning of the selection thinning in the young pole phase to the last thinning made in the optimal phase. This means that the average distance between crop trees increases during the period from the first up to the last thinning. Leibundgut [31] suggested approx. 1210 crop trees per hectare in a beech stand with a dominant height (h_{dom}) of 10 m and 140 crop trees in the stand with $h_{\text{dom}} = 35$ m. The selection of crop trees is made with respect to tree species, stem quality, crown characteristics, vitality, stability and the spatial distribution of trees [19, 27, 30, 44]. The frequency of thinnings depends mostly on the increment of stand dominant height, such that thinnings are usually carried out after the stand dominant height increases by 2–4 m [1, 27]. The number of crop trees at each stage of stand development, and the intensity of removal of their competitors are the most important questions addressed by selection thinning [23, 31, 44, 46]. In the current economic situation, the classical concept of selection thinning can be costly, and therefore some new approaches have been developed based on a smaller number of crop (selected) trees in the first thinning and thinning intensities, taking account of economical factors [46, 51].

In Slovenia, selective thinning is the main type of thinning [34]. However, the thinning of beech forest stands was not widespread a few decades ago due to low prices of beech timber and small price differences between beech timber of different quality. The objective of this study was to examine the effects of two types of selective thinning on beech stands development in south-eastern Slovenia, these two types differing by the number of selected crop trees and the intensity of thinning. Thinning operations began rather cautiously during the pole phase of the stands – at the age of 70 years. Specifically, we studied the efficiency of selective thinning by comparing stand structure and growth (basal area increment), development of crop trees (growth, number), and the spatial distribution of dominant trees in the two differently thinned and their unthinned (control) subplots over a 21-year period. This is one of the first beech thinning experiments in Slovenia, and it is characterised by a design without replications.

2. MATERIALS AND METHODS

2.1. Site description

The research was carried out in the Kocevje region of SE Slovenia (45° 37’ N, 15° 00’ E), where ninety percent of the landscape is forested. Parts of the region have received little human disturbance, and include several old-growth forest stands. The research site lies in a mountain vegetation belt at an elevation of approximately 650 m. The local climate is a combination of maritime and continental effects, characterised by cold, snow-rich winters and hot summers. Annual precipitation is abundant (1500 mm year^{-1}) with maxima in spring and autumn. The average annual temperature is 8.3 °C [39]. A carbonate substrate (limestone, dolomite) and very diverse and rocky karst topography are typical for the region. Brown soils, derived from the carbonate parent material, predominate in the study area, and soil depth varies between 30 and 70 cm. Forests in the region are dominated by beech and fir (*Abies alba*)-beech communities. The study area comprises more or less pure beech forests that originated from natural regeneration following a final cut of the original stand in 1910, and is characterized by an *Enneaphyllo-Fagetum* (*Lamio-orvalae Fagetum*) vegetation type.

2.2. Sampling, measurements and analyses

Two 1-ha permanent research plots were established in 1980 (P1 and P2). In the first plot (P1), a smaller number of crop trees was designed and a heavier thinning intensity was applied in one half of the plot (T1), while the other half served as a control (C1). In the second plot (P2) situated approximately 700 m away from the first plot, a normal number of crop trees was designed and a moderate thinning intensity was applied in one half of the plot (T2), while the other half served as a control (C2).

All trees with diameter at breast height ($d_{1.3} \geq 10$ cm) were numbered and tagged at 1.3 m for repeated diameter measurements [5]. The $d_{1.3}$ of all trees was measured six times (in 1980, 1986, 1989, 1991, 1993, and 2001) to the nearest 0.1 cm. A total of 10821 $d_{1.3}$ measurements were recorded on 2134 trees between 1980–2001. Basal area increments were then calculated for each tree using the repeated measurement data. In 1991, trees were mapped to the nearest 0.1 m. The height of 407 removed trees was measured after thinnings were carried out in 1980 and 1991, and the relationship between height (h) and diameter ($d_{1.3}$) for both periods was determined. Symbols used for designing tree or stand variables are summarised in Table I, together with the units of each variable:

$$h = 1.3 + 32.64 \times \exp(-9.05/d_{1.3}) \; (n = 407, r^2 = 0.81). \tag{1}$$

Tree volume (V) was determined using the following equation [38] and Equation (1):

$$V = (1745.5 + 49.384\, d_{1.3} - 222.25\, h - 3.0398\, d_{1.3}^2 - 14.677\, d_{1.3}\, h + 4.3234\, d_{1.3}^2\, h + 0.00011546\, d_{1.3}^3\, h^2 + 12.878\, h^2 - 0.20662\, d_{1.3}\, h^2)/100000. \tag{2}$$

The thinning trial started in 1980; no data are available before that date. In 1980, 1991 and 2001, crop trees in the thinned subplots (T1 and T2) were selected. Stem quality, crown size, vitality, spatial distribution of potential crop trees, social status, diameter, and tree

Table I. Explanation of symbols.

Symbol	Dimension	Description
$d_{1.3}$	cm	Tree diameter at breast height
d_{dom}	cm	Dominant diameter: mean diameter of the 100 thickest trees per hectare
h	m	Tree height
i_g	cm^2	Annual basal area increment of trees
l_{dom}	m	Average distance between dominant trees
p		Probability, that the values are significantly different, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
q_D		Ration of the quadratic mean diameters of removed trees and of remaining trees
t		Value of *t*-test
N	ha^{-1}	Tree number per hectare
G	$\mathrm{m}^2\ \mathrm{ha}^{-1}$	Stand basal area per hectare
ΔG	$\mathrm{m}^2\ \mathrm{ha}^{-1}$	Annual stand basal area increment per hectare
GS	$\mathrm{m}^3\ \mathrm{ha}^{-1}$	Stand growing stock (standing merchantable volume) per hectare
$SSDI$		Standardized stand density index
V	m^3	Tree volume (volume refers to merchantable wood; i.e. over 7 cm minimum diameter at the smaller end)

Table II. Intensity and kind of thinning illustrated respectively by the reduction in stem number (*N*), basal area (*G*) and growing stock (*GS*) as a percentage of the values per hectare before harvesting, and by the ratio q_D of the quadratic mean diameters of removed trees and remaining trees. The standardised density index (*SSDI*) is also given for each thinning period.

Thinned subplots	Year	*N* (%)	*G* (%)	*GS* (%)	q_D	*SSDI*
T1	1980	29.9	26.8	26.2	0.93	0.71
	1991	24.0	18.4	17.2	0.84	0.63
	2001	20.6	21.1	20.9	1.02	0.50
T2	1980	22.5	21.7	21.2	0.98	0.82
	1991	21.5	16.2	15.0	0.84	0.74
	2001	21.9	22.1	21.7	1.01	0.64

damages were taken into account when selecting the crop trees. Despite the criteria used, the selection of crop trees partly depends on the subjective assessment of forest experts. However, crop trees were usually dominant trees in the canopy layer (classes 1 and 2 according to Kraft). Competing trees were marked and cut in the same years (Tab. II). Thinning was restricted to the removal of competing trees with regard to crop trees, usually from classes 2 and 3 according to Kraft. In both cases (T1 and T2) selective thinning was carried out. The kind of thinning can be assessed by the quotient q_D [37] where q_D is the ratio of the quadratic mean diameters of removed trees and of remaining trees; the more the thinning interferes in the middle and upper storey, the higher is q_D.

In the T1 thinning subplot, a stronger intensity was carried out; in the first two thinnings (1980 and 1991) the reduction of stem number, basal area, and growing stock was more severe compared to the T2 subplot. Furthermore, a smaller number of crop trees was chosen in the T1 subplot. In the T2 subplot, the type of thinning corresponded to common beech silviculture in the region at that time; the thinning was of moderate intensity, and a high number of crop trees was selected. The intensity of thinning can be indicated by the standardized stand density index (*SSDI*), which is the quotient between the *SDI* of the thinned stand and the *SDI* of the control stand [37] at the time just after thinning.

Trees that were not removed or selected as crop trees were described as indifferent trees. The analysis of the thinning trial was divided into two periods, 1980–1991 and 1991–2001, and basic stand structural characteristics were calculated for each period. Stand parameters were observed just before thinning (thus, for years 1980, 1991, 2001).

The following three parameters for each crop tree were assessed at each crop tree selection, using ranks from 1 to 5: crown size (1, large; 2, of normal size and symmetrical; 3, of normal size and asymmetrical; 4, small; 5, extraordinary small), crown suppression (1, free growing tree; 2, up to 25% of the crown with competing neighbouring crowns; 3, 25–50%; 4, 50–75%; 5, more than 75% of the crown with competing neighbouring crowns respectively), and social status (1, predominant; 2, dominant; 3, codominant; 4, intermediate; 5, suppressed) according to Kraft classes [2].

The analysis of variance (enter method) was used to test the influence of $d_{1.3}$ class and of the three parameters mentioned above on the basal area increment of crop trees. Basal area increments (i_g) per $d_{1.3}$ classes (5 cm large) for trees in the thinned and the control stands were compared with *t*-tests. Additionally, we analysed i_g of dominant trees (100 largest trees per hectare) in the thinned and control stands on both plots. The same test was applied to compare the basal area increment of crop trees and of other trees of the same size in the thinned stands.

The spatial distribution of trees was analysed using aggregation index (*R*) according to Clark-Evans [11], where edge effect was corrected according to Donnelly [12]. *R* indicates the type of distribution: a value of *R* less than 1.0 indicates a clumped distribution, larger than 1.0 a uniform distribution, and close to 1.0 a random distribution [36]. All calculations were done using SPSS (version 13.0), MapInfo Professional (Version 7.8) and Statistica (Version 6.0).

Eight relevés (inventories) of plant species composition were taken for two plots of approx. 400 m^2 each within the thinned (T1 and T2) and the control stands (C1 and C2) in July 1994. All plant species

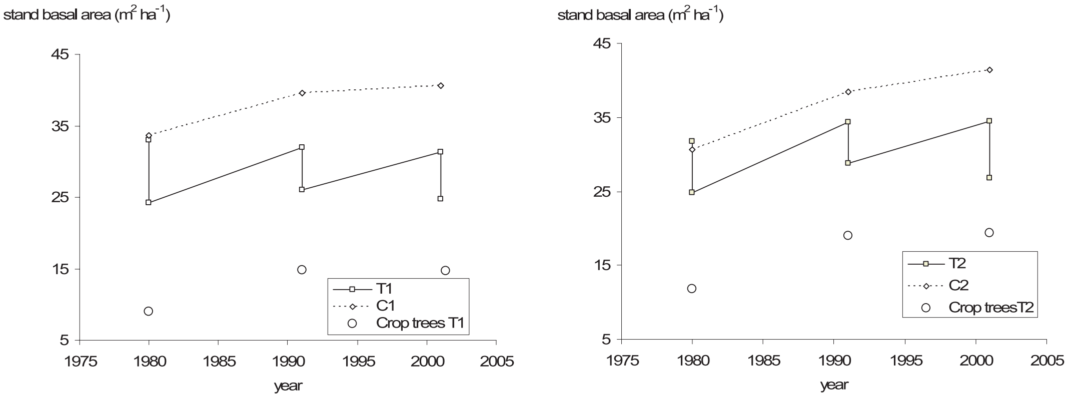

Figure 1. Development of stand basal area of the thinned (T1 and T2) and control (C1 and C2) stands.

were recorded and their abundance was estimated for each plot using the Braun-Blanquet system [6]. The estimated Braun-Blanquet cover-abundance values were replaced by the fully numerical 1–9 scale using the van der Maarel transformation [32]. Vegetation data were analysed using cluster analysis with the Euclidean distance as a measure of similarity between relevés and complete linkage method.

3. RESULTS

3.1. Stand structure and growth

The stand structure in the control subplots developed through growth, competition, and natural stem exclusion, while in the thinned subplots competition was significantly reduced (Tab. II). Between 1980–2001, stand basal area of the thinned stands decreased (T1) or slightly increased (T2), which was in contrast to the control stands, where stand basal area progressively increased (Fig. 1). At the beginning of the study, the growing stock of the thinned and control subplots was almost the same. Before the last thinning in 2001, the growing stock of the control stands C1 and C2 was 23% and 18% higher compared to the growing stock of the thinned stands T1 and T2, respectively (Tab. III).

The dominant diameter (d_{dom}) of the subplot T1 was significantly large than d_{dom} in the C1 for the whole period ($t_{1980} = 3.22^{**}$, $t_{1991} = 3.33^{**}$, $t_{2001} = 4.40^{***}$, $df = 98$) (Tab. III). In the subplot P2, no significant difference in d_{dom} between the thinned (T2) and the control stand (C2) was observed, except in 2001 ($t = 2.22^{*}$, $df = 98$).

A comparison of the diameter distribution between the thinned and control subplots in 2001 shows a smaller number of trees in the thinned subplots (Tab. III, Fig. 2). More importantly, the number of trees ≥ 40 cm $d_{1.3}$ is much higher in the thinned stands (40 tph versus 18 tph in the P1 and 36 tph versus 24 tph in the P2). Because of the selective thinning used in the thinning trial, only trees competing with up trees were removed, while small trees (10–14 cm) were left in the subplots (Fig. 2). Overall, mortality was higher in the control subplots, where it amounted to 137 tph in the C1 and 99 tph in the C2 between 1980–2001. During the same period in the thinned subplots, mortality reached only 28 tph in the T1 and 47 tph in the T2.

Table III. Stand data – development of tree number (N), mean dominant diameter (d_{dom}), stand growing stock (GS) and stand basal area (G) in the period 1980–2001.

	Year	T1	C1	T2	C2
N (ha^{-1})	1980	1002	1070	1094	982
	1991	700	1022	864	944
	2001	506	802	612	802
d_{dom}(cm)	1980	32.7	30.6	29.8	30.3
	1991	36.5	34.3	35.3	34.9
	2001	40.0	37.0	39.6	39.9
GS (m^3 ha^{-1})	1980	367	367	339	335
	1991	383	456	402	448
	2001	398	491	432	508
G (m^2 ha^{-1})	1980	33.0	33.6	31.7	30.7
	1991	31.9	39.6	34.4	38.4
	2001	31.3	40.6	34.5	41.5

Despite a lower stand density after thinning (Tab. II and Fig. 1), the annual basal increment of thinned stands (T1 and T2) between 1980 and 1991 was 22% and 15% higher than in the control subplots C1 and C2 (Tab. IV). In the second period, the annual basal area increment was still higher in the thinned stands T1 (27%) and T2 (21%) compared to the control stands C1 and C2, respectively (Tab. IV).

3.2. Basal area increment of trees

The mean annual basal area increment of trees in the thinned subplots T1 and T2 between 1980 and 1991 was respectively 78% and 25% larger (Tab. IV) than in the control subplots (C1 and C2). Between 1991 and 2001, the difference was even greater between trees of the thinned and control subplots, amounting to 105% between T1 and C1 and 61% between T2 and C2. The analysis of dominant trees (100 tph)

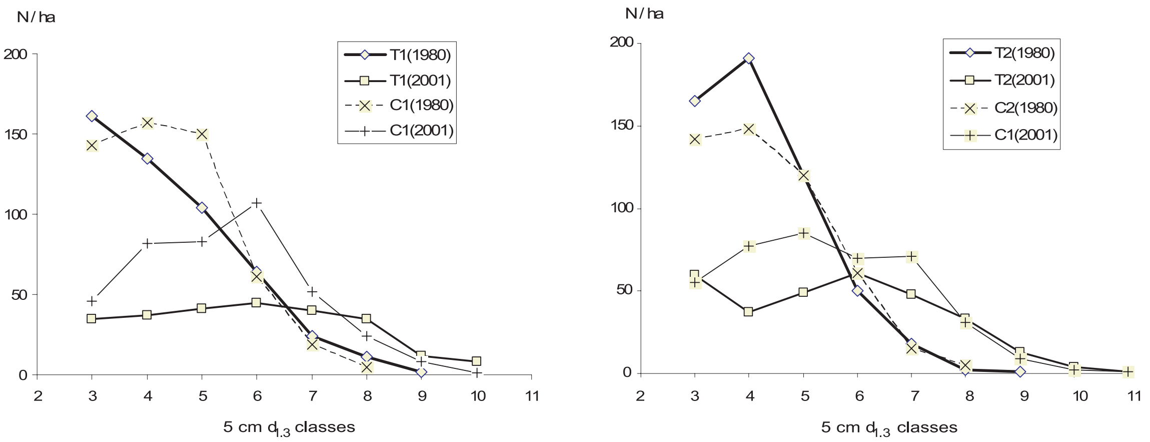

Figure 2. Diameter structure of the thinned (T1 and T2) and control (C1 and C2) stands in the years 1980 and 2001.

Table IV. Comparison of mean annual basal area increment of trees in the thinned and control subplots.

	All trees				Dominant trees	
Subplot (period)	i_g (cm^2)	N	t-test	ΔG (m^2 ha^{-1})	i_g (cm^2)	t-test
T1$_{(1980–1991)}$	10.6	700	$t = 9.01$; $df = 859$;	0.74	25.9	$t = 7.00$; $df = 98$;
C1$_{(1980–1991)}$	6.0	1022	$p < 0.001$	0.61	17.5	$p < 0.001$
T2$_{(1980–1991)}$	10.1	864	$t = 3.60$; $df = 902$;	0.87	28.2	$t = 5.01$; $df = 98$;
C2$_{(1980–1991)}$	8.1	944	$p < 0.001$	0.76	21.7	$p < 0.001$
T1$_{(1991–2001)}$	11.5	506	$t = 10.10$; $df = 654$;	0.58	23.9	$t = 7.66$; $df = 98$;
C1$_{(1991–2001)}$	5.6	806	$p < 0.001$	0.46	15.3	$p < 0.001$
T2$_{(1991–2001)}$	10.8	612	$t = 6.64$; $df = 705$;	0.66	26.0	$t = 6.71$; $df = 98$;
C2$_{(1991–2001)}$	6.7	802	$p < 0.001$	0.55	18.0	$p < 0.001$

shows similar patterns, although the difference between the dominant trees in the thinned and the control stands is smaller, amounting from 30% to 56% (Tab. IV). Moreover, there were large differences in the basal area increments between trees of different diameter classes: the basal area increment increases generally with $d_{1.3}$ class (Fig. 3). It is significantly larger in the thinned than in the control subplots for corresponding diameter classes, except for the class 8 (Fig. 3).

3.3. Number and growth of crop trees

At the beginning of the study, 176 tph were chosen as crop trees in the T1 subplot and their competitors were removed (Fig. 4). During the following two thinnings in 1991 and 2001, respectively, 188 and 184 crop trees were selected. Of the initial 176 crop trees, 126 (72%) were chosen again during the last thinning, while 36 trees of the initial crop trees (20%) were cut either in the second or the last thinning. In the T2, 258 crop trees were chosen in 1980, followed by 282 and 216 tph during the second and last thinning, respectively. Only 160 trees of the original crop trees (62%) were chosen again during the last thinning, and 70 trees (27%) of the initial crop trees were cut in the second or last thinning. In 2001, the average distance between crop trees in the T1 and the T2 subplots amounted to 5.2 and 5.0 m, respectively.

The basal area increment differed between the crop trees and indifferent trees in the thinned subplots (Fig. 5). Overall, the growth of crop trees was significantly higher. In T1, their average basal area increment in the first period was 18.9 cm^2 ($n = 88$), compared to 8.0 cm^2 ($n = 254$) for indifferent trees ($t = 11.53$, $p < 0.001$, $df = 340$). In T2, the average basal area increment of crop trees was 19.1 cm^2 ($n = 129$), compared to 6.7 cm^2 for indifferent trees ($t = 16.10$, $p < 0.001$, $df = 408$). Similarly, the average basal area increment of crop trees in the second period was 20.4 cm^2 ($n = 94$) compared to 6.5 cm^2 for indifferent trees in the T1 ($t = 17.30$, $p < 0.001$, $df = 246$) and 18.2 cm^2 ($n = 141$) versus 4.5 cm^2 ($n = 167$) for indifferent trees in the T2 ($t = 17.89$, $p < 0.001$, $df = 306$).

When analysing the trees of initial same size, which was possible for diameter classes 17.5, 22.5, 27.5 and 32.5 cm, the basal area increment of crop and indifferent trees was significantly different (t-test, $p < 0.05$) only for trees of small diameter classes (17.5 and 22.5 cm) (Fig. 5).

Analyses of variance showed that crown suppression, social status and $d_{1.3}$ classes of crop trees selected in 1991 significantly influenced the basal area increment between 1991 and

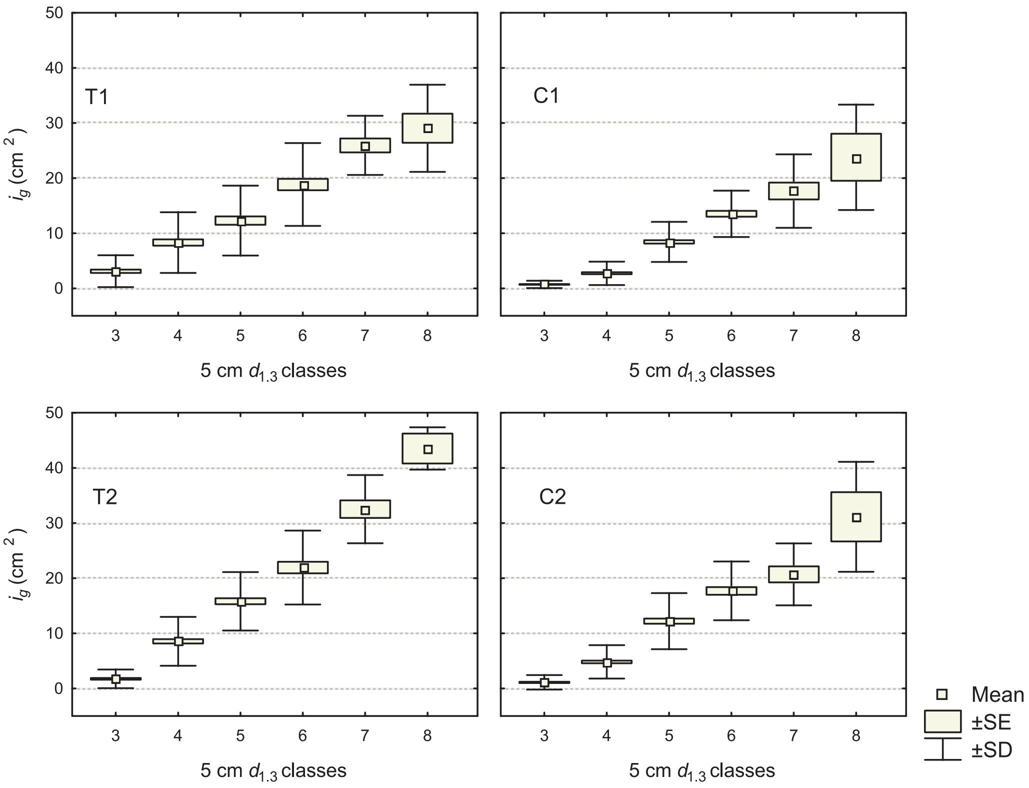

Figure 3. Annual basal area increment of trees per 5 cm $d_{1.3}$ classes between 1980 and 1991 for the thinned (T1 and T2) and the control (C1 and C2) subplots.

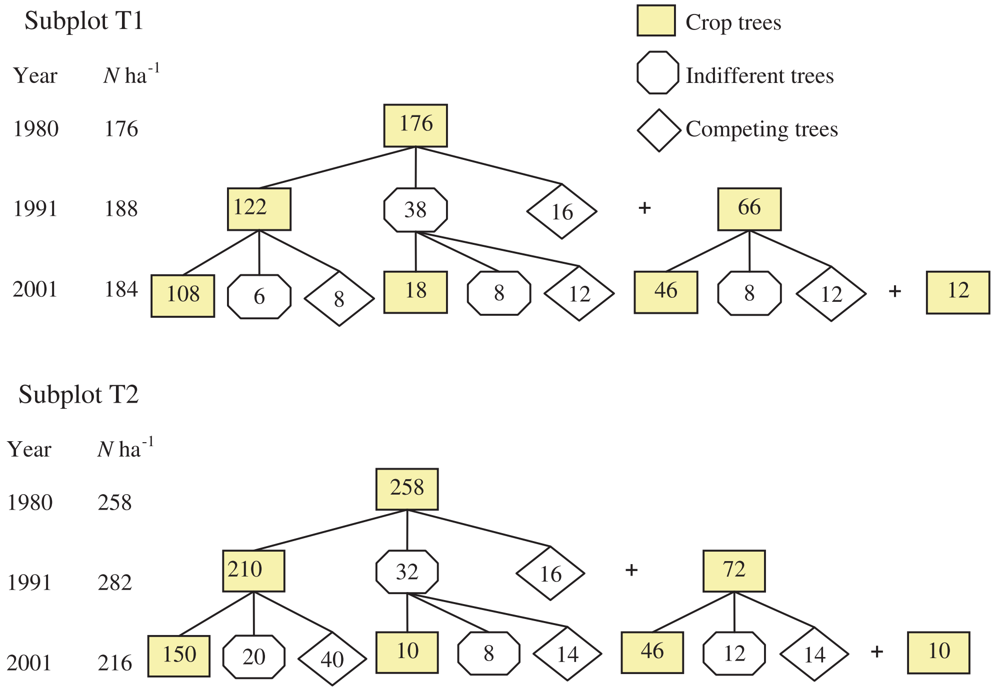

Figure 4. Evolution of the population of crop trees in the thinned stands (T1 and T2) in the period 1980–2001.

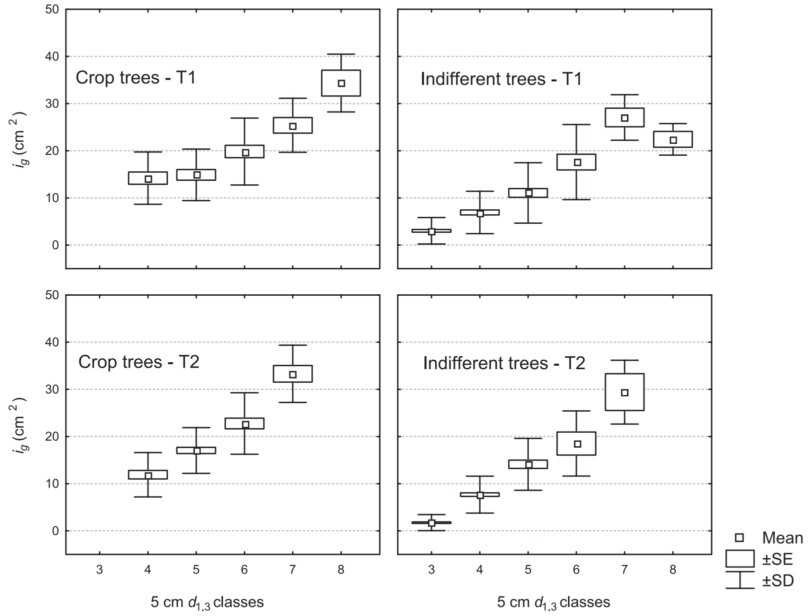

Figure 5. Mean annual basal area increment of the crop trees and indifferent trees per 5 cm $d_{1.3}$ classes in the period 1980–1991, for thinned subplots (T1 and T2).

Table V. Table of variance analyses for average basal area increment of the crop trees of the thinned stands (T1 and T2) designed in 1980 for the period 1980–1991, and of the crop trees designed in 1991 for the period 1991–2001.

Period		*df*	*SS*	*MS*	*F*	*p*
	Intercept	1	2296.22	2296.22	78.22	0.0000
	Diameter class	6	1747.81	291.30	9.92	0.0000
1980–1991	Social status	2	89.21	44.60	1.52	0.2213
	Crown size	3	133.64	44.55	1.52	0.2111
	Crown suppression	4	1031.99	258.00	8.79	0.0000
	Error	201	5900.25	29.35		
	Intercept	1	2405.84	2405.84	94.71	0.0000
	Diameter class	5	1611.46	322.29	12.69	0.0000
1991–2001	Social status	2	10.35	5.17	0.20	0.8159
	Crown size	3	61.66	20.55	0.81	0.4900
	Crown suppression	4	339.91	84.98	3.35	0.0110
	Error	220	5588.49	25.40		

2000 when the following four factors were tested: $d_{1.3}$ class, crown size, crown suppression, and social status (Tab. V).

3.4. Tree spatial distribution

The results showed that the distribution of trees in the thinned subplots was slightly more uniform compared to the control (unthinned) stands. However, crop trees in the thinned subplots were distributed even more uniformly (Tab. VI).

Clark-Evans index showed that dominant trees in the thinned stands (T1 and T2) were more uniformly distributed when compared to the dominant trees in the control subplots (C1 and C2). *t*-test of the average distance between dominant trees (l_{dom}) indicated significant differences in l_{dom} between the T1 and its control stand (C1) in 2001 ($t_{1991} = 1.79$,

Table VI. Clark-Evans index values (respecting Donnelly correction) for the spatial distribution of trees in the thinned (T1 and T2) and control stands (C1 and C2).

Sample of trees	Year	T1	C1	T2	C2
Dominant trees	1991	1.26	1.06	1.26	1.11
Dominant trees	2001	1.32	1.07	1.28	1.22
Dominant trees	2001’	1.44	1.07	1.22	1.22
Crop trees	1991	1.35	–	1.43	–
Crop trees	2001	1.41	–	1.48	–
All trees	2001	1.25	1.10	1.27	1.18

2001’: just after thinning in 2001.

Table VII. Species richness and abundance of plant species in the herb layer in the thinned and control subplots.

Subplot	Relevés	Coverage of herb layer (%)	Species richness	Mean number of species per relevé	Average sum of cover-abundance values of plants per relevé
T1	R1, R2	37.5	57	40.5	97.5
C1	R3, R4	17.5	43	31.5	69.5
T2	R5, R6	6.5	24	17.5	41.5
C2	R7, R8	7.0	21	16.0	33.5
Total	8	17.1	68	26.4	60.5

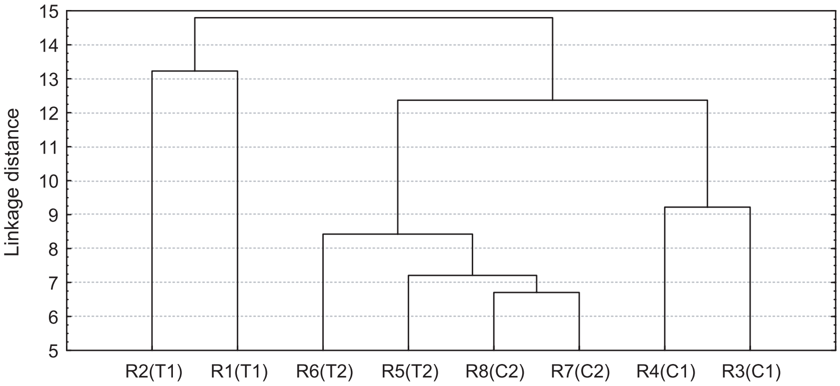

Figure 6. Cluster analysis of eight relevés of plant species in the herb layer.

t_{2001} = 2.22* and t_{2001}' = 3.23**). However, no significant difference in the I_{dom} between the dominant trees of the T2 and the control stand C2 was detected.

3.5. Species richness and abundance of herb layer

The floristic composition is more diverse and the abundance of plant species is greater in the thinned stands compared to their control stands (Tab. VII). This is more significant in the P1, where 57 plant species where recorded in the T1 (thinned with heavier intensity) versus 43 in the control stand (C1). There is just a slight difference in species richness between the T2 (thinned with moderate intensity) and its control (C2).

The highest similarity of floristic composition is found between the relevés taken in the same subplot (Fig. 6). However, relevés from the T2 and its control stand (C2) are quite similar. The floristic composition from the control stand C1 is more similar to the one of the T2 and C2 subplots although they are 700 m far, than to the floristic composition of T1 lying close to C1. Comparison of relevés from the control stands (R3 and R4 versus R7 and R8) indicates differences in site conditions between plots P1 and P2 (Fig. 6 and Tab. VII).

4. DISCUSSION AND CONCLUSIONS

Thinning caused significant changes in the forest structure during the experiment. Although the selection type of thinning is primarily oriented to the crop trees, the results concerning total stand growth are also interesting. One of the major changes in the thinned subplots, compared to the control subplots, was the decrease in standing basal area accompanied by an increase in basal area increment. During the 21-year thinning trial, the stand basal area increment was approximately 20% higher in the thinned subplots compared to the control subplots. This phenomenon is known as "growth acceleration". Similar results were found in other Central European forests [2, 15, 28, 37]. Compared to the control subplots, the increase of basal area increment was higher in the T1, where higher thinning intensity was carried out. The results are partly in accordance with Pretzsch model of periodic annual volume increment dependent on stand density [37], where periodic volume increment increases predominantly in young beech stands on favourable sites with decreasing stand density. However, his model describes growth reaction to thinnings from below.

There was a significant difference in the basal area growth of dominant trees (100 thickest tph) between the thinned and control subplots; in both thinning periods average basal area increments of dominant trees are 30–56% larger compared to those of dominant trees in control subplots. In both thinning periods the relative basal area increment of dominant trees is greater in the subplot with higher thinning intensity T1 when compared to the relative i_g of dominant trees in the T2, 1.48 and 1.56 versus 1.30 and 1.40, respectively. This is slightly different if compared to the results of Utschig [50], who studied the effects of thinning from below in beech stands. In his study a 20% reduction in stand basal area compared to that of a control stand did not significantly influence the diameter increment of the largest diameter beech trees. A reduction of 30% resulted in a temporary increase of the diameter increment of large trees in the thinned stand, and a reduction of 40% resulted in a higher increment for large trees compared to the control stands throughout the experiment. However, diameter increment of large trees does not depend only on stand basal area reduction but significantly on thinning type. Under selection thinning, the main competitors of crop trees are removed, and usually they belong to dominant trees. The results from our research show a difference in growth between crop trees and other (indifferent) trees of the same diameter in the thinned subplots. However, the difference is significant only for small diameter trees, which probably benefit more than larger ones of the removal of competitors in the dominant layer. Similar results were found by Utschig and Kusters [49].

In our research site, diameter was an important factor that influenced basal area growth in the thinned and control subplots. At the same time, the difference in basal area growth between trees of the same diameter class in the thinned and control subplots, as well as between crop trees and other trees in the thinned subplots, showed the importance of competition through the release of tree crowns which benefited from thinning. Analyses of variance show that for basal area growth of crop trees, crown suppression and diameter class are more important factors than social status or crown size. The results are in agreement with a nonlinear model of basal area increment for beech developed by Cescatti and Piutti [10], where 88% of the variability of tree basal area increment was explained by tree diameter and a competition index.

Under the concept of selective thinning, the number of crop trees should decrease with stand development [31, 43]. The results of our study concerning the density of crop trees are rather surprising. Before the first thinning 176 and 258 crop trees per hectare were selected in the T1 and T2, respectively. The number of crop trees selected in the second thinning increased (188 and 282 in the T1 and T2, respectively), while only in the third thinning a reduction in crop tree number is noticeable (184 tph and 216 tph in the T1 and T2, respectively). The criteria for crop tree selection were more severe at the first selection, as in some "thinning cells" no crop trees were selected and then the total number of crop trees was lower compared to the next thinning. Considering the dominant heights of the thinned stand (25.5–27.3 m) in the period 1981–2001, the number of crop trees are lower compared to Leibundgut's [31] suggestion for beech stands, amounting to 320 and 220 crop trees per hectare at the dominant heights of 25 and 30 m, respectively. On the other hand, the number of crop trees in the three thinning periods is rather high compared to other approaches, where at the beginning of thinnings a smaller number of crop trees are selected, e.g. 100–160 tph in Lower Saxony [16]. In one of the long-term research plots in that region, 188 crop trees were selected at a stand age of 52 years and only 96 crop trees remained at a stand age of 154 years following thinnings [16]. In the final state, we expect around 150 crop trees per hectare (approx. 130 in the T1 and 170 in the T2). Under the traditional beech silviculture of this region even higher numbers of crop trees were suggested (170 to 200 tph). Schütz [46] recommended a value of 150 final crop trees per hectare in beech stands, and in the thinning trial "Fabrikschleichach 15" 97–156 final crop trees were registered [15], while much lower (< 100 tph) numbers of crop trees were recommended for beech stands thinned from above [16, 23].

In spite of a decreasing number of crop trees with stand development, some trees not selected as crop trees in past thinnings can be newly selected as crop trees in subsequent thinnings. This is typical for selection type of thinning, even more evident in mixed than in pure stands [33,44]. Several different processes, including decision making from forest managers and natural processes, are involved in crop tree selection. Before the next thinning, the selection of crop trees may be slightly different because of an insufficient reaction of former crop trees to thinning [33] or due to damage caused by thinning itself [25]. Schober [44] presented on overview of "alteration of crop and dominant trees" in the stand development, arguing for higher number of crop trees, selected in younger phases compared to the final number of crop trees.

The number of selected crop trees and thinning intensity may influence the "alteration" of crop trees. In the second thinning and partly in the third thinning of our trial, it is likely that too many crop trees were selected. This is enlightened by the cutting of ex-crop trees in subsequent thinnings. The recommended guideline could be that crop trees should be selected before the thinning in such a way that they would not be cut as competitors of the selected crop trees in the next thinning. If too many crop trees are selected relatively to the thinning intensity, then selective thinning cannot be beneficial to all selected trees. This is evident also from our study, especially in the stand T2 (lower thinning intensity), where only 62% of the initial crop trees were selected again in the last thinning compared to 72% in the T1 (higher thinning intensity).

The high number of crop trees in the young stands and alteration of crop trees caused one of the main weaknesses of the selection thinning type, namely, high costs. In the total stand tending costs, thinning represents the major part [46]. Therefore, modifications of selection thinning towards the designation of a smaller number of crop trees in the young stands compared to classical selection thinning are recommended. In this phase thinning intensity would be lower; in older stands, when timber of removed trees reaches higher prices on the market [46], thinning should be of higher intensity. By this approach, it is still possible to alter the population of crop trees during the stand development, which can be especially important in mixed stands to help adapt tree species composition to changing timber markets. Moreover, the concept of "classical" selection thinning is often understood as nature based thinning [13] as the number of crop trees correspondently decreases with the total number of stand trees.

The type of thinning used in our research contributed to the uniform spatial distribution of trees, especially for crop trees, but also dominant trees in the stand T1 (thinned with heavier intensity), which were more uniformly distributed than the dominant trees in the control subplot. A more uniform spatial distribution of crop trees was expected because spatial distribution of trees was considered when selecting crop trees. If trees are not uniformly distributed with regard to the quality and vitality, then crop trees can be selected into clumps. On sites where trees naturally tend to form clumps (our site was not such a case), it is advisable to maintain such a distribution when thinning to ensure the stability of the stands.

Aside from stand growth and production, thinning indirectly influences other components of the forest ecosystem. The results from our study show a significant influence on the herb layer. In the thinned subplots, the species richness and abundance of plant species were higher. Similar results were found in beech and oak forests in southern Sweden [7].

In this study, only some of the effects of thinning were studied, while many other aspects of thinning, important for the management of beech forests, including timber quality, the incidence of red heart, stand stability, and habitat conditions were put aside. Therefore, there is a strong need to gain knowledge about the effects of different thinning regimes in beech forests, which will contribute to improve beech forest management.

Acknowledgements: We would like to thank Marijan Kotar, Tom Nagel, and anonymous reviewers for improving an earlier version of the manuscript.

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