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Pre-commercial thinning in naturally regenerated stands of European beech (*Fagus sylvatica* L.): effects of thinning pattern, stand density and pruning on tree growth and stem quality

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Pre-commercial thinning in naturally regenerated stands of European beech is often expensive and must be justified by improved development of the remaining crop. Based on a field experiment established in two 14-year-old naturally regenerated beech stands in Denmark, we investigated some effects of pre-commercial thinning and pruning on future crop tree growth and stem quality. The treatments included (1) no thinning, (2) moderate to heavy strip thinning, with or without subsequent selective thinning, and (3) extremely heavy strip thinning in two perpendicular directions (checkerboard thinning), with or without subsequent selective thinning and with or without pruning. The resulting residual stand densities ranged from 10^5 to only 200 ha^{-1}. Treatment effects were evaluated on one potential future crop tree for every 100 m^2. Potential future crop trees were selected 32 years after germination based on spatial distribution, growth potential and stem quality. Total crop tree height was unaffected by strip thinning, but reduced by checkerboard thinning. Stem diameter at 1.30 m above ground level increased with decreasing stand density but, for checkerboard thinning, was reduced by pruning. The lower live branch was located at a lower position with heavy strip thinning and with checkerboard thinning without pruning. The frequency of crop trees with a forked stem was largest with checkerboard thinning and these forks were located at a lower position. Stem tilt and stem bend (stem straightness) were essentially unaffected by thinning practice. However, pruned trees tilted less and had straighter stems. The initial formation of epicormic branches on crop trees was unrelated to thinning and pruning practice, but crop trees that had been pruned for these were less prone to subsequently develop epicormic branches. In summary, moderate to heavy pre-commercial thinning had no effect on stem quality, while extremely heavy thinning without pruning resulted in unacceptably low stem quality. The no-thinning option resulted in acceptable growth and stem quality of the crop trees and this remains a viable management alternative for young beech.

Introduction

Transition to close-to-nature forestry over much of Europe has led to increased focus on native tree species that regenerate naturally in continuous cover forestry systems. As part of this process, European beech (*Fagus sylvatica* L.) covering 120,000 km^2 (Hemery, 2008) is likely to become an increasingly important species in large parts of Europe.

Natural regeneration of beech often results in high stand densities and are generally managed according to two alternative strategies (Teissier du Cros, 1981; Henriksen, 1988; Armand, 2002): (1) the stand is left unthinned until natural pruning has progressed to a sufficient height above ground, or (2) tending and thinning interventions are initiated quite early to promote stem diameter growth. With the second strategy, the first thinning aims to reduce competition by removing wolf trees and other undesirable competitors and to gain access to the stand interior. Such thinning operations are often made at a cost for the forest owner and are commonly justified by faster growth or improved stem quality of the most valuable trees in the stand, i.e. the potential future crop trees (hereafter referred to as crop trees). To reduce the costs of early thinning, mechanized systematic thinning, such as mulching of 1–4 m wide strips, is sometimes used in Denmark (Bruun, 1999; Madsen and Petersen, 2002), Sweden (Löf *et al.*, 2009) and France (Armand, 2002).

While many studies have found that thinning of beech results in increased diameter growth (e.g. Bryndum, 1980; Ekö *et al.*, 1995; Bončina *et al.* 2007; Diaconu *et al.*, 2015), studies that investigate the effect of early thinning on stem quality in beech are scarce. Studies of planted beech stands indicate that stem quality deteriorates for planting densities less than ~5000 trees ha^{-1} (Jørgensen and Hansen, 2004; Jørgensen and

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Hansen, 2012; Leonhardt and Wagner, 2006), and some, possibly more perfectionistic interpretations, indicate a decrease in stem quality for initial stand densities less than ~10 000 trees ha^{-1} (Krahl-Urban, 1963). This indicates that a substantial reduction in stand density could have adverse effects on stem quality in young stands. Other studies indicate, however, that unthinned beech stands have less straight stems than thinned stands (Holmsgard, 1985). Another effect of heavy thinning in beech is the maintenance of a long green crown and thus a shorter branch-free ('clean') bole (e.g. Bryndum, 1980; Langshausen, 2009). Therefore, to maintain fast individual tree growth while ensuring sufficient bole length, heavy thinning is sometimes combined with pruning of crop trees (Skovsgaard *et al.*, 2018). However, severe pruning of trees has been reported to reduce diameter growth (Møller, 1962) and may provoke formation of epicormic branches in some species (e.g. Savill *et al.* 1997).

In this study we used different combinations of selective and systematic thinning in two young, naturally regenerated beech stands to obtain a wide range of residual stand densities and investigated the effect of thinning on tree growth and a range of variables related to stem quality. We specifically addressed:

- the effect of early thinning on crop tree height, stem diameter and stem quality; and
- the effect of pruning on crop tree height, stem diameter and stem quality in heavily thinned beech stands.

Material and methods

The data were collected in Denmark from three replicated blocks of a thinning experiment in naturally regenerated beech (Figure 1). Blocks 1416W and 1416E are located adjacent to each other in Boller Upper Forest [WGS84: 55.833790 °N, 9.868695 °E], and block 1417A is located ~3 km away in Rold Forest [WGS84: 55.819400 °N, 9.906880 °E].

All blocks are situated in moderately undulating terrain at an elevation of 33–41 m above sea level on soils derived from glacial till (Table 1). At installation of the experiment, the ground flora was dominated by *Anemone nemorosa* L., *Stellaria holostea* L., *Deschampsia cespitosa* (L.) P. Beauv. and *Rubus idaeus* L. During 2001–2010 the mean annual precipitation was 700 mm, the average annual temperature was 8.6°C, and during the 5-month growing season from May to September the mean precipitation was 327 mm and the mean temperature was 14.5°C (Wang, 2013).

Blocks 1416 W (2.56 ha) and 1416E (2.04 ha) were installed adjacent to each other in a beech stand that germinated mainly in 1984. The previous generation was beech of local origin with a sparse admixture of European larch (*Larix decidua* Mill.). Site preparation was carried out by disc harrowing during autumn 1983, and following seed fall, the mast was subsequently mixed and covered loosely with soil, humus and litter by dragging a log across the area. There was no thinning in the overstorey at the time of regeneration. Most of the overstorey trees were felled in 1985, 1997 and 2002–2004, but a few trees of beech and larch were left in the stand (Table 2). The retained beech trees were ring-barked in 2009 to decay naturally and to allow for the development of the regeneration while avoiding felling damage. Block 1417A (1.2 ha) was installed in a pure beech stand that was regenerated using a similar method as in blocks 1416 W and 1416E (Table 2). The regeneration was remarkably dense and uniform in all three blocks.

The experiment was installed in spring 1998, 14 years after germination. When the treatments were initiated in 1998, the live stand density of young beech averaged 126 000 ha^{-1} before thinning, but individual plot stand densities ranged between 78 000 and 133 000 ha^{-1}. Before thinning, individual plot basal areas ranged between 5.1 and 8.9 m^2ha^{-1}. Mean total tree height (h_{total}) was 2.59 m in block 1416 W (n = 2393), 2.33 m in 1416E (n = 2392), and 2.48 m in 1417A (n = 918). The ranges of h_{total} were almost identical among blocks (0.16–5.60 m).

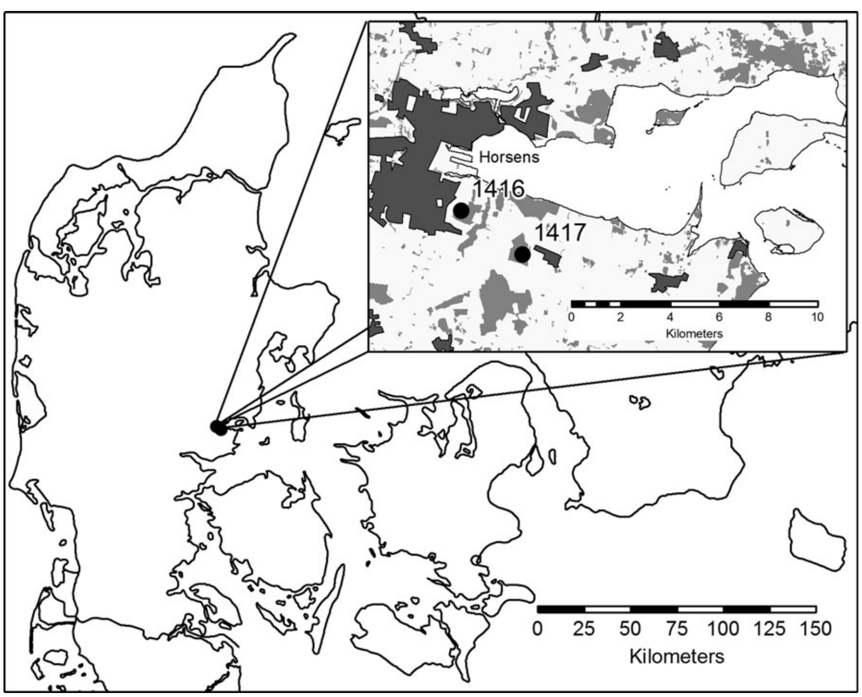

Figure 1 Location of the three experimental blocks 1416W, 1416E and 1417A near the city of Horsens in Denmark. Legend: black dot = experimental block, grey = forest, dark grey = urban area.

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Table 1 Soil characteristics of the beech thinning experiment in Boller Upper Forest and Rold Forest

Block	pH[1]	N mg g^{-1}	P mg g^{-1}	K mg g^{-1}	Ca mg g^{-1}	Mg mg g^{-1}	Na mg g^{-1}	C mg g^{-1}	C/N	CEC mmol(+) g^{-1}	BS %	Organic matter %	Clay[2] %	Silt[2] %	Sand[2] %
1416W	3.9	0.84	51.6	78.1	379.4	128.4	39.6	9.3	11.1	6.8	45.0	1.63	15.3	26.5	58.3
1416E	3.9	0.59	21.1	66.4	231.3	116.4	29.6	6.8	11.5	6.5	35.4	1.30	16.5	28.3	55.3
1417A	4.0	0.77	27.4	31.1	166.9	63.2	23.7	12.3	16.0	4.2	32.9	2.25	9.5	23.3	67.3

Mean block values for the upper 1 m of topsoil sampled in four randomly selected treatments (1, 2, 2.5 and one checkerboard treatment) of each block during 2005. According to FAO's international soil classification system (WRB, 2015) the soil textures can all be classified as sandy loam.
[1]pH was measured in $CaCl_2$. P was measured in 0.1 M H_2SO_4; K, Ca, Mg and Na in NH_4NO_3 (Na by ICP).
[2]Soil texture limits: clay = 0–2 μm, silt = 2–63 μm, sand = 63–2000 μm. Soil texture was adjusted for organic matter content.

Table 2 Overstorey trees in the thinning experiment in beech for the blocks 1416W, 1416E and 1417A

Block	Germ.		1998 at installation				2002 before thinning				2003 after thinning			2004 after thinning		
		Size ha	N ha^{-1}	H m	D_g cm	V m^3ha^{-1}	N ha^{-1}	H m	D_g cm	V m^3ha^{-1}	N ha^{-1}	D_g cm	V m^3ha^{-1}	N ha^{-1}	V m^3ha^{-1}	Larch %
1416W	1894	2.54	38	31.3	65	231	36	32.4	67	246	21	66	135	4	26	10
1416E	1906	2.04	53	30.8	60	274	52	32.0	63	303	27	62	159	5	32	36
1417A	1892	1.20	57	29.1	62	292	56	29.7	65	320	27	61	136	3	13	0

Germ. = year of germination for overstorey trees, N = stem number, H = mean stand height, D_g = quadratic mean diameter, V = standing total stem and branch volume, Larch = percentage larch (by stem number) in the remaining overstorey.

Stand top height (calculated according to the footnote in Table 4) was between 3.3 and 4.7 m.

The average size of the plots included in this study was 799 m^2 (range: 330–1659 m^2). The variation in plot size was due to the physical shape of the forest, the forest structure at the initiation of the experiment, and consideration to the expected stem numbers at the end of the rotation for the different treatments. Each plot is surrounded by a buffer zone of varying width subjected to the same treatment as the plot. The experiment includes nine different treatments, ranging from a strictly unthinned control (treatment 1) to different variations of systematic and selective thinning and pruning carried out at different stages of stand development (treatments 2, 2.5, 3, 3.5, 3 P, 3.5 P and 8, see Table 3 and Figure 2). One treatment, (treatment 5, late thinning) was still unthinned at the initiation of this study and therefore served as a replicate of the unthinned controls. Each of the investigated treatments are replicated in a randomized block design, apart from two treatment replicates which, due to the limited area available, did not fit into block 1417A (Table 4).

In the unthinned control plots (Figure 3a), no trees, whether dead or alive, were felled or removed at any time during the duration of the experiment.

Systematic thinning was applied only in 1998. In treatments 2 and 2.5 (Figure 3b), a tractor-driven mulcher removed an entire 1.5 m swath (range of swath width: 1–2 m) of young beech trees alternating with 1.5 m wide strips of beech remaining through the stand (range of strip width: 1–2 m). In these treatments, stand density was reduced by ~50 per cent, and the remaining strips of beech remained fully stocked. In treatment 8, the mulcher removed 3 m wide strips alternating with 1.5 m wide strips of beech. In this treatment, stand density was reduced by two-thirds and, again, with fully stocked strips of beech across the area. Treatments 3, 3.5, 3 P and 3.5 P (Figure 3c) were thinned by mulching a 1–2 m swath of young beech trees both transversally and longitudinally through the stand. This created a type of checkerboard pattern of disconnected, fully stocked, ~1 m^2 squares of beech. This resulted in a reduction in stand density of 83–89 per cent.

Selective thinning was initiated in treatments 2.5, 3, 3.5, 3 P and 3.5 P during spring 2002 (1416 W and 1416E, age = 18 years) and 2003 (1417A age = 19 years). In treatment 2.5, one superior tree in terms of growth potential and stem quality was selected for every 1 m strip length to remain in the stand and all other trees were felled motor-manually. This resulted in a residual stand density of ~3000 trees ha^{-1}. In the checkerboard treatments 3, 3.5, 3 P and 3.5 P, one superior tree was selected for each 1-m^2-square and all other trees were removed by thinning using a brush cutter. In treatments 3 P and 3.5 P, approximately one third of the remaining trees (mean h_{total} = 6.12 m) were pruned to a mean height of 3.17 m above ground level (range: 1.46–4.30 m) in 2003 (age = 19 years). The mean height to lower live branch (h_{llb}) before pruning in 2003 is unknown but was 1.58 m in unpruned plots in 2005. Thus, ~35 per cent of the live crown length was pruned in 2003. In 2009 (age = 25 years), treatments 3.5 and 3.5 P were thinned to a residual stand density of ~200 ha^{-1} and in all 3 P and 3.5 P plots a similar number of trees were pruned or re-pruned to a mean height of 6.10 m above ground level (range: 2.15–7.25 m). Mean h_{total} of the pruned trees in 2009 was 8.53 m. Given the assumption that h_{llb} did not change between after pruning in 2003 and before pruning in 2009, roughly 40 per cent of the live crown length was removed in the pruning in 2009. In 2013 (age = 29 years), pruned trees were re-pruned for epicormic branches up to 6 m. In 2017, stand basal area in the investigated plots ranged from 4.8 to 36.8 m^2ha^{-1} as a result of the large differences in thinning intensity between treatments (Table 4).

Selection of crop trees

In 2016 (age = 32 years), one potential future crop tree was selected for every 100 m^2 plot area. Only trees inside the net plots were

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Table 3 Treatment overview. Legend: x indicates the year and type of intervention in each treatment, and the percentage (systematic thinning) or number (selective thinning) of remaining trees is given in parentheses.

Treatment	Description	Year (age)					
		1998 (14 yrs.) Pre-commercial thinning	2002 (18 yrs.) Heavy selective thinning	2003 (19 yrs.) First pruning lift to 3 m (P)	2009 (25 yrs.) Heavy selective thinning	2009 (25 yrs.) Final pruning to 6 m	2013 (29 yrs.) Pruning of epicormics to 6 m
1	Unthinned control	(100%)					
2	Strip thinning (spacing ~1.5 m)	x (50%)					
2.5	Strip thinning (spacing ~1.5 m) and selective thinning	x (50%)	x (3000 ha^{-1})				
8	Wide strip thinning (spacing ~3 m)	x (33%)					
3	Checkerboard thinning and selective thinning	x (15%)	x (800 ha^{-1})				
3 P	Checkerboard thinning, selective thinning and pruning of 200 trees/ha	x (15%)	x (800 ha^{-1})	x		x	x
3.5	Checkerboard thinning and two selective thinnings	x (15%)	x (800 ha^{-1})		x (200 ha^{-1})		
3.5 P	Checkerboard thinning, two selective thinnings and pruning of remaining trees	x (15%)	x (800 ha^{-1})	x	x (200 ha^{-1})	x	x

considered. A total of 221 crop trees were selected according to the following criteria (in order of priority):

- Regular spatial distribution. Each plot was divided into sub-plots of 10 m × 10 m. Within each sub-plot only one crop tree could be selected and, as a general rule, a crop tree should be located at least 7 m away from any other crop tree and at least 2 m away from the plot edge.
- Forking. Trees without forking or forking above 6 m were preferred. Forking is defined as a branching into two or more stems for which the diameter of the second largest is more than 50 per cent of that of the largest and the branching is at a steep angle.
- Large stem diameter and large crown. Trees with a large crown and a large stem diameter, indicating a large growth potential, were preferred. As a consequence, crop trees were practically always selected among the dominant trees in the stand.
- Straight stem. Trees with a straight stem were preferred.
- Vertical stem. Trees with a vertically rising stem were preferred.
- High natural pruning. Trees with a high natural pruning were preferred.
- No thick steep branches. Trees without steep branches on the lower stem were preferred.
- Low tendency to produce epicormic branches. Trees without epicormic branches were preferred.

The identification and selection of crop trees included an element of subjectivity, but great care was exerted to ensure consistent use of the selection criteria. In several plots, crop tree selection was inspired by previous work (thinning, pruning and early, preliminary marking of potential future crop trees, as outlined above), but no previous markings or selections were given priority in the final selection. The selection of crop trees for this study was performed by one of the authors and, after data collection, subsequently reviewed and revised carefully together with a co-author.

Measured variables

In 2016, 11 different measurements were made on each crop tree, resulting in 14 different variables related to growth capacity and exterior stem quality. The measurements are described in Table 5 and also depicted in Figure 4 for some of the qualitative variables. Spiral grain was originally included in the measurements as a visual assessment, but was dismissed because no crop trees with exterior signs of spiral grain were encountered.

To evaluate the effect of overstorey trees on growth and stem quality, the presence of overstorey trees was noted if the distance was less than 10 m from the crop tree.

The presence and number of epicormic branches on crop trees was recorded in 2013 (after crop trees had been high pruned in 2003 and 2009, but before being pruned for epicormic branches in 2013) and again in 2016. In our analyses, we included the presence of epicormic branches in both 2013 (epicormic $branches_{2013}$) and 2016 (epicormic $branches_{2016}$) to assess (1) the effect of high pruning (i.e. removal of a large part of the foliage) on the emergence of epicormic branches and (2) the effect of thinning regime on the reemergence of epicormic branches that had been pruned.

Statistical analysis

We divided the analyses into two separate parts. The first analysis focused on the effects of thinning and included only unpruned plots (179 crop trees). The second analysis focused on the effect of pruning and included pruned and un-pruned replicates (69 crop trees in

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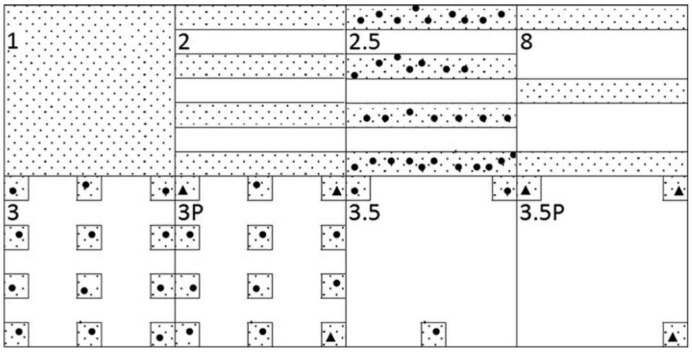

Figure 2 Treatments included in this investigation. Legend: for treatments without selective thinning (1, 2 and 8) small dots indicate remaining trees. For other treatments small dots indicate trees removed in selective thinning in 2002, large dots indicate remaining trees, and large triangles indicate remaining, pruned trees.

treatments 3, 3 P, 3.5 and 3.5 P). For the second analysis we excluded treatments 3 P and 3.5 P in block 1417A because this block did not include the un-pruned treatments 3 and 3.5 for comparison. This resulted in a balanced design and ensured a valid statistical test of the effect of pruning.

We analyzed the treatment effects on the continuous variables in Table 5, using the following two mixed linear models for the first (1) and second (2) analysis, respectively:

$$V_i = \mu + \alpha(Thinning_i) + \theta(Overstorey_i) + \delta(H_{98}) + \beta(Block_i) + \varepsilon_i, \quad (1)$$

$$V_i = \mu + \alpha(Thinning_i) + \gamma(Pruning_i) + \theta(Overstorey_i) + \delta(H_{98}) + \beta(Block_i) + \varepsilon_i, \quad (2)$$

where V_i is any of the continuous variables (e.g. *dbh*, h_{total} or h_{llb}) measured for the *i*th tree, *Thinning* is a class variable indicating the thinning treatment, *Pruning* is an indicator variable of pruning or no pruning, H_{98} is the plot-specific top height at initiation of the experiment in 1998

Table 4 Plot data for treatments

Treatment	Number of plots	Plot size (m^2)	Stem number (ha^{-1})	Basal area ($m^2\ ha^{-1}$)	Top height[1] (m)	
			2017	2017	1998	2016
1	8	700–900	4688–8313	28.0–35.3	3.3–4.7	14.7–16.6
2	4	588–1183	4886–6633	31.7–36.8	3.8–4.3	14.9–16.4
2.5	3	719–1013	2671–2865	25.4–29.1	3.7–4.1	15.1–16.3
8	3	463–825	4163–6609	30.8–33.7	3.5–4.1	14.7–16.9
3	2	735–1659	766–789	19.8–20.2	3.6–4.0	14.0–14.7
3 P	3	543–996	653–866	17.7–20.4	3.7–4.1	13.5–14.8
3.5	2	524–656	191–213	8.7–9.6	3.6–4.0	13.6–14.6
3.5 P	3	330–1056	182–297	4.8–10.0	3.8–4.3	12.8–14.2

[1]In 1998, the mean height of the three tallest trees in each of three transects (total transect area was roughly 5 per cent of total plot area) was used as a proxy for stand top height in plots smaller than 950 m^2. For every 300 m^2 increase in plot size, one more tree in each transect was used for the calculation. In 2016, the mean crop tree height was used as a proxy for stand top height.

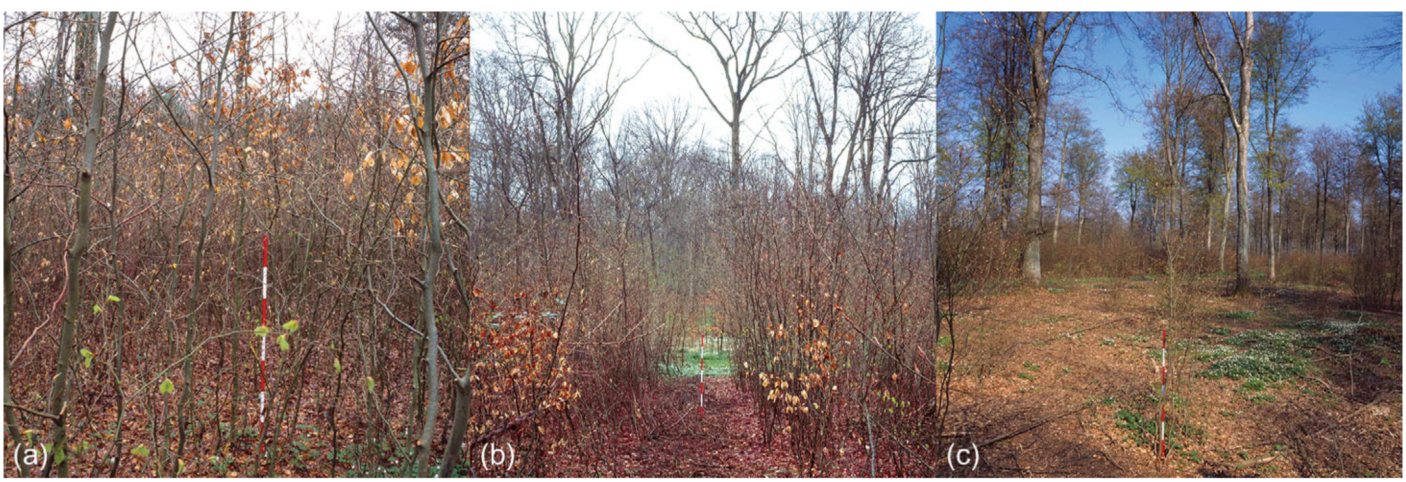

Figure 3 Young naturally regenerated beech stands (a) without thinning, (b) with strip thinning, and (c) with checkerboard thinning. Photos: Jens Peter Skovsgaard, experiment 1416 in spring 1999 (one year after the first pre-commercial thinning).

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Table 5 Variables measured directly or derived from measurements on selected crop trees

Variable	Description	Variable type
dbh	Diameter at 1.3 m above ground level measured by cross-calipering.	Continuous
h_{total}	Vertical distance from ground level to tree top measured using a Haglöf Vertex IV clinometer.	Continuous
h_{llb}	Height to the uppermost part of the junction between stem and branch measured with an 8 m Messfix telescope measuring stick. Only branches below 8 m were included.	Continuous
h_{fork}	Height to the uppermost point of the junction between the two (or more) stems measured with an 8 m Messfix telescope. Only forks below 8 m were included.	Continuous
Tilt	Absolute stem deviation from vertical, measured as the distance from the stem base to a vertical projection of the stem at 1.3, 3.0 and 6.0 m above ground.	Continuous
Angle of tilt	The direction of the stem tilting (to the nearest 5°).	Continuous
Bend	The maximum deviation of the stem from a hypothetical straight line from 0 m to the 6 m at 1.3 or 3 m derived from the tilt measurement.	Continuous
Forking	Presence of one or more live forks below 8 m.	Binary
Epicormic branches	Presence of live epicormic branches below 6 m. Presence of epicormics was recorded in 2013 (before cutting off epicormic branches) and 2016, and both assessments were included in the analyses.	Binary
Straightness	Whether or not the stem was straight in 2 planes below 6 m.	Binary
Transverse bends	Number of sinuous bends on the stem below 6 m.	Count

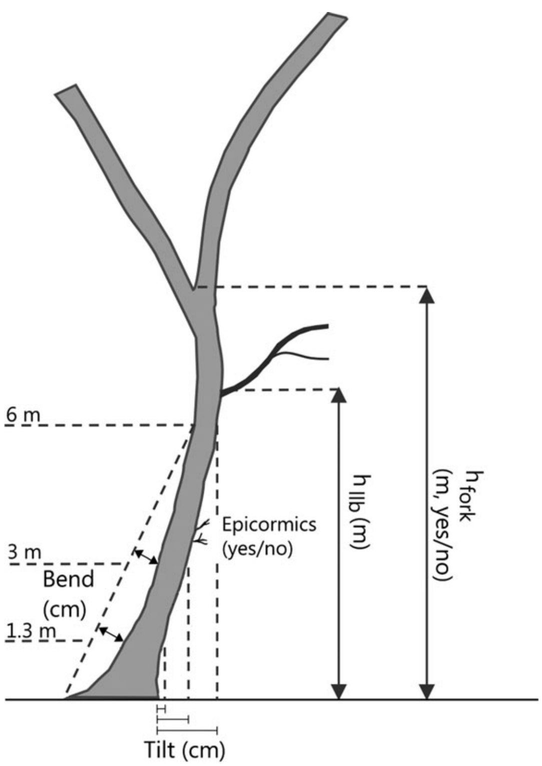

Figure 4 Measurements of variables related to stem quality. Legend: h_{llb}=height of lower live branch, h_{fork}=forking height.

(described in Table 4), *Overstorey* is an indicator variable for the presence of an overstorey tree within 10 m from the *i*th tree, $Block \sim N(0, \sigma_B^2)$ is a random effect, and $\varepsilon_i \sim N(0, \sigma^2)$ is the residual error.

During the initial evaluation of different variance structures, a likelihood-ratio test of equation (1) using h_{total} as the response variable showed a significant effect (P<0.001) on model likelihood of *Block* included as a random effect. We also attempted using the individual plots as a random variable to account for within-plot correlations but this resulted in poorer (larger) AIC values. Consequently, reflecting the statistical design of the experiment, we used *Block* as a random effect through all analyses to mitigate possible correlations between trees within the same block.

The statistical analyses of the continuous variables were performed using the *lme* function of the *nlme* package in R (using the maximum likelihood method for model reduction, and using the restricted maximum likelihood method for extracting estimates as well as pairwise comparisons). Some response variables were transformed by square root (tilt at 1.30, 3.00 and 6.00 m and bend), squaring (h_{llb} in the analysis of pruning effects) and cubing (h_{fork}) because this resulted in improved normality and homoscedastic residuals. Model reduction of variables was performed by likelihood-ratio tests, and pairwise comparisons between groups of variables were tested using a Wald test. Unless both the variable and some pairwise comparisons were significant, the variable in question was considered not to have a significant impact. As H_{98} was a continuous variable, it was evaluated only from the likelihood-ratio test.

For variables that had a binary or count response, the function *glmer* in the package *lme4* was used for analysis of generalized mixed linear models, with either logistic or Poisson regression. The statistical models are similar to (1) and (2) except for the response variable. Model evaluation was made using the function *cumres* in the package *gof*. As for continuous variables, H_{98} was included in the initial models for the categorical response variables. However, the covariate had to be rescaled ($H_{98\_rescaled} = (H_{98} - mean(H_{98}))/standard\ deviation(H_{98})$). Furthermore, the covariate had to be excluded for two categorical variables (epicormic branches$_{2013}$ and transverse bending) in the second analysis because the model evaluation results were too poor (P<0.05 for either Kolmogorov–Smirnov-test or Cramer von Mises-test in the *cumres* function).

Multiple comparisons were performed using the *lsmeans* package with Tukey's method for pairwise comparisons. Multiple comparisons were not taken into account for model reduction.

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Results

Analysis of thinning effects

A visual assessment of the response of *dbh*, h_{total}, and h_{llb} to different thinning treatments showed a progressively larger effect with increasing thinning weight (Figure 5). Forking height (h_{fork}), bend, tilt variables (tilt at 3.00 and 6.00 m show a similar tendency as tilt at 1.30 m and are not shown) and transverse bends (not shown) had large within-treatment variability compared with the variability between treatments, and consequently, the effects of different thinning treatments were less obvious.

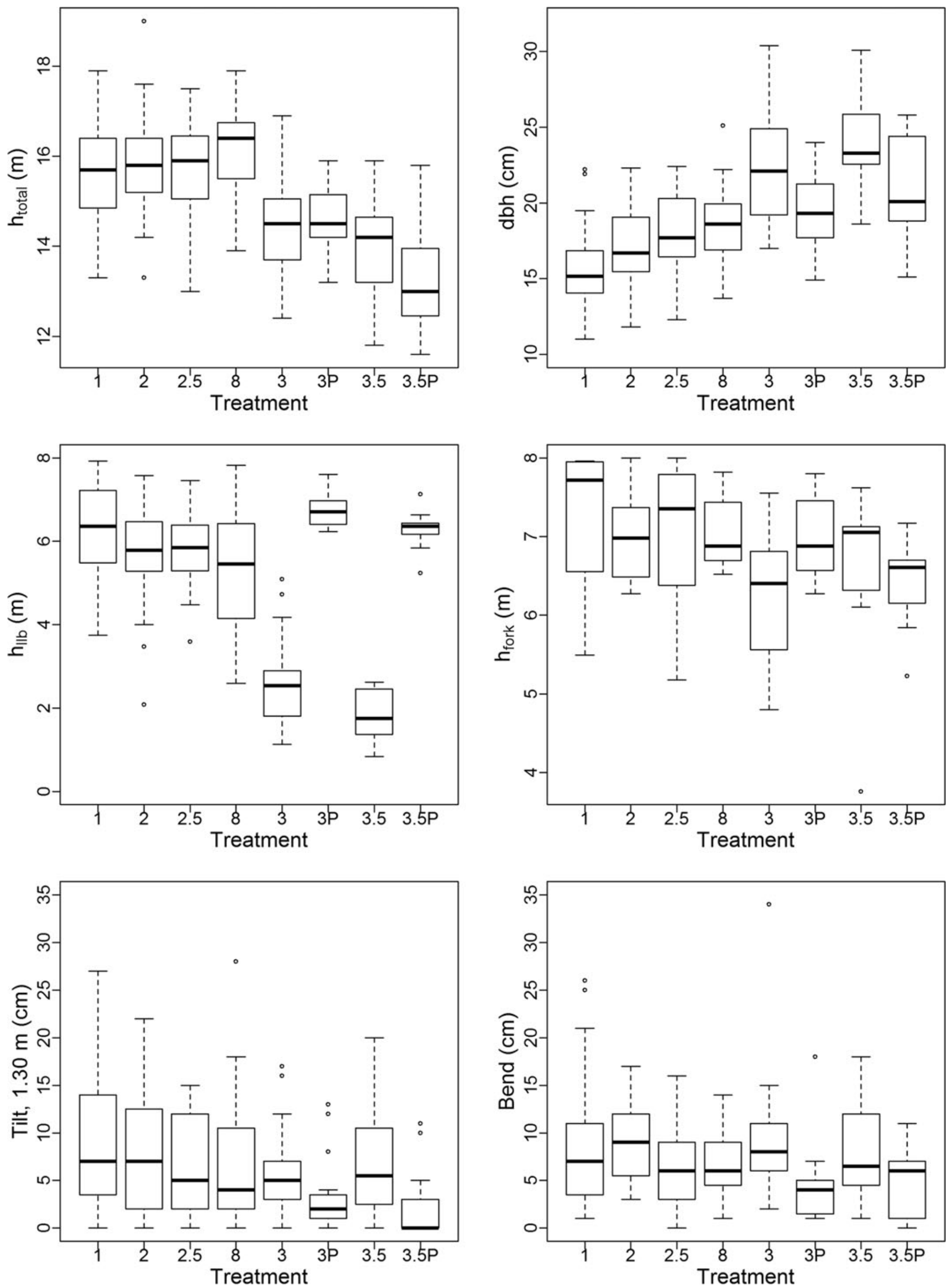

Figure 5 Boxplot of the effect of treatment on selected continuous response variables. Legend: Thick lines are the median of observations, boxes show the range from the 1st to the 3rd quartile, and the whiskers show the minimum and maximum of the observed variable; dbh=diameter at breast height, h_{total}=total tree height, h_{llb}=height of lower live branch, h_{fork}=forking height.

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Table 6 Results from the thinning analysis without pruned trees (equation (1))

Effect Unit	h_{total} m	*dbh* cm	h_{llb} m	h_{fork} m	Tilt, 1.30 m cm	Tilt, 3.00 m cm	Tilt, 6.00 m cm	Tilt direction degrees	Bend cm	Epicormic branches Probability[1]	Forking Probability[2]
Intercept	15.7	15.6	6.20	7.32	7	12	21	171	7	0.035	0.102
Thinning											
P-value	<0.001	<0.001	<0.001	<0.05	0.77	<0.05	0.19	0.22	0.14	<0.001	<0.001
1	0.0^{a}	0.0^{a}	0.00^{a}	0.00^{a}	0^{a}	0^{ab}	0^{a}	–	0^{a}	0.000^{a}	0.000^{a}
2	-0.2^{a}	1.4^{b}	-0.62^{ab}	-0.26^{ab}	-1^{a}	6^{a}	5^{a}	–	1^{a}	0.079^{a}	0.238^{ab}
2.5	0.0^{a}	2.8^{b}	-0.45^{ab}	-0.19^{ab}	-2^{a}	-4^{b}	-5^{a}	–	-2^{a}	-0.005^{a}	0.228^{ab}
8	0.3^{a}	3.0^{b}	-0.84^{b}	-0.23^{ab}	-2^{a}	-2^{ab}	-4^{a}	–	-1^{a}	-0.018^{a}	0.251^{ab}
3	-1.6^{b}	6.8^{c}	-3.58^{c}	-1.03^{b}	-1^{a}	-4^{ab}	-8^{a}	–	1^{a}	0.158^{a}	0.525^{b}
3.5	-1.9^{b}	8.8^{c}	-4.41^{c}	-0.65^{ab}	-1^{a}	-4^{ab}	-9^{a}	–	0^{a}	0.775^{b}	0.386^{b}
Overstorey tree											
P-value	<0.05	0.05	0.22	0.93	0.14	0.29	0.35	<0.05	0.70	0.19	0.23
Yes	-0.4^{*}	-1.2^{*}	0.28^{ns}	-0.02^{ns}	2^{ns}	3^{ns}	4^{ns}	-43^{*}	0^{ns}	0.046^{ns}	0.071^{ns}
$\boldsymbol{H_{98}}$											
P-value	<0.05	0.44	0.16	0.93	0.43	0.36	0.14	0.69	0.92	0.64	0.17

Thinning treatments with the same letter are not significantly different. Parameter estimates are back-transformed from the original model. For indicator variables, the significance is indicated as: 'ns' (non-significant), '*' ($P < 0.05$), '**'($P < 0.01$), or '***' ($P < 0.001$). For H_{98}, only the likelihood-ratio test is shown. Parameter estimates are from the initial models, P-values and significance levels are from the reduced models. Non-significant categorical variables are not shown

[1]Epicormic branches: Probability of having epicormic branches.

[2]Forking: Probability of having a fork below 8 m.

Crop tree h_{total} in 2016 was significantly influenced by thinning weight (P<0.001, Table 6). Specifically, treatments 3 and 3.5 lead to a decrease in average h_{total} of 1.6–1.9 m, while other thinning treatments had no effect on h_{total}. In the analysis we observed a significant effect of H_{98} (P<0.05) as well as of the proximity of overstorey trees (P<0.05), possibly reflecting initial variation in site productivity and/or stand conditions as well as in the local growing conditions for individual trees.

Crop tree *dbh* increased progressively with increasing thinning weight (P<0.001) and all thinning treatments resulted in a significantly larger *dbh* compared with the unthinned control (Table 6). For the most heavily thinned plots (treatment 3.5) mean crop tree *dbh* was 88 mm (56 per cent) larger than for the unthinned plots, and the checkerboard thinning (treatments 3 and 3.5) resulted in a significantly larger *dbh* than any of the other treatments.

Thinning significantly influenced h_{llb} (P<0.001, Table 6). In the unthinned plots, mean h_{llb} was 6.20 m and there were no significant differences in h_{llb} between the unthinned plots and the lighter thinning regimes (2, 2.5). However, wide strip thinning reduced h_{llb} to 5.36 m and checkerboard thinning significantly reduced h_{llb} to 1.8–2.6 m. Moreover, thinned plots had a significantly larger number of crop trees with forked stems (P<0.001) and h_{fork} was lower (P<0.05). The probability of forking was largest in the checkerboard treatments and these forks were also located at a lower position, although only significantly lower for treatment 3.

The presence of epicormic branches in 2016 was significantly influenced by thinning (P<0.001). The probability of having epicormic branches was 3 per cent for trees in unthinned control plots and 82 per cent for trees in the most heavily thinned checkerboard plots.

Stem tilt measured at 1.30, 3.00 and 6.00 m above ground was generally not significantly influenced by thinning (Table 6), but there was a tendency for trees on heavily thinned plots to tilt less. Stem tilt measured at 3.00 m was significantly influenced by thinning (P<0.05), but only treatment 2 and 2.5 were significantly different from each other. Stem bend (derived from tilt measurements), stem straightness and transverse bending were not significantly influenced by thinning (P=0.14,P=0.14 and P=0.75, respectively).

Analysis of pruning effects

Pruning had a negative effect on *dbh* (P<0.001, Table 7), but no effect on h_{total}, h_{fork} or whether the crop tree had a fork. As expected, pruning led to a significantly higher h_{llb} (P<0.001). Epicormic branches_{2013} were not significantly influenced by pruning (P=0.23). Hence the formation of epicormic branches was not significantly influenced by the high pruning conducted in 2004 and 2009. However, epicormic branches_{2016} was significantly influenced by pruning (P<0.01), so crop trees that had been high pruned in both 2004 and 2009 and had been pruned for epicormic branches in 2013 had a significantly lower probability of having epicormic branches. Pruned trees tilted less at 1.30 m, had a different tilt direction, had less stem bending and had straighter stems (P<0.001, P<0.05, P<0.001 and P<0.05, respectively). The number of transverse bends was unaffected by pruning (P=0.68).

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Table 7 Results from the analysis of thinning treatments including both pruned and non-pruned replicates (equation (2))

Effect Unit	*dbh* cm	Tilt, 1.30 m cm	Bend cm	h_{llb} m	Epicormic branches$_{2016}$ Probability[1]	Straightness Probability[2]
Intercept	22.9	7	9	2.68	0.190	0.142
Thinning						
P-value	<0.01	0.42	0.44	<0.001	<0.001	0.64
3	0.0^{a}	0^{a}	0^{a}	0.00^{a}	0^{a}	0^{a}
3.5	2.4^{b}	-1^{a}	-1^{a}	-1.43^{b}	0.461^{b}	0.035^{a}
Overstorey tree						
P-value	<0.01	0.98	0.72	<0.05	0.20	0.15
Yes	-3.5^{**}	0^{ns}	1^{ns}	0.86^{*}	0.252^{ns}	0.216^{ns}
Pruning						
P-value	<0.001	<0.001	<0.001	<0.001	<0.01	<0.05
Yes	-4.7^{***}	-5^{***}	-5^{***}	4.06^{***}	-0.119^{*}	0.324^{*}
H_{98}						
P-value	0.46	<0.05	0.20	0.93	0.51	0.49

Thinning treatments with the same letter are not significantly different. Parameter estimates are back-transformed from the original model. For indicator variables, the significance is indicated as: 'ns' (non-significant), '*' (P<0.05), '**' (P<0.01), or '***'(P<0.001). For H_{98}, only the likelihood-ratio test is shown. Parameter estimates are from the initial models, P-values and significance levels are from the reduced models. Only variables significantly influenced by pruning are shown (tilt direction was significantly influnced but is not shown).
[1]Epicormic branches$_{2016}$: Probability of having epicormic branches in 2016.
[2]Straightness: Probability of being straight in two planes.

Discussion

Tree growth

Initial explorative analyses of the crop tree height (not shown) revealed significant differences among blocks, indicating local variation in inherent site productivity. The previous generation of beech, i.e. the overstorey trees, indicated a similar pattern (Table 2) and the observed variation in h_{total} correlated well with observed soil characteristics (Table 1). Analyses of thinning experiments have previously demonstrated that considerable site productivity variation may occur in apparently homogeneous stands (Skovsgaard, 2006, 2009; Skovsgaard and Vanclay, 2013). Consequently, we attempted to account for variation in inherent site productivity by including a random effect of block in the final analyses. Moreover, to adjust for fine-grained differences in initial stand conditions, we included the plot-specific pre-treatment stand top height as a covariate.

Our analyses indicated a significant effect of thinning on total height growth. More specifically, crop tree h_{total} was significantly reduced by heavy thinning but unaffected by lighter thinning. The absence of an effect of lighter thinning is in accordance with other studies in pre-commercially thinned beech (Skovsgaard *et al.*, 2006). Furthermore, the reduction in total height growth resulting from heavy thinning is in accordance with results from an experiment on planting spacing in beech. The experiment was planted at 1.30 m between the rows and included two different provenances in separate blocks. At age 16 years, when the experiment was still unthinned, h_{total} was unaffected for initial within-row spacings at or below 1.35 m (≥ 5,700 stem per ha), but reduced for spacings at or above 2.70 m (≤ 2,800 stems per ha) (Jørgensen and Hansen, 2004; Jørgensen and Hansen, 2012). This is in line with the general notion that broadleaf trees that are free from shading focus resources on lateral expansion rather than height growth (Pretzsch and Rais, 2016). Our finding challenges the general assumption that stand volume growth correlates well with dominant stand height, i.e. that site productivity can be estimated based on dominant stand height (Skovsgaard and Vanclay, 2008), and consequently corroborates a line of similar research results contradicting or refining the comprehension of this fundamental principle of forest production (Skovsgaard and Vanclay, 2013).

We observed a general increase in crop tree *dbh* growth with increasing thinning intensity. Although diameter growth generally increases with increasing growing space, our observation was made from crop trees that, among other criteria, were selected partly based on social dominance. Increased *dbh* growth of trees from the dominant class following thinning is in line with findings from other studies (Klädtke, 2002; Bončina *et al.* 2007; Diaconu *et al.*, 2015). However, it was somewhat surprising that even the extremely heavy thinning applied in our study resulted in increased *dbh* growth as the dramatic change in the stand-interior forest climate resulting from this thinning regime might be expected to reduce stand level as well as individual tree growth. The increase in *dbh* growth was greatly reduced when heavy thinning was combined with pruning, presumably due to the immediate reduction in foliage volume. Roughly 35 per cent of the crown length of pruned crop trees was removed in the pruning in 2003 and roughly 40 per cent in 2009. Studies on the effect of pruning on diameter growth in broadleaves are scarce, and absent for beech. However, studies of other species show that removal of up to one quarter of the live crown has no or little effect on *dbh* growth while removal of larger parts of the crown reduces *dbh* growth (Møller, 1962; O'Hara, 1991; Pinkard and Beadle, 2000; Alcorn *et al.*, 2008; Mäkinen *et al.*, 2014). Based on the quite severe pruning conducted in our study, the decrease in *dbh* of pruned crop trees was consequently to be expected.

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Height to the lowest live branch and fork and frequency of forking

In line with the findings of other studies, thinning led to a decrease in bole length (Bryndum, 1980; Holmsgard, 1985; Langshausen, 2009). However, there were no significant differences between the lighter thinning regimes and the unthinned plots, except for treatment 8, suggesting that increased *dbh* growth may be achieved without reducing stem quality. The heaviest thinning regimes (3 and 3.5) resulted in an average bole length of 2.6 and 1.8 m, respectively, while the unthinned control and the lighter thinning regimes resulted in average bole lengths of 5.4–6.2 m. In order to achieve two 3-m logs, which at a target *dbh* of 60 cm include 20 cm of clearwood ('knot free wood') outside the so-called knotty core, natural pruning should preferably have progressed to ~6 m before or when stem *dbh* has reached 20 cm. In our experiment, heavy thinning (checkerboard thinning) resulted in bole lengths of only 1.8–2.6 m and consequently, natural pruning was insufficient to achieve the desired stem quality. Heavy thinning combined with high pruning resulted in fast *dbh* growth as well as sufficient bole length. It should be noted that natural pruning progresses at a slower rate than h_{llb} because dead branches have to get shredded or knocked off, for example during thinning operations, before occlusion can occur. In a 51-year-old thinning experiment in beech the average difference between the height to the lowest branch (live or dead) and the lowest live branch was 1–2 m and depended on *dbh* (Holmsgaard, 1985).

In contrast to another thinning experiment in beech (Bryndum, 1980), heavy thinning led to an increased frequency of forking among the crop trees and it marginally reduced h_{fork}. A possible reason for the discrepancy is that in our study, thinning was predominantly systematic (rather than selective) and this may result in more space to develop forks while trees with forked stems are not being selectively disfavored and removed through thinning operations. Moreover, our experiment was not suited to analyze the formation of forks as (1) trees with forked stems were disfavored in the selection of crop trees and hence not measured and (2) some forks or potential forks would have been removed in the pruning process. The higher percentage of crop trees with forked stems in the heavily thinned plots has implications for stem quality even when the lowest live branch is located lower than h_{fork} (Figure 4). While a knot originating from a branch will degrade a log, a fork will normally end the commercial log section of the tree, and will consequently influence directly the quantity of wood sold at premium price.

Stem bending, straightness and tilt

Thinning did not significantly influence the bending or the straightness of crop trees in our study. This is in contrast to one study which indicated that unthinned beech stands have more bending stems than thinned stands (Holmsgaard, 1985), but is in accordance with other thinning (Ekö *et al.*, 1995) and planting density experiments in beech (Jørgensen and Hansen, 2004; Jørgensen and Hansen, 2012; Houšková and Mauer, 2013). Beech grows according to the so-called Troll model having only plagiotropic axes that allow the tree to expand its branches horizontally towards the light (Oldeman, 1990). Due to stronger competition for light between larger numbers of trees this may result in more bending stems in unthinned stands. However, competition by overtopping and the resulting changes in growing direction was most likely less pronounced for the dominant trees selected for analyses in our study, as well as for trees in the above mentioned planting density experiments where canopy closure had not yet been achieved. Although tilt was not significantly influenced by the treatments in our experiment, there was a tendency of less tilt on crop trees in the heavily thinned plots. This is in line with other studies (Polge, 1981) and may correlate with the H/D ratio (Beimgraben, 2002; Jullien *et al.*, 2013).

Surprisingly, pruning resulted in less bending, less tilting and a higher percentage of straight crop trees with a different tilting direction. To our knowledge, this effect of pruning has not been reported in other studies. Less growth on side branches may improve the symmetric development of the crown (Jacobsen, 1969) and reduce wind pressure, with a resulting smaller risk of a bending stem, and it is possible that this could also result in less tilting of the stem or, to some extent, compensatory growth on the stem resulting in reduced tilt. Only the tilt measurement at 1.30 m was found to be smaller in the pruned stands. However, in broadleaves, a tilting stem results in the production of tension wood and causes the stem to reorient and restore verticality (Wilson and Gartner, 1996; Dassot *et al.*, 2012). As a result, tilting trees bend "backwards" further up the stem and turn into bending trees. This explains why both bending was smaller and more crop trees were straight in two planes in pruned stands and also indicates that the bend in the plane where the tilts were measured was typically the most important bend and therefore included in our measurements. The reported bending of crop trees was rather small (Figure 4) when evaluated in relation to the classification rules for hardwood logs in Denmark (DSH, 2008) and should not have any large impact on the commercial quality of logs. Tension wood, however, can be a problem for wood quality, but this characteristic is typically not included in log grading rules (DSH, 2008).

Epicormic branches

High pruning alone did not significantly influence the proportion of crop trees with epicormic branches, but high pruning in combination with pruning of epicormic branches did. This indicates that beech has a smaller tendency to produce epicormic branches following foliage loss as compared with oak (see, for example, Attocchi, 2013). Only the most heavily thinned plots (treatment 3.5) had a higher probability of epicormic branches, indicating that beech stems can be exposed to high levels of light before dormant buds on the stem are activated. These epicormic branches may be of limited importance for stem quality, because h_{llb} is generally located low on the stem in treatment 3.5. Moreover, our observations revealed that the epicormic branches nearly always emerged above the lowest live branch. Increased formation of epicormic branches in the most heavily thinned plots is in contrast to other findings for beech (Holmsgaard, 1985) as well as for oak (Attocchi, 2013). A possible reason for this is that our study only included dominant trees which are less likely to initiate growth of epicormic branches, as a reaction to light deficiency.

Summary of the effects of thinning and pruning on stem quality and implications of results

Throughout the analyses it was implicitly assumed that stem quality can be evaluated based only on exterior characteristics,

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that this evaluation is independent of stand treatment, and that stem quality at this stage of stand development can be taken as a reliable indicator of final crop stem quality. However, as trees grow, stem defects such as tilting and bending may become masked due to formation of tension wood, knots occlude and wounds become overgrown. We consequently expect that heavily thinned plots will be evaluated more positively as a simple effect of faster stem growth and the associated, gradual concealment of visible stem defects.

In our study, we concentrated on the quantitative and qualitative development of selected potential future crop trees depending on thinning regime. The study ignored that the early and heavy stand density reduction in some of the treatments restricted the selection potential for crop trees due to the lower stand density and therefore limited the number of options within a given space within the stand. As a result, heavy early thinning inevitably reduces the possibilities for finding a replacement in case an original crop tree is lost. Another implication is that the substantial stand density reduction in some of the treatments results in a reduction in overall stand growth (Bryndum, 1987), as also indicated from the development of stand basal areas (Table 4).

A substantial reduction in rotation length is one of the main commercial advantages of early, heavy thinning. This option is profitable only if the increase in net present value from reduced rotation length is larger than the costs associated with (1) the reduction in stand volume growth, (2) the costs of pruning and (3) the difference in thinning costs between, in this case, the checkerboard thinning and the unthinned stand treatment options. We have not attempted any economic evaluation of these or other alternative management options, but high salary costs, such as in Denmark, obviously reduce profitability of labor intensive management regimes. Future technological development might change this, for example as a consequence of a higher degree of automatization in forest machinery, implementation of robot techniques (Vestlund, 2005), etc. so that an operation such as pruning would require fewer man hours.

Strip thinned and unthinned plots were found to be very similar, although strip variants had developed a modestly larger *dbh*. The basal area estimates from Table 4 indicate that the volume production should be roughly similar for the strip thinning and the unthinned control. The question that remains unanswered then is whether a reduction in rotation length of 5–6 years can pay for the investment in strip thinning roughly 80–100 years before the final return on the investment.

In our study the stem quality of beech crop trees was not much affected by inner stand edges, such as those arising from up to 3 m spacing, as long as the stand bordering the open spacing was dense (treatment 8). The stem quality was also not affected when crop trees were at 1–1.5 m distance to the nearest neighbor trees (treatment 2.5). On the other hand, crop trees at roughly 3 m distance to all neighbors experienced a highly significant reduction in stem quality (treatment 3). Compared to treatment 3, the stem quality of crop trees was not degraded much further when spacing increased to roughly 6 m (treatment 3.5). The reduction in stem quality with heavy thinning (treatment 3 and 3.5) was due only to a more prolific branching behavior (affecting h_{llb}, h_{fork} and formation of forks and epicormic branches). In summary, the results indicate that inner edges in stands are hardly a major problem for stem quality as long as the stand density in the remaining stand is relatively high. On the other hand, as soon as spacing between individual trees increases, the stem quality of individual trees may deteriorate rapidly.

There is an ongoing debate on how close-to-nature and other irregular forest types will affect wood quality (see, for example, Wilhelm and Rieger, 2013; Pretzsch and Rais, 2016). Unfortunately, there are only a few scientific studies on this topic. It has been stated that irregular forests will lead to a larger number of edge trees, because there will be many trees standing next to a regeneration gap which will have a similar effect as if the trees were standing on the edge of the stand (Macdonald *et al*., 2009). The effect of a regeneration gap would also be similar to that of the inner edges investigated in our study. This suggests that as long as stand density can be maintained sufficiently high during early development stages to ensure (rapid) natural pruning, high quality logs may result from irregular forests.

As a caution to these concerns, some effects of irregular forests cannot be predicted reliably from even-aged thinning experiments (Macdonald *et al*., 2009). Growing up in the moderate shade of overstorey trees (shade for a longer time than in the shelterwood system which these experiments emerged from) will influence stem quality because it reduces the growth of side branches (Jacobsen, 1969). As a result, for a given density and edge situation in the understorey, the natural pruning will typically be faster in irregular forests. However, the result from our study that the bending of young beech crop trees is unaffected by thinning intensity would probably not be valid in uneven-aged stands. Young trees cannot be truly dominant in uneven-aged stands, because there will be larger overstorey trees present and the young trees will not have unrestricted access to overhead light. Due to the strategy of beech in such an environment (Oldeman, 1990), young crop trees in an uneven-aged forest will probably have a more bending stem form as compared with young dominant trees in even-aged stands. No effect of overstorey trees on the natural pruning and bending of beech crop trees was observed in our study. However, there were not many overstorey trees left (roughly 4 ha^{-1}, Table 2), and they were ringbarked.

Conclusion

Despite the importance of beech in European forestry, the effect of early thinning on stem quality is poorly understood. The results from our study showed that strip mulching may result in faster stem growth without reducing the stem quality of beech crop trees. However, the *dbh* increase was modest. Delaying pre-commercial thinning until a bole length of 6 m has been reached is a viable alternative resulting in satisfactory stand development and expensive thinning in young dense stands can be avoided. Other, heavier pre-commercial thinning methods resulted in a larger *dbh* of crop trees, but reduced stem quality to an unacceptable level. Pruning heavily thinned crop trees reduced *dbh* growth relative to similar but unpruned thinning treatments, but improved stem quality. The combination of pruning and heavy thinning resulted in crop trees with a larger *dbh* and with a satisfactory stem quality. However, this combination causes a yet unquantified reduction in stand productivity,

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requires costly investments in early thinning and early pruning, and possibly reduces the number of candidates for potential future crop trees.

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Conflict of interest statement

None declared.

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