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Thinning Intensity and Growth of Mixed Spruce-Birch Stands on Drained Peatlands in Finland

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The impacts of thinning at various intensities on the growth and mortality of mixed spruce-birch stands were investigated in thinning experiments on spruce swamps in northern and south-eastern Finland. At the time of establishment, three of the stands had recently reached the first commercial thinning stage and four were more advanced. The monitoring period was mainly 15 years, and the thinning intensity varied from heavy thinning (ca. 46 per cent of the basal area removed) to no thinning. Basal area removals of light and moderate thinning were ca. 22% and 39%, respectively.

Unthinned plots had the highest volume increment. Light and moderate thinning slightly decreased the 15-year volume increment by, on an average, 1% and 8%, respectively. Heavy thinning led to a greater reduction (22%) in volume increment.

The growth response to thinning intensity was evident as a higher relative volume and mean diameter increment of the living trees with decreasing stand density. Part of the volume increment on the unthinned plots was lost through natural mortality. Even light thinning significantly decreased natural mortality.

Keywords thinning, *Picea abies*, *Betula pubescens*, spruce swamps, growth, forest drainage
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1 Introduction

Spruce swamps are widespread, treed peatland types in the boreal regions of Eurasia. In their pristine stage, the tree stands of these sites are characterized by various mixtures of Norway spruce (*Picea abies* (L.) Karst.) and hardwood species, mainly pubescent birch (*Betula pubescens* Erhr.), with a highly uneven stand structure (Heikurainen 1971, Hörnberg 1995, Norokorpi et al. 1997, Sarkkola et al. 2003). Spruce is generally predominant on drier, forested swamps and birch on the wetter, treed fens. The tree cover varies greatly according to the hydrological regime, and wood productivity is generally limited by high water levels (Heikurainen 1971, Gustavsen and Päivänen 1986). Many of these minerotrophic sites have been drained for forestry in Fennoscandia, in the Baltic countries, and in northwestern Russia (Paavilainen and Päivänen 1995), and they have generally shown a high wood production potential (Valk 1983, Hånell 1988, Penttilä 1990, Gustavsen et al. 1998, Hökkä and Penttilä 1999, Zalitis and Indriksons 2004). In Finland, spruce swamps account for 26%, or 2.3 million ha, of all the sites classified as peatlands which total, according to the Finnish National Forest Inventory (FNFI), 8.9 million ha (Hökkä et al. 2002).

Silviculture involving the application of thinnings is a widely recognized management practice in well-productive spruce stands on upland sites, where it results in similar or slightly lower volume growth (Assmann 1954, Vuokila 1985, Eriksson and Karlsson 1997, Mäkinen and Isomäki 2004) but economically superior yields compared to management without thinnings (Hynynen et al. 2005). The impacts of thinnings on the growth and yield of drained spruce peatland stands are, however, poorly known. Based on the results of the FNFI, it has been suggested that silvicultural thinnings should be carried out over large areas of spruce peatlands (Hökkä et al. 2002). At the present time, the silvicultural guidelines for thinnings on peatlands are the same as those for upland spruce stands (Hyvän metsänhoidon… 2001).

The structure of spruce-dominated stands on drained peatlands, as depicted by their diameter (at breast height) distributions, generally deviates from that of managed spruce stands on upland sites. The variation in tree age and size is much larger in peatland stands, and this large inequality may prevail for several decades after drainage, even up to the stage of regeneration maturity (Sarkkola et al. 2003). Treed fens, especially, tend to retain their heterogeneous and clumped stand structure and they may contain large proportions of low-valued birch. Determination of the need for and proper timing of silvicultural thinnings may be very difficult in such stands. Accordingly, the possible responses of the retained crop trees to thinnings may differ from those of upland spruce stands. The aims of this study were i) to quantify the impacts of commercial thinnings at various intensities on the growth and mortality of the retained stands, and ii) to describe the temporal dynamics of the thinning response using empirical data from a set of thinning experiments in peatland spruce stands in Finland.

2 Material and Methods

2.1 Sites and Experimental Design

The study material consisted of seven thinning experiments set up by the Finnish Forest Research Institute between 1985 and 1994, six in northern and one in eastern Finland, representing mesotrophic to eutrophic sites (Table 1). At establishment of the experiments, three of the stands had just reached the stage of first commercial thinning, as determined by their dominant height (H_{dom}) of 12–13 m, and four were more advanced (medium stage) with a H_{dom} of between 16–20 m (Table 1). The previous management of the stands varied from no treatment to pre-commercial thinning with an unknown intensity. Average stand stocking varied between 98 and 292 m^3 ha^{-1}, 5 to 60 per cent of which was birch (Table 1).

The experimental design was randomized blocks consisting of four treatments: i) no thinning, ii) light thinning, iii) moderate thinning, and iv) heavy thinning, arranged in two or three blocks on each site. The treatments were applied to 7–12 rectangular plots per site, ranging in size from 520 to 1600 m^2, and in a 4- to 5-m-wide buffer zone. The basal area removals in light, moderate and heavy thinning were ca. 22%, 39% and 46%.

Table 1. Average stand characteristics at establishment of the experiments.

No.	Location	Co-ordinate P	Co-ordinate I	Temp. sum, dd	Drainage, year	Peat thickness, cm	Site type	G, m^2/ha	D_g, cm	H_{dom}, m	V, m^3/ha	Birch, %
5918	Heinävesi	6929334	3606345	1211	1963	100	MK	35.1	19.6	20.5	292.3	5.5
5920	Tervola	7334334	3418927	952	1950	35	RhK	23.8	11.4	12.4	114.5	59.4
5927	Tervola	7341835	3452892	910	1964	40	VLK	24.9	17.9	15.8	145.9	27.6
5930	Tornio	7320467	3386718	977	1936	40	LhK	22.0	21.2	16.6	144.7	21.0
5935	Rovaniemi	7352064	3419402	943	1966	30	VLK	20.6	13.1	13.1	101.8	40.0
5948	Ranua	7308839	3454406	907	1964	20	RhK	20.1	13.1	12.0	98.0	57.9
5951	Rovaniemi	7348343	3452032	905	1930	20	RhK	28.9	19.2	16.4	181.5	49.7

dd = average annual temperature sum with a +5 °C threshold, MK = *Vaccinium myrtillus* spruce swamp, RhK = Herb-rich hardwood-spruce swamp, VLK = Eutrophic spruce fen, LhK = Eutrophic paludified harwood-spruce forest, G = stand basal area, H_{dom} = height of dominant trees, D_g = mean diameter at breast height (weighted with tree basal area), V = stand volume, birch = proportion from basal area.

After moderate thinning, the retained stand density corresponded to present management guidelines for upland spruce stands of corresponding site quality (Hyvän metsänhoidon… 2001). The retained basal area was 20% lower for heavy and 20% higher for light thinning. Site #5930 lacked the light thinning treatment, and on site #5935 the unthinned plots were omitted because the basal area of the non-thinned plots did not differ from that of the light thinning ones. In sites #5918 and #5920 the treatments were also replicated within blocks. Blocks were formed within each site in order to control within-site variation in site type, level of stand stocking, and proportion of birch. The thinnings were designed to reduce stand density, especially in clumps, so that the thinnings decreased the horizontal rather than the vertical heterogeneity. The selection of the retained trees was based on favoring individual spruces possessing good external stem quality, and applying thinning from below when selecting from otherwise similar candidates.

2.2 Field Measurements and Data Analysis

The trees on each plot were measured when the treatments were carried out, followed by 1–3 sequential measurements at 4–10 years intervals. The total measurement period was 14 or 15 years, except in experiment #5918 where the period was ten years. Each tree on the plot was mapped and the tree species, diameter at breast height and tree class, the retained living trees and those to be cut and dead trees separately, were recorded. The sample trees (about 30 per plot) were systematically selected from the diameter distribution. Tree height, diameter at 6 m height and crown base were measured on each sample tree. The stand characteristics for the plots were calculated using the KPL software developed at the Finnish Research Institute (Heinonen 1994).

The way in which the thinning treatments were applied varied to some extent depending on the stage of stand development and, in some cases, among the blocks: In the more advanced stands, the thinning intensity varied through different levels of retained basal area relative to dominant height, while a varying density in terms of retained stem number was applied in the other stands. Because of this variation in the experimental design and the aim of obtaining a similar measure for stand density, a specific, plot-wise density index was calculated for the tree stands. The density index (G_i) for a given plot was defined as the ratio of the retained basal area of the plot (G_0) and the average basal area recommended to be retained (G_m) according to current forest management guidelines for private forest owners (Hyvän metsänhoidon… 2001, Fig. 1), as follows:

$$G_i = G_0 / G_m \tag{1}$$

where
G_i = Stand density index after thinning, m^2 ha^{-1}
G_0 = Retained basal area on the plot after thinning, m^2 ha^{-1}

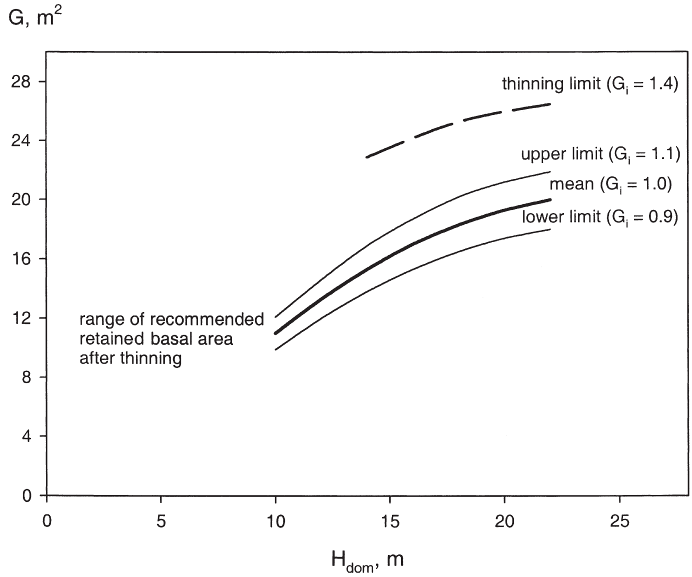


Fig. 1. The management guidelines for the thinning of Norway spruce stand on fertile sites (Northern Finland). The thinning limit illustrates the point (development of basal area related to dominant height) when the stand is in need of thinning.

G_m was obtained by fitting the curve (Eq. 2) to the management guidelines presented in graphic form.

$$G_m = -5.893 + 2.112 H_{\mathrm{dom}} - 0.043\ (H_{\mathrm{dom}})^2 \qquad (2)$$

where
H_{dom} = Dominant height, m

Thus, for a retained stand thinned according to the management guidelines, the density index would be equal to 1. The upper and lower limit of the tolerance interval, as defined in the management guidelines (Fig. 1), would correspond to density indices 1.1 and 0.9, respectively, and the thinning limit, depicting the point in time when the stand is in need of thinning, would correspond to a density index of 1.4 (Fig. 1).

In our material the density index (G_i) of the plots ranged between 0.6–2.0. The average density index for the unthinned treatment (G_i = 1.5) was, in most of the experiments, higher than that of the thinning limit, and that for the retained stands following moderate thinning (G_i = 1.0) corresponded very well to the management guidelines (Table 2). For light (G_i = 1.2) and heavy (G_i = 0.8) thinning, the average density indices deviated by ±20% from G_m (Table 2). This was 10% higher or lower than the upper and lower limit of the management guidelines (Fig. 1). The proportion of birch was highest on the unthinned plots (Table 2).

2.3 Statistical Analyses

The data were analyzed in two phases. First we constructed a model for analyzing the average impacts of the thinning intensity on growth and natural mortality during the entire study period. The study material was unbalanced and hierarchically structured at the stand, block and plot levels. Therefore, the linear mixed models technique with fixed and random effects was used in the analyses:

$$Y_{ijk} = u + u_i + b x_{ijk} + u_{ij} + e_{ijk} \qquad (3)$$

Table 2. Mean basal area (G), density index (G_i), thinning removal (G_{rem}), proportion of birch (Birch) of total basal area, periodic annual volume increment of all trees (iV_{tot}) and living trees (iV_{net}) by thinning treatments.

Site	G, $m^2 ha^{-1}$	G_i	G_{rem}, %	Birch, %	iV_{tot}, $m^3 ha^{-1} a^{-1}$	iV_{net}, $m^3 ha^{-1} a^{-1}$
Unthinned						
5918	34.9	1.69	3.6 [a]	15.0	9.49	8.06
5920	24.4	1.79	4.4 [a]	61.4	6.82	5.38
5927	22.4	1.29	16.1 [a]	26.0	5.11	4.68
5930	20.2	1.17	4.3 [a]	22.3	3.40	2.83
5935	-	-	-	-	-	-
5948	19.7	1.45	9.2 [a]	44.3	7.22	6.57
5951	26.1	1.56	7.5 [a]	50.6	2.62	2.00
Mean	24.6	1.52	7.5 [a]	37.5	5.77	4.84
Light thinning						
5918	25.9	1.27	7.6	7.6	10.41	9.98
5920	12.9	1.02	50.0	36.3	5.84	5.70
5927	21.3	1.25	21.1	16.0	4.87	4.82
5930	-	-	-	-	-	-
5935	15.1	1.02	32.6	22.6	5.98	5.65
5948	19.2	1.39	13.6	53.7	7.08	6.89
5951	22.7	1.43	14.5	56.4	2.47	1.59
Mean	19.5	1.20	23.3	30.1	6.37	6.04
Moderate thinning						
5918	21.4	1.05	39.6	1.2	9.53	9.24
5920	10.6	0.79	56.7	38.6	5.72	5.62
5927	15.3	0.91	38.1	19.9	4.03	3.75
5930	16.3	0.94	35.9	8.5	3.23	3.16
5935	11.6	0.80	41.8	21.4	4.74	4.43
5948	15.5	1.22	22.2	49.6	7.24	6.98
5951	18.1	1.04	39.5	30.4	3.16	3.08
Mean	14.6	0.97	39.0	24.1	5.44	5.25
Heavy thinning						
5918	15.9	0.81	49.6	2.9	8.20	8.16
5920	8.5	0.68	60.1	32.0	4.27	4.12
5927	11.7	0.68	45.6	5.8	4.17	4.17
5930	11.9	0.71	39.1	22.4	2.48	2.37
5935	8.9	0.63	47.3	12.7	3.68	3.54
5948	11.9	0.97	38.3	46.7	5.79	5.65
5951	12.8	0.79	47.5	24.0	1.81	1.59
Mean	11.0	0.77	46.3	22.2	4.38	4.30

[a] Thinning removal (G_{rem}) from unthinned plots consisted of dead trees and trees removed from along the logging trail.

where Y_{ijk} is a dependent variable, u is the overall mean, u_i the intercept of site i, b the regression coefficient of density index, and u_{ij} and e_{ijk} are random effects for block j and plot k. When needed, the interaction between site and stand density and different covariates (H_{dom}, and proportion of birch) were included in the fixed part of the model.

The periodic annual increment of the growing stock was calculated as the difference between volumes in two successive measurements divided by the number of years in the period. The periodic annual volume increment (iV, $m^3 ha^{-1} a^{-1}$) was calculated for both living trees (iV_{net}) and all trees (iV_{tot}), which also includes the trees that had died during the measurement period:

$$iV_{net} = (V_2 - V_1) / T \quad (4)$$

$$iV_{tot} = (V_{tot} - V_1) / T \quad (5)$$

where
V_1 = Volume of retained, living trees at the establishment of the experiment, $m^3\,ha^{-1}$
V_2 = Volume of living trees at the end of the measurement period, $m^3\,ha^{-1}$
V_{tot} = Volume of all trees at the end of the measurement period, $m^3\,ha^{-1}$
T = Time interval between two successive measurements, years

The periodic annual relative volume increment was calculated as follows:

$$iV_{rel} = iV_{net} / V_1 \quad (6)$$

Periodic annual basal area increment ($m^2\,ha^{-1}\,a^{-1}$):

$$iG = (G_2 - G_1) / T \quad (7)$$

where
G_1 = Basal area at establishment of the experiment, m^2
G_2 = Basal area of living trees at the end of the period, m^2
T = Length of the measurement period, years

Periodic annual relative basal area increment:

$$iG_{rel} = iG / G_1 \quad (8)$$

The periodic increment of the basal area weighted mean diameter (cm):

$$iD_g = D_{g2} - D_{g1} \quad (9)$$

where
D_{g1} = Mean diameter at establishment of the experiment, cm
D_{g2} = Mean diameter at the end of the measurement period, cm

For the volume of natural mortality during the measurement period (V_{mor}, $m^3\,ha^{-1}$) a logarithmic transformation $\ln(V_{mor}+1)$ was used.

The second analysis was carried out to detect the temporal variation of the thinning response by making use of sites #5920 and #5948, where the measurements had been performed four times at 5-year intervals. In the longitudinal data, the covariance structure of the successive 5-year measurement periods was described by the first-order autoregressive structure. The model was as follows:

$$Y_{ijk} = u + u_i + bx_{ijk} + u_{ij} + e_{ijk}(t) \quad (10)$$

where $e_{ijk}(t)$ is the residual error as a function of time (t). In the periodic analysis iV_{net} and iV_{rel} were used as response variables. The development of basal area and natural mortality were also studied during the 5-year period. Restricted maximum likelihood (REML) in MIXED procedure of SAS (SAS Institute 1999) was used in estimating both models.

3 Results

3.1 Post-thinning Productivity

The periodic annual volume increment of living trees (iV_{net}) varied between 1.6 and 9.2 $m^3\,ha^{-1}$, depending on the site and thinning intensity (Table 2). In northern Finland, the average iV_{net} was 4.3 $m^3\,ha^{-1}$ and the maximum iV_{net} occurred on site #5918 in south-eastern Finland. To a certain extent, both the volume increment of living trees (iV_{net}) and all trees (iV_{tot}) correlated positively with the volume of retained stand (Fig. 2). The unthinned treatments, with a stand density at or above the thinning limit at establishment of the experiments, generally showed the highest average iV_{net} and iV_{tot} (Fig. 2). iV_{tot} decreased only on the plots with the highest density. In cases where the density index was close to 2, i.e. twice that recommended for stands retained after thinning, iV_{net} was, however, decreased by up to 1.7 $m^3\,ha^{-1}$. Heavy thinning decreased iV_{net} by 1.8 and moderate thinning by 0.6 $m^3\,ha^{-1}$ compared to the highest iV_{net} (Fig. 2). Generally, iV_{net} correlated positively and relatively linearly with the stand density index when the index value was less than 1.1 (Fig. 2), i.e. below the upper tolerance limit of the recommended stand density as defined by the current management guidelines

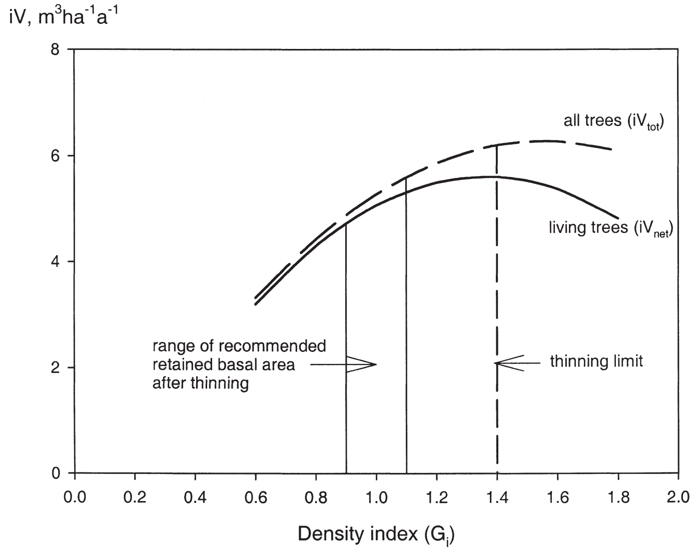


Fig. 2. Periodic annual volume increment during the 15-year period as a function of density index after thinning.

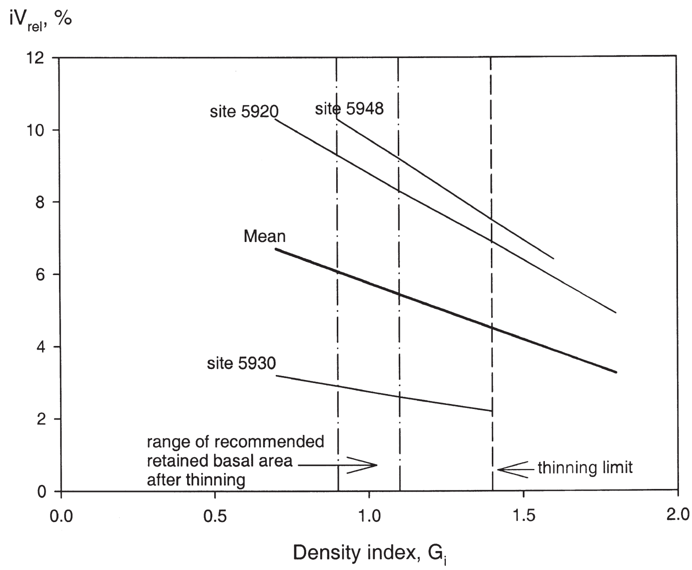


Fig. 3. Relative volume increment of the growing stock using different thinning intensities.

for mineral soil stands. The impact of thinning intensity on iV_{net} was similar on all sites, i.e. there was no interaction between treatment and site. A high proportion of pubescent birch, used as a covariate in the model, significantly decreased iV_{net} (Table 3).

The thinning intensity had a clear linear impact on stand relative volume increment (iV_{rel}) on all sites: a lower retained stand density resulted in a higher relative growth rate (Fig. 3). Thus, the

Table 3. Models for periodic annual volume (iV_{net}, iV_{tot}), relative volume (iV_{rel}), basal area (iG), relative basal area (iG_{rel}) and mean diameter (iD_g) increment and natural mortality (V_{mor}) during the study period. Standard error of parameter estimates in parentheses.

Variable	iV_{net}, m^3 ha^{-1} a^{-1} Estimate	iV_{tot}, m^3 ha^{-1} a^{-1} Estimate	iV_{rel}, % Estimate	iG, m^2 ha^{-1} a^{-1} Estimate	iG_{rel}, % Estimate	iD_g, cm Estimate	V_{mor}, m^3 ha^{-1} Estimate
Intercept	–3.955 (1.242)	–3.732 (1.135)	8.481 (2.026)	–0.391 (0.154)	2.850 (0.658)	4.079 (0.559)	2.586 (0.722)
Site 5918	5.809 (0.595)	6.141 (0.552)	6.282 (1.351)	0.343 (0.062)	3.870 (0.919)	–0.069 (0.774)	–3.454 (0.999)
Site 5920	3.749 (0.450)	3.875 (0.422)	8.909 (1.356)	0.458 (0.064)	7.336 (0.825)	2.322 (0.716)	–3.555 (0.882)
Site 5927	1.650 (0.533)	1.757 (0.496)	4.999 (1.882)	0.205 (0.067)	2.173 (1.206)	0.771 (1.022)	–2.481 (1.343)
Site 5930	0.426 (0.477)	0.665 (0.443)	0.732 (1.687)	0.038 (0.061)	1.207 (1.126)	–0.082 (0.973)	–3.128 (1.244)
Site 5935	2.614 (0.479)	2.989 (0.446)	4.367 (2.024)	0.360 (0.064)	3.957 (1.344)	0.509 (1.135)	–1.949 (1.445)
Site 5948	4.214 (0.443)	4.143 (0.413)	10.507 (2.100)	0.587 (0.060)	9.991 (1.320)	7.748 (1.186)	–4.853 (1.460)
Site 5951	0	0	0	0	0	0	0
G_i^2	–4.139 (0.788)	–3.238 (0.719)		1.230 (0.248)			
G_i	11.279 (1.963)	10.084 (1.791)	–1.440 (0.791)	–0.546 (0.099)	–1.280 (0.509)	–0.204 (0.549)	0.424 (0.580)
G_i*site 5918			–1.698 (1.127)		–2.072 (0.692)	–0.399 (0.622)	1.811 (0.792)
G_i*site 5920			–3.412 (0.993)		–3.129 (0.624)	–1.163 (0.545)	2.126 (0.714)
G_i*site 5927			–2.627 (1.705)		–0.790 (1.065)	–0.993 (0.918)	0.792 (1.221)
G_i*site 5930			–0.097 (1.632)		–0.970 (1.058)	–0.417 (0.957)	2.118 (1.199)
G_i*site 5935			–0.367 (2.146)		–0.863 (1.459)	0.325 (1.241)	0.580 (1.578)
G_i*site 5948			–4.142 (1.607)		–4.633 (1.045)	–3.102 (0.928)	2.946 (1.174)
G_i*site 5951			0		0	0	0
Hdom			–0.310 (0.104)				
Birch	–2.519 (1.247)	–2.066 (1.139)				–2.391 (0.854)	
u_i^2	0.100	0.095	0.064	0.003	0.135	0.075	0.043
e_{ij}^2	0.582	0.483	0.743	0.009	0.305	0.223	0.404

G_i = density index, Birch = Birch proportion (0–1), u_i^2 = variance between blocks, e_{ij}^2 = random error

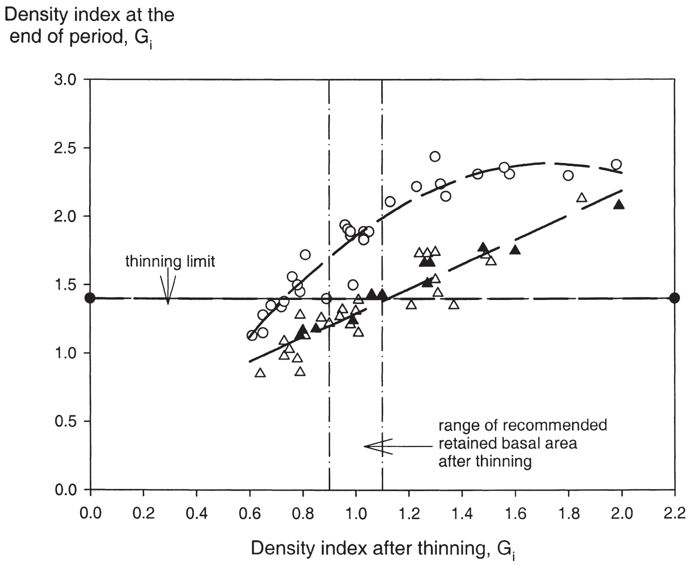


Fig. 4. The relationship between density index (G_i) after thinning and at the end of the study period. The young stands are marked with a circle and advanced stands with a triangle. The advanced stand with 10-year period located in South Finland is marked with a black triangle.

relative growth varied between thinning intensities; for heavily thinned plots it was 2.2 units higher than that of unthinned plots (Table 3 and Fig. 3). The effect of thinning on the relative growth rate varied depending on the site, and a significant interaction was detected between the density index of the retained stand and the site (Table 3). Stands at the first commercial thinning stage (sites 5920 and 5948) showed the strongest responses to thinning.

The impact of thinning on the periodic annual increment of basal area (iG) for living trees differed from that of iV_{net}. The differences among the treatments were smaller, and moderate and light thinning showed the highest basal area growth rates when compared to the non-thinning (–5%) and heavy thinning (–14%) treatments (Table 3). The relative basal area growth (iG_{rel}) increased along with an increasing thinning intensity: the non-thinned treatments had 1.0–5.5 percent-units lower relative growth rates compared to the heavily thinned stands (Table 3). At the end of the 15-year period, the stand densities in the young thinned stands again exceeded the thinning limit as defined by the present management guidelines, except for the heavy thinning treatment (Fig. 4).

The effect of thinning intensity on the stand mean diameter increment (iD_g) varied widely depending on the site (Fig. 5). Heavy thinning increased iD_g by 0.1–2.3 cm during the entire study period (Table 3). Increased iD_g due to thinning was only found for spruce, and not for birch.

3.2 Stand Density and Mortality

Natural mortality (V_{mor}) showed a very clear response to thinning: the unthinned plots had the highest mortality rate (totalling 4–50 $m^3 ha^{-1}$) during the entire study period (Table 3). As an average for the whole study period, unthinned plots with $G_i \geq 1.4$ (a density index exceeding the thinning limit $G_i = 1.4$) had an about 12–15 $m^3 ha^{-1}$ higher mortality compared to heavily thinned plots with $G_i = 0.8$ (Fig. 6). In some sites, the difference between the unthinned and heavily thinned plots was much more distinct. Even light

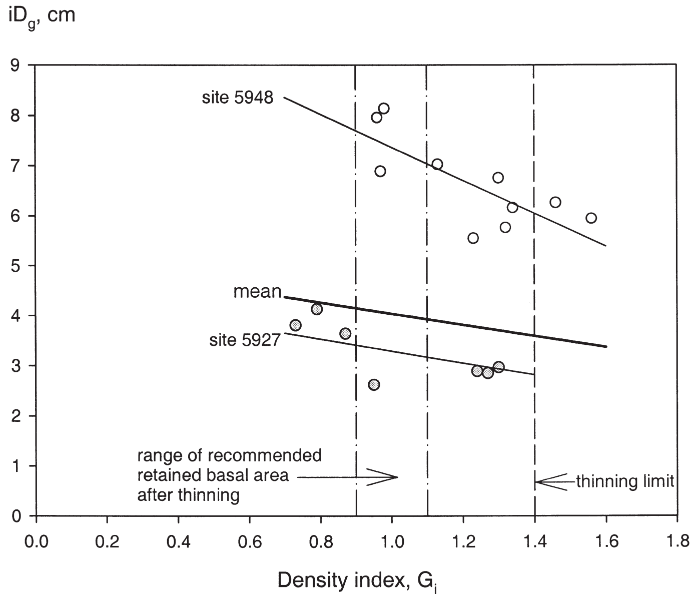


Fig. 5. Increment of basal area weighted mean diameter during the 15-year study period as a function of density index (G_i). The points are measured values and the line is the respective regression.

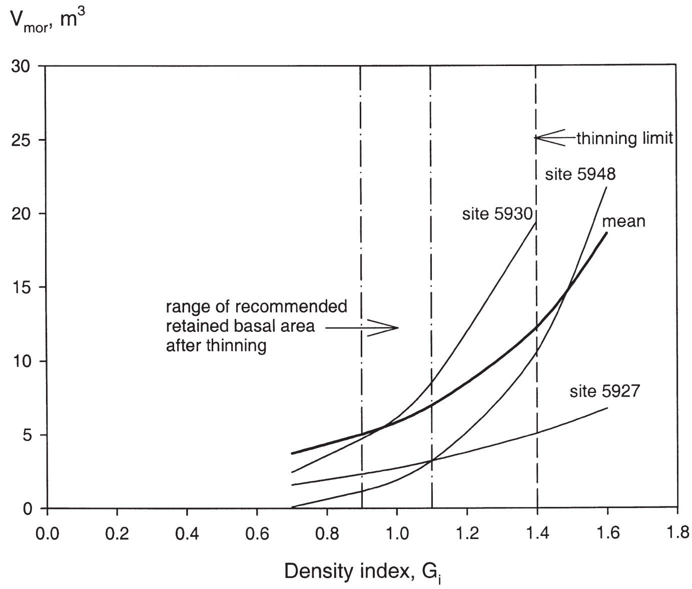


Fig. 6. The effect of stand density on the volume of natural mortality during the 15-year period.

thinning resulted in a clear reduction in mortality. Thinning in accordance with the present guidelines (i.e. moderate thinning) resulted in fairly low mortality rates, totalling 5–7 $m^3 ha^{-1}$ during the study period. Natural mortality rates of both spruce and birch were comparable, with birch having a slightly higher probability of dying. At site #5951 natural mortality was at an exceptionally high level in all the treatments due to an insect (*Ips* sp.) out-break following thinning.

3.3 Temporal Dynamics of the Thinning Response

Differences in iV_{net} among the thinning treatments were generally larger during the first than during the second and third 5-year period. In the first period iV_{net} correlated positively with the density index of the retained stand (Table 4 and Fig. 7). When the density index exceeded 1.4, however, the correlation was not clear. During the second 5-year period, the differences among the thinned treatments were smaller and the iV_{net} of the non-thinned plots collapsed (Fig. 7), partly due to natural mortality. During the third 5-year period, the iV_{net} of the non-thinned plots again increased.

The relative volume increment (iV_{rel}) was higher at a lower stand density during all 5-year periods (Table 4 and Fig. 8). The thinning response was the strongest during the second 5-year period: iV_{rel} was five percent units higher on the heavily thinned plots compared to the unthinned plots. The difference in the relative volume increment was only 0.5–1.0 percentage units per period for plots thinned to the upper or lower limit of the present management guidelines.

Natural mortality (V_{mor}) on both sites increased in all the treatments along with increasing time that had elapsed since thinning (Table 5). In the thinned plots natural mortality was 0.27–3.66 $m^3 ha^{-1} a^{-5}$. In the unthinned plots natural mortality was low during the first 5-year period, but increased noticeably in the second and third 5-year period, when the natural mortality was 11–12 $m^3 ha^{-1}$ per period (Table 5).

Compared to the present thinning guidelines for mineral soil stands, the moderately thinned plots reached the thinning limit during the third period (10–15 year after thinning) and the plots with light thinning during the second 5-year period (Fig. 9). The heavily thinned plots did not reach the thinning limit within 15 years.

Table 4. Models for periodic annual volume increment (iV_{tot}) and periodic annual relative volume increment (iV_{rel}) in 5-year periods. Standard error of estimates in parentheses.

Variable	iV_{tot}, $m^3 ha^{-1} a^{-1}$ Estimate	iV_{rel}, % Estimate
Intercept	0.248 (2.142)	8.612 (0.763)
Site 5920	0.297 (0.504)	–0.065 (0.451)
Site 5949	0	0
Period 1	–0.671 (0.634)	4.155 (1.045)
Period 2	–0.697 (0.579)	1.944 (0.956)
Period 3	0	0
G_i	10.084 (3.309)	–2.572 (0.567)
G_i^2*period 1	–2.661 (1.292)	
G_i^2*period 2	–4.639 (1.292)	
G_i^2*period 3	–3.557 (1.292)	
G_i*period 1		0.325 (0.785)
G_i*period 2		–2.411 (0.718)
G_i*period 3		0
Site*period 5920 1	–2.639 (0.570)	–3.526 (0.569)
Site*period 5920 2	0.494 (0.521)	1.076 (0.521)
Site*period 5920 3	0	0
Site*period 5948 1	0	0
Site*period 5948 2	0	0
Site*period 5948 3	0	0
u_i^2	0.020	0.041
pv_{ij-1}	0.197	0.194
e_{ij}^2	0.911	0.876

pv_{ij-1} = covariance of sequential periods.

Table 5. Average mortality ($m^3 ha^{-1}$) by thinning intensities during the 5-year periods in experiments 5920 and 5948.

Thinning intensity	1. period	2. period	3. period
Heavy (G_i = 0.74)	0.27	0.56	1.69
Moderate (G_i = 0.99)	0.10	0.87	2.02
Light (G_i = 1.22)	0.73	1.19	3.66
Unthinned (G_i = 1.58)	3.42	11.3	11.97

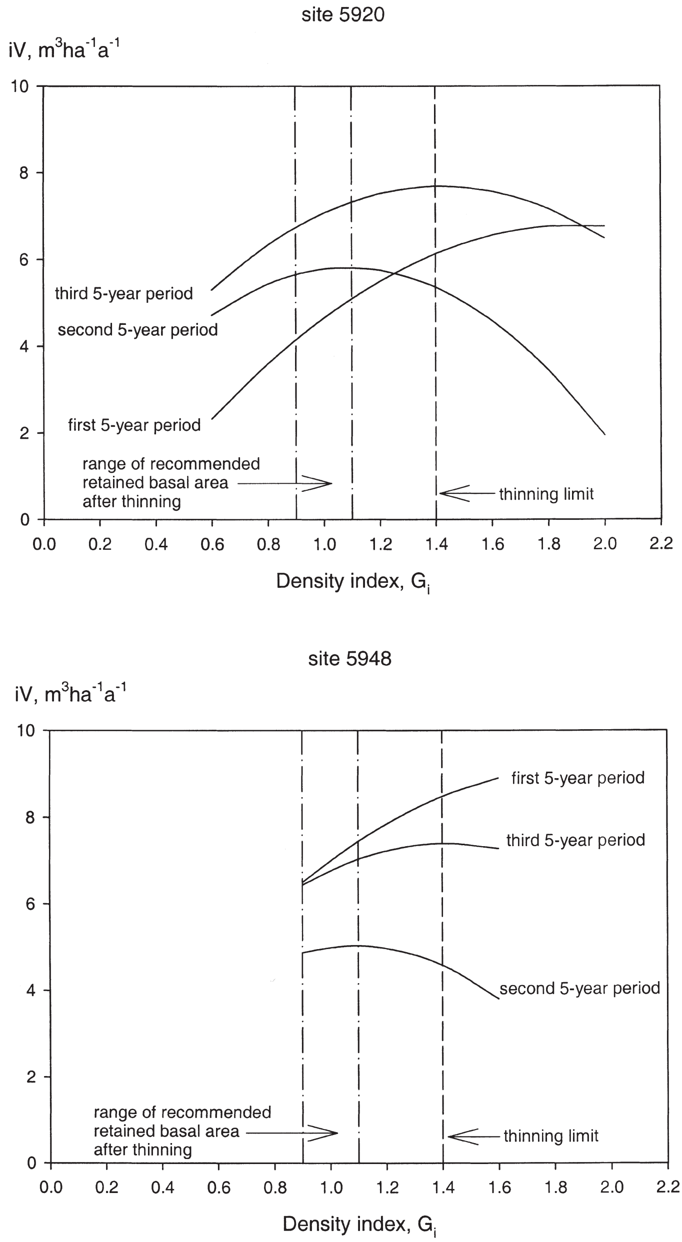
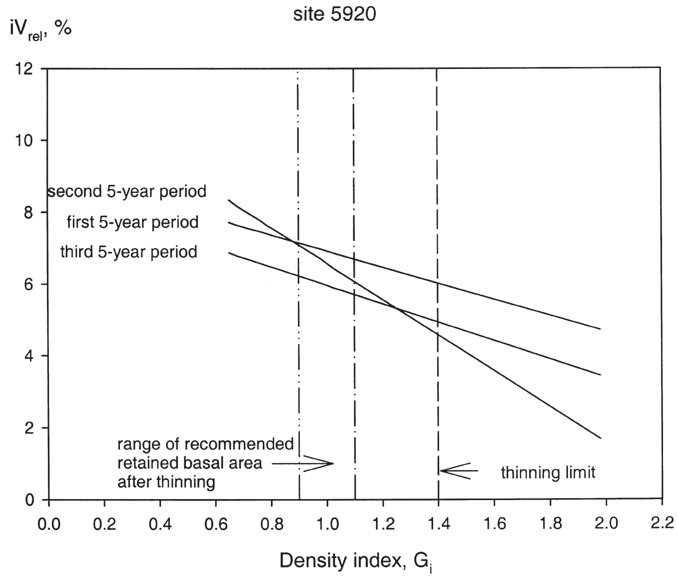


Fig. 7. The effect of thinning intensity on periodic annual volume increment in the 5-year periods in sites 5920 and 5948. Density index (G_i) describes the growing stock after thinning, at the beginning of the first 5-year period.



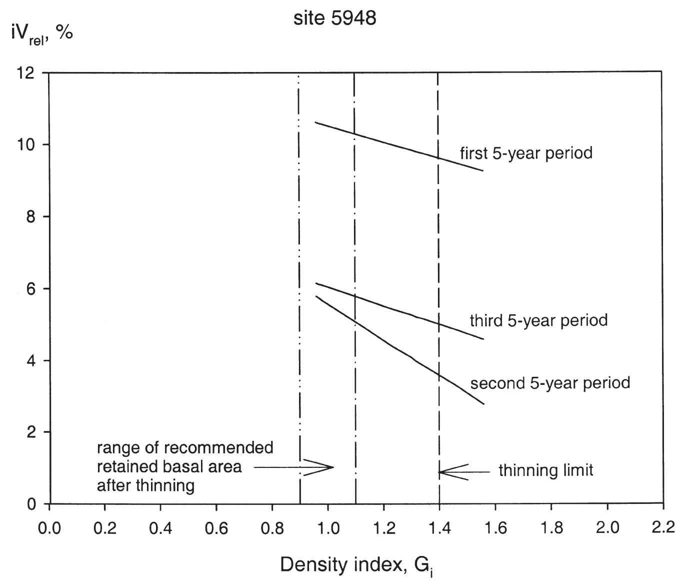


Fig. 8. The effect of thinning intensity on periodic annual volume increment in the 5-year periods in sites 5920 and 5948. Density index (G_i) describes the growing stock after thinning, at the beginning of the first 5-year period.

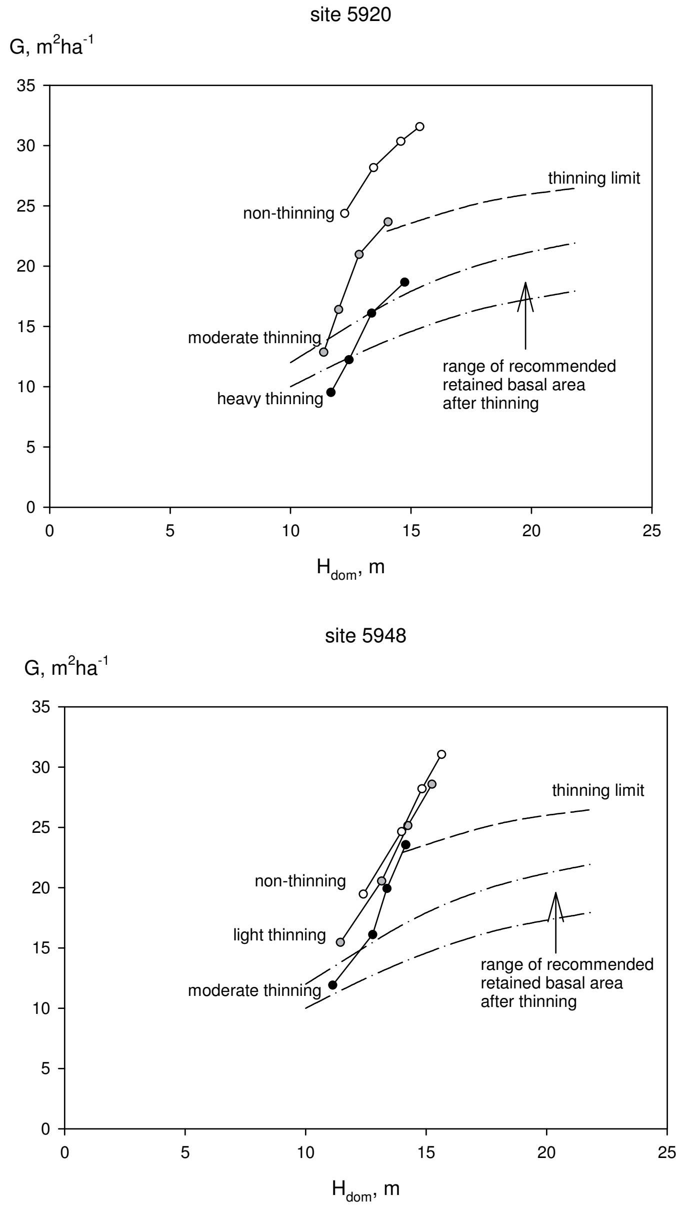


Fig. 9. The development of basal area and dominant height of the growing stock in 5-year periods using different thinning intensities in sites 5920 and 5948.

4 Discussion

This study was based on seven field experiments established in naturally regenerated drained spruce and mixed spruce-birch stands mainly situated in northern Finland. The results concerned a period of 10–15 years after thinning. The highest total stem wood productivity was found on the non-thinned plots. However, on these plots the highest densities were also associated with reduced growth of all the trees. Light, moderate and heavy thinning decreased the volume increment of the living trees on the average by 1, 8, and 22%, respectively. When all trees, including dead trees, were taken into account the differences between the thinning treatments were even larger. Mäkinen and Isomäki (2004) reported clearly smaller differences between thinning treatments: only a 4–7%, reduction of volume increment was found between heavily thinned and unthinned treatments on fertile and highly fertile upland sites in southern Finland. Furthermore, Eriksson and Karlsson (1997) showed that even a 50% removal of the growing stock did not lead to a significant reduction in the post-thinning volume increment in upland spruce stands in Sweden. The results are not directly comparable, because the management history, the range of thinning intensities, number of thinnings and length of the study period vary among the studies. However, the effect of retained volume increment appeared to be more important in our data than in earlier studies on upland sites where a wide range of stand density had only a marginal effect on the volume increment of Norway spruce (Assmann 1954, Vuokila 1985, Eriksson and Karlsson 1997, Mäkinen and Isomäki 2004).

One reason for the differing responses to heavy thinning especially may lie in site productivity. The results from upland sites are for fertile or highly fertile sites, where the retained trees rapidly occupy the free growing space (Mäkinen and Isomäki 2004). Due to their mostly northern locations, our sites were on the average less productive, and this may be one reason for the relatively weaker or slower response. Furthermore, the results from upland sites are from pure or almost pure Norway spruce stands, while our material represented mixed spruce-birch stands where the higher proportions of a pubescent birch admixture was related to lower productivity of the living trees.

Heavy thinning decreases canopy interception and transpiration, thus allowing more precipitation to enter the ground. In peatland sites this may raise the ground water level, which in turn can result in reduced volume increment. Although ditch network maintenance was performed at the time of establishment of the experiments, the ground water level may have risen after heavy thinning.

The growth response to thinning was visible as a higher relative stand volume and mean diameter increment of the living trees with decreasing density of the retained stand. Stands at the first commercial thinning stage showed the strongest responses to thinning. In the more advanced stands, the response was also notable but not as strong as in the younger stands. This agrees well with the findings of Holgén et al. (2003) concerning the effects of shelterwood cuttings to different densities in a drained peatland spruce stand in Sweden.

The stand volume increment, and especially the basal area increment, did not decrease proportionally with decreasing stand density, which suggested that the growth response to thinning was the highest in the lower parts of the stems. This has been reported in other Nordic studies for Norway spruce (Agestam et al. 1978, Vuokila 1985, Eriksson and Karlsson 1997, Holgén et al. 2003, Mäkinen and Isomäki 2004).

Our results have several implications for operational forestry on drained spruce peatlands. Thinnings are very important if management is aimed at maximum yields of living trees and merchantable timber. In order to avoid natural mortality due to high densities, the timing of thinning is especially important for stands that have reached the density criteria for first commercial thinning. In such stands, even a delay of five years in thinning may significantly increase the mortality. For the same reason, the thinning interval in spruce stands on well-productive sites should be clearly shorter than e.g. in less productive pine stands. If the forest management guidelines (Hyvän metsänhoidon… 2001) are applied, then stands corresponding to the first thinning stage in our material, would again reach the thinning criteria 15 years after the first thinning. Light thinning would lead to even shorter thinning intervals, and heavy thinning to somewhat longer intervals. It should also be kept in mind that when the proportion of pubescent birch was high after heavy thinning, the post-thinning volume production was clearly lower. Most of the pubescent birch stems should be harvested in the first or second thinning because of birch's weak thinning response, low wood production capacity, and low expected value as saw timber.

In addition to thinning, good ditch network condition has to be assured in the management of drained peatland forests. The need for thinning may not coincide with the need to maintain the ditches but, in general, it is advisable to carry them out simultaneously. This is especially important if the thinning intensity is heavy. Otherwise the ground water table may rise and the thinning response is likely to be lower than that expected on the basis of the increase in growing space.

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