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Timing and Intensity of Precommercial Thinning and Their Effects on the First Commercial Thinning in Scots Pine Stands

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The effects of the timing and intensity of precommercial thinning on the stand diameter development and wood production in Scots pine stands was addressed. A model was developed in order to assess the thinning response of the stand diameter development. The effect of precommercial and first commercial thinning on the stand volume and the thinning removal at first commercial thinning were also modelled. The models were developed to be applicable for forest management planning purposes. The results are based on Scots pine (*Pinus sylvestris* L.) trials (13 experiments and 169 plots) located in Southern and Central Finland.

Precommercial thinning considerably enhanced the diameter development. Precommercial thinning (at H_{dom} 3 m to 2000 trees per hectare) increased the mean diameter by 15% at the first commercial thinning stage (H_{dom} 14 m) compared to the unthinned stand (3000 trees ha^{-1}). Early and intensive precommercial thinning resulted in the strongest response in diameter development. Wide spacing also enhanced the diameter increment. In naturally regenerated stands the diameter development was ca 13% slower than that in seeded stands.

The total volume at the time of first commercial thinning was affected by the timing of thinning and the stand structure. The volume of merchantable thinning removal depended on the timing and intensity of precommercial and first commercial thinnings. Delaying the first commercial thinning from 12 meters (H_{dom}) to 16 meters increased the volume of thinning removal by ca.70%. The early and light precommercial thinning (H_{dom} 3 m, to density of 3000 trees per hectare) increased the thinning removal by 40% compared to the late and intensive precommercial thinning (at 7 meters to the density of 2000 trees per hectare).

Keywords Scots pine, *Pinus sylvestris*, precommercial thinning, first commercial thinning, diameter development, growth and yield, growth modelling
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1 Introduction

A forest management programme is a chain of successive management practices. One of the most crucial activities in the chain is the management of young stands. Success or failure in young Scots pine (*Pinus sylvestris* L.) stand management has long-term effects on stand development and, subsequently, on the profitability of forest management. Precommercial thinning is the key management practice in young Scots pine stands. The timing and intensity of precommercial thinnings affect the yield and quality development of young stands and, furthermore, the timing and profitability of the first commercial thinning.

In Finland, and in other Nordic countries, the effects of precommercial thinning have been a widely studied issue. The studies have mainly been focused on the timing and the intensity of precommercial thinning. In general, during the whole rotation, thinning is known to reduce the total yield, but the resulting increase in growing space accelerates tree diameter and volume increment, and enhances crown development (Assman 1970, Vuokila 1981). In young stands, early and intensive precommercial thinning accelerates the volume growth of the trees, and increases the yield of merchantable wood at the first commercial thinning stage. Due to the increased growing space, the branches grow thicker and longer and crown recession slows down (Kellomäki and Tuimala 1981, Fahlvik et al. 2005). As a result, intensive management impairs the external stem quality by increasing tapering and promoting branchiness.

The management strategy of young stands is defined by the goals of forest management and wood production. If the goal is to maximise the production of merchantable wood in terms of quantity, early and intensive precommercial thinnings are favoured (Vuokila 1972, Parviainen 1978). Based on Scandinavian growth and yield studies (e.g. Vuokila 1972 and Vestjordet 1977), the recommended timing of precommercial thinning is at a dominant height of 2.5 m.

The high density of young Scots pine stands results in slower tree diameter and branch development. Although the growth rate decreases, retarded branchiness improves the external stem quality. If the goal of Scots pine management is to produce high quality saw timber, late precommercial thinnings have been recommended. According to Varmola (1996) and Varmola et al. (1998), thinning is required only after the mean height reaches 5 m in seeded Scots pine stands in Southern Finland. In Northern Finland, Ruha and Varmola (1997) proposed precommercial thinnings at a dominant height of 8 m.

When assessing the intensity of precommercial thinning, both silvicultural and economical aspects are usually considered. In practice, the goal of young stand management is to promote the development of the most vital and valuable trees in as cost-effective a manner as possible.

Heavy precommercial thinning results in considerable yield losses. Varmola and Salminen (2004) noticed considerable loss in merchantable wood production in stands where the remaining stand density after precommercial thinning was 1000 trees per hectare. The loss was substantially smaller at stand densities ranging from 1600 to 2200 (Varmola and Salminen 2004).

Light precommercial thinnings (>2500 or even more than 4000 trees per hectare) are favourable in terms of stem quality development (Huuri et al. 1987, Varmola 1996, Agestam et al. 1998, Varmola and Salminen 2004). From the point of view of forest management profitability, however, light precommercial thinnings are less favourable. Carrying out a light precommercial thinning may result in the need for another costly precommercial thinning, or early first commercial thinning with a small removal of merchantable wood and negligible thinning incomes.

In many Nordic studies, stand densities from 2000 to 3000 after precommercial thinnings are proposed as a compromise between the silvicultural and economical aspects (Vuokila 1972, Vestjordet 1977, Pettersson 1993, Salminen and Varmola 1990, Ruha and Varmola 1997).

First commercial thinning is a management practice in which both the silvicultural and economical aspects have to be taken into account. From the silvicultural point of view, the goal of the first commercial thinning is to provide enough growing space, and thus improve the vitality of the future crop trees. The timing and intensity of the first commercial thinning are affected by the earlier management of the stand.

On the other hand, the first commercial thinning is the first opportunity for a forest owner to obtain income during the rotation. The profitability of commercial thinnings is determined by the amount and the value of thinning removal on the one hand, and by the logging costs on the other hand. In first commercial thinnings, the removals are usually small, and consist mostly of small-size pulpwood, with a relatively low value and high logging costs. Therefore, the profitability of the first commercial thinning is substantially lower than that in later thinnings or the final felling. The profitability is affected by the intensity and the timing of the thinning measure. In managed, young Scots pine stands, a 10–15-year delay in the first commercial thinnings has been found to result in a significant increase in the thinning removal and revenues (Hynynen and Saramäki 1995, Hynynen and Arola 1999, Huuskonen and Ahtikoski 2005).

Heavy commercial thinnings decrease the amount of growing stock and result in a loss of merchantable yield at the stand level. In Scots pine stands this loss cannot be compensated by the increased diameter development of individual trees (Vuokila 1981, Hynynen and Niemistö 2001). According to the results of long-term experiments in Scots pine stands in Finland, heavy thinnings (average basal area less than 64% of that on the control plots) decrease the volume increment by about 25% (Mäkinen and Isomäki 2004). In Swedish studies, the decrease in volume growth has been 30–37% (Eriksson and Karlsson 1997, Valinger et al. 2000).

The interaction between the precommercial and the first commercial thinning has not been studied experimentally. So far, the focus in studies has been either on the early stand development and on the precommercial thinning, or on the development of mature stands and their response to commercial thinnings.

This study focuses on stand development from the precommercial thinning stage to the first commercial thinning stage in Scots pine stands. The results are based on extensive data collected from permanent, long-term experiments located in Southern and Central Finland. The objective is to study the effect of the timing and intensity of precommercial thinning on stand diameter development and wood production, as well as on the amount of thinning removal in the first commercial thinning. The aim is also to develop robust models for a) assessing the effect of precommercial thinning on the diameter development in young stands, and b) assessing the total stand volume and the attainable removal of merchantable wood in the first commercial thinning in young Scots pine stands.

2 Material and Methods

2.1 Experiments

The data set was collected from 13 Scots pine (*Pinus sylvestris* L.) experiments in Southern and Central Finland (Fig. 1). The experiments were established by the Finnish Forest Research Institute in the early 1970s and the early 1980s (Table 1). The sites were classified as the *Vaccinium* forest stand type (Cajander 1949) or dryish sites according to Tonteri et al. (1990), which is a typical site for Scots pine. The data set consisted of the unfertilized plots in stands where the first commercial thinnings were carried out.

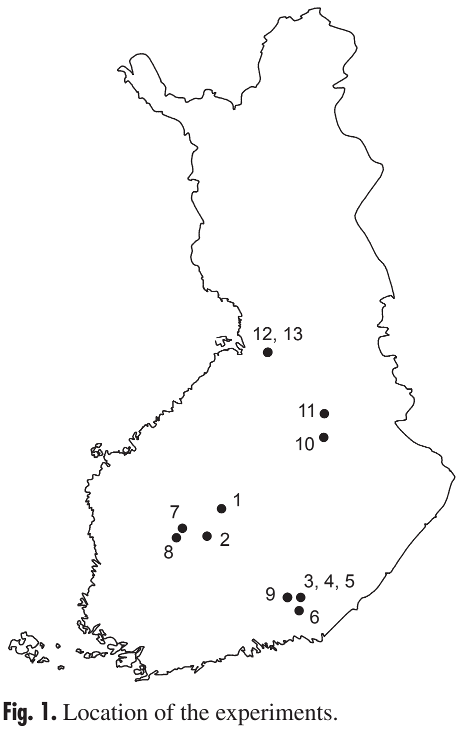

Fig. 1. Location of the experiments.

Table 1. Mean characteristics and treatment sets of precommercial (PCT) and first commercial (FCT) thinnings of the experimental stands.

No.	No of plots at establishment	Year of regeneration	Observation period	No of measurements	Timing of PCT, Dominant height, m	Intensity of PCT, trees ha^{-1} after thinning	Timing of FCT, Dominant height, m	Intensity of FCT, trees ha^{-1} after thinning	FCT removal, %
1	11	1961	1974–2003	5	3.5, 5, 8	600, 1000,1600, 2700	16	1000	23–43
2	11	1954	1972–2000	5	7	700, 1000, 1600, 2200, 3000	13, 20	600, 800, 1000, 1200	1–71
3	12	1955	1973–1996	4	7	1000, 1600, 2200, 3000, 3300	17	400, 800, 1200, 1600, 2000	17–62
4	10	1955	1973–1996	4	7	500, 1000, 1600, 2200, 3000	13, 17	700, 800, 900, 1000, 1200, 1600, 1800	15–66
5	16	1964	1973–1998	3	4	600, 1000, 1600, 2200, 3000	16	400, 600, 1000, 1200, 1500, 1800	28–63
6	9	1950	1974–1997	4	7	1000, 1600, 2200, 3000	12, 16	400, 600, 800, 1200, 1600	43–62
7	22	1952	1972–2000	5	7	1000, 1200, 1600, 2200, 4000	16	400, 600, 800, 1000, 1200, 1600	7–78
8	19	1953	1973–2000	4	6	1000, 1600, 2200, 3000	15	600, 900, 1200	13–80
9	17	1954	1974–1994	4	7	1500, 2000, 2500	13	750, 1200, 1600	32–52
10	17	1954	1974–1989	3	7	1500, 2000, 2500	14	750, 1250, 1750	29–52
11	17	1955	1974–1988	3	6	1500, 2000, 2200	12	750, 1250, 1750	20–51
12	4	1961	1981–2001	5	2	1000, 1500, 2100	13, 15	1000, 4300	19–52
13	4	1961	1980–2001	5	2	1000, 1600, 2100	14	1000	38–52

The stands were even-aged, pure or almost pure Scots pine stands growing on mineral soil. They were established by seeding (10 stands) or natural regeneration (3 stands; nrs. 6, 8, 12). The principal aim of the experiments was to investigate the effect of precommercial thinning intensity or timing on the growth and yield of Scots pine stands at different stages of stand development. The data set consisted of different kinds of experiments that also included a fertilization treatment. The results of these experiments have earlier been reported by Varmola (1982), Eerola (1983), Salminen and Varmola (1990), Nikkola (1985), Lampola (1991) and Varmola and Salminen (2004). Only the unfertilized plots were included in the present study.

Rectangular plots were established in each stand. The total number of sample plots was 694. In some of the experiments with a high initial stand density, only four circular sub-plots inside the rectangular plot were measured at the first measurement instance. Later on, the measurements covered the whole plot. The plot area varied between 136–3750 m^2, with an average plot size of 997 m^2.

The timing of precommercial thinning varied from 2 m to 8 m, and the stand density after precommercial thinning between 500–3000 trees per hectare (Table 1). The timing of first commercial thinning varied from 12 m to 20 m, and the density after first commercial thinning between 400–4300 trees per hectare (Table 1). Some of the experiments also included unmanaged control plots. The number of sample plots within an experiment varied from 4 to 22. In most experiments the treatments were replicated twice or even more in a randomised block design (Table 1). In some experiments (3, 4, 5, 9), some plots were split in two during the measurement period. Furthermore, at the time the experiments were established, the common practice was to remove all the broadleaved trees in coniferous stands. This kind of treatment was also applied on the control plots. Strip roads were located outside the plots.

2.2 Measurements

The experiments were re-measured from three to five times (Table 1). At the time of the last measurement, the stand age ranged from 34 to 49 years, with an average age of 42 years. In most of the experiments each tree was measured for diameter at breast height (1.3 m above ground). In some of the experiments, the trees were tallied by tree species and diameter classes at the first measurement instance. In each plot, sample trees were measured for tree height. In the later measurements, the diameter at 6 m height and the height to the base of the crown were also measured on sample trees.

Stand characteristics were calculated using the KPL software, developed at the Finnish Forest Research Institute (Heinonen, 1994). All the analyses were based on the plot level data calculated on the basis of tree data. The height of the tally trees was predicted using Näslund's height curve (Näslund, 1936) that was fitted for each plot with the help of the tree heights measured on the sample trees. The dominant height was calculated as the mean height of the 100 thickest trees ha^{-1}. Stem volume of the sample trees was calculated using volume functions based on the measured stem diameters ($d_{1.3}$, $d_{6.0}$) and tree height (Laasasenaho, 1982). The volume of the other trees was calculated using smoothing functions fitted to the sample tree data of each plot.

The merchantable stem volume was calculated using the assortment rules that are widely applied in Finland. The minimum length applied for pulpwood was 3.0 m, and the minimum top diameter over bark for Scots pine and birch was 6.0 cm and for Norway spruce 8.0 cm. The minimum log length was 3.1 m for Scots pine and birch, and 3.7 m for Norway spruce. The minimum top diameter for log over bark was 20.5 cm for Scots pine, 19.5 cm for Norway spruce and 18 cm for birch. For birch this minimum value was constant. However, the minimum top diameter decreased progressively with increasing log length, being 15 cm for Scots pine and 16 cm for Norway spruce when the log length was over 4.3 m.

For each experimental stand, the annual, long-term average, effective temperature sum (in degree-days, d.d., threshold value +5^{o}C), based on latitude, longitude, and elevation of each stand, was estimated by the model of Ojansuu and Henttonen (1983).

2.3 Model for the Diameter Development

The effect of stand management on the diameter development was modelled on the basis of the following diameter-height model formulation:

$$D = b_0 \times H^{b_1} \times \varepsilon \tag{1}$$

where the development of arithmetic mean diameter at breast height (1.3 m above ground) over bark (D) was expressed as a function of dominant height (H), b_0 and b_1 are the model parameters, and ε is the random error.

Dominant height was chosen to be an independent variable because it reflects the effect of the site type and the stand age. Therefore, no site index was included in the model. The effect of the actual stand density was added to the model using stem number per hectare. The initial spacing was described by the initial stem number. The effect of regeneration method was included as a categorical variable in the case of seeding, while natural regeneration was taken as the basic level. The data contained no planted stands. The model was assumed to be of multiplicative form as follows:

$$D = \exp(a_0 + a_4 S) \times N_{ini}^{a_1} \times H^{a_2} \times N^{a_3} \times \varepsilon \tag{2}$$

where N_{ini} is the number of trees at the initial stage, N is the actual stem number, S is the categorical variable for a seeded stand, and a_0–a_2 are parameters.

Model 2 was linearized using logarithmic transformation as:

$$\begin{aligned} &\ln(D) = \\ &a_0 + a_1 \ln\left(N_{ini}\right) + a_2 \ln(H - 1.3) + a_3 \ln\left(N\right) + a_4 S + \varepsilon \end{aligned} \tag{3}$$

where ln is the natural logarithm of the issued variable.

The effect of precommercial thinning (PCT) on mean diameter development was added to the model. It was assumed that PCT accelerates the diameter development. Based on this assumption, stand mean diameter at any point of domi-

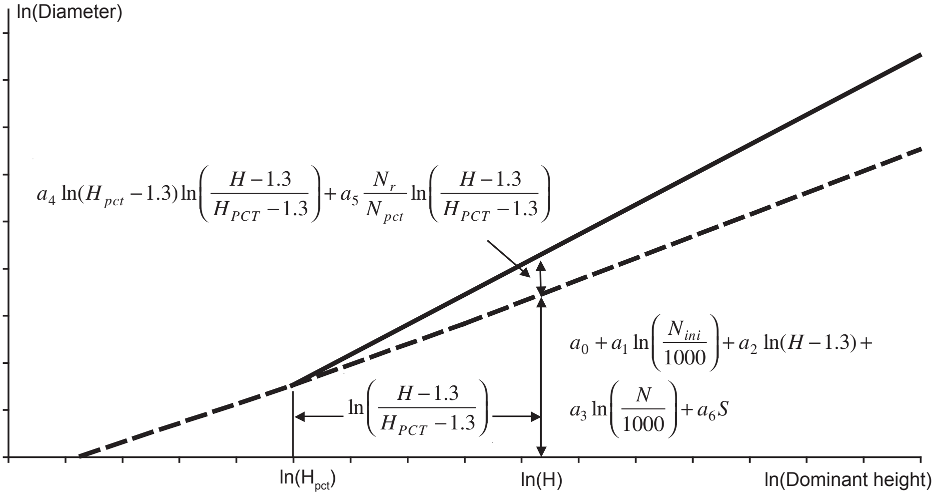

Fig. 2. The principle used in defining the effect of precommercial thinning on the diameter development at a logarithmic (linear) scale. In a stand where no precommercial thinning (dashed line) has been carried out, the diameter (*D*) development is predicted as a function of dominant height (*H*), initial stand density (N_{ini}) and the actual stem number of the growing stock (*N*), and the regeneration method (*S*). If precommercial thinning is carried out (solid line), the predicted response in diameter increment is dependent on the timing of precommercial thinning (H_{pct}, H–$H_{pct,}$), and the thinning intensity, determined as the ratio between the number of removed trees (N_r) and the stem number before thinning (N_{pct}).

nant height (*H*) following PCT can be defined as the sum of i) the diameter corresponding to the dominant height at the time of PCT (H_{pct}), and ii) the cumulative increase in diameter during the post-PCT period expressed in terms of the difference in the dominant heights (H–H_{pct}) (Fig. 2). A comparable approach has been used before by Hökkä and Ojansuu (2004) when modelling the height development on peatlands on the basis of the age and time of drainage. In the model, height minus a constant value of 1.3 m (*H*–1.3) is used in order to guarantee logical values for diameter (in young stands) when the height is close to 1.3 m.

Both the timing and the intensity of PCT were assumed to affect stand diameter development. The effect of timing on the slope of the post-PCT part of the model was included in the model (see Fig. 2). The intensity of PCT was expressed as the ratio between the stem number of removed trees (N_r) to the stem number before PCT (N_{pct}). It was assumed to affect the slope of the diameter development after PCT.

Due to the longitudinal data structure (i.e. repeatedly measured experimental plots), mixed-effect modelling was applied (e.g. Snijders and Bosker, 1999). The observations at different measurement instances were correlated. This can be taken into account by adding the random experiment (stand) effects and repeated structure of random error into the variance component model (e.g. Searle et al., 1992).

The final diameter-height model, including the effect of timing and intensity of PCT on Scots pine stands, can be expressed as follows:

$$\begin{aligned}&\ln(D_{ik}) = \\ &a_0 + a_1 \ln\left(\frac{N_{ini,ik}}{1000}\right) + a_2 \ln(H_{ik} - 1.3) + a_3 \ln\left(\frac{N_{ik}}{1000}\right) + \\ &PCT\left[a_4 \ln\left(H_{pct,ik} - 1.3\right)\left[\ln\left(\frac{H_{ik}-1.3}{H_{pct,ik}-1.3}\right)\right] + \right. \\ &\left. a_5\left(\frac{N_{r,ik}}{N_{pct,ik}}\right)\left[\ln\left(\frac{H_{ik}-1.3}{H_{pct,ik}-1.3}\right)\right]\right] + a_6 S_k + \mu_k + \varepsilon_{ik}\end{aligned} \tag{4}$$

where the symbols are the same as in Eqs. 2 and 3. N_r is the number of removed stems at PCT, and N_{pct} is the stem number before PCT. PCT = 1 if

Table 2. Data sets used in parameter[a] estimation of diameter Model 4.

	D, cm	H, m	N, N ha^{-1}	N_{ini}, N ha^{-1}	H_{pct}, m	N_r, N ha^{-1}	N_{pct}, N ha^{-1}
Mean	11.1	11.3	1844	6962	6.3	5095	7204
Minimum	1.7	3.0	328	1304	2.0	17	1304
Maximum	23.7	21.5	19191	38220	9.2	37520	38220
S.D	4.4	4.4	1439	5128	1.7	5304	5351
N	694	694	694	694	608	608	608

[a] *D* is the stand mean diameter at breast height, *H* is dominant height, *N* is actual stem number and N_{ini} is stem number per hectare at the initial stage, H_{pct} is dominant height at the time of precommercial thinning, N_r is number of removed trees and N_{pct} is stem number before precommercial thinning.

Table 3. Data set used in parameter[a] estimation of the model of total volume (6).

	V_t, m^3 ha^{-1}	H_{fct}, m	D_{fct}, cm	N_{fct}, N ha^{-1}	DD, d.d.
Mean	176	13.1	14.6	1883	1167
Minimum	103	7.6	11.4	610	1006
Maximum	327	19.5	21.3	4372	1290
S.D	48	2.3	2.0	644	104
N	139	139	139	139	139

[a] V_t is total volume, H_{fct} is dominant height, D_{fct} is stand mean diameter at breast height, N_{fct} is stem number before the first commercial thinning, and *DD* is effective temperature sum.

precommercial thinning is carried out, otherwise it is 0. μ_k is the random stand effect and ε_{ik} is the random error. The effect of climatic factors on the diameter increment was tested by adding the temperature sum to the Model 4. However, the effect proved to be non significant, probably due to the relatively narrow variation in the climatic conditions in the modelling data. The data set used in diameter modelling is presented in Table 2.

2.4 Model for the Stand Volume at the Time of the First Commercial Thinning

The total volume at the time of the first commercial thinning (FCT) was assumed to be affected by the stand mean diameter, stand density, and dominant height at the time of FCT. The model for the total volume was formulated as follows:

$$V_t = b_0 \times D^{a_1} H^{a_2} \times N_{fct}{}^{a_3} \times \varepsilon \tag{5}$$

where the total volume at the time of FCT (V_t) is predicted as a function of the stand mean diameter (*D*) and dominant height (*H*) before the FCT, and stem number before the thinning (N_{fct}). In the model, ε depicts the random error.

The effects of climate (temperature sum), and regeneration method were also tested. The regeneration method was not significant in the model for total volume. However, the regeneration method affected the diameter development (see Model 4). The final linearized model can be expressed as:

$$\begin{aligned} &\ln\left(V_{t,ik}\right) = \\ &a_0 + a_1 \ln\left(D_{fct,ik}\right) + a_2 \ln\left(H_{fct,ik} - 1.3\right) + \\ &a_3 \ln\left(N_{fct,ik}\right) + a_4\left(\frac{DD_k}{1000}\right) + \mu_k + \varepsilon_{ik} \end{aligned} \tag{6}$$

where ln is the natural logarithm of the issued variable. D_{fct} is the stand mean diameter, H_{fct} is the stand dominant height and N_{fct} is the number of trees before FCT, DD is the annual average temperature sum, and μ_k includes the random effect, and ε_{ik} is the random error. The modelling data of the total volume consisted of the measurements, which were carried out at the time of FCT (Table 3).

2.5 Model for the Thinning Removal of the First Commercial Thinning

A model was developed for the removed volume of merchantable wood in FCT. The thinning removal was assumed to be affected by the timing and the intensity of the first commercial thinning (FCT). The initial model formulation for the FCT removal was as follows:

$$V_r = a_0 \times D^{a_1} H^{a_2} \times \left(\frac{N_r}{N_{fct}}\right)^{a_3} \times \varepsilon \tag{7}$$

where the merchantable wood removal of FCT (V_r) is predicted as a function of the stand mean diameter (*D*) and dominant height (*H*) before the FCT, and the intensity of FCT, described by the proportion of the removed stem number (N_r) out of the stem number before the thinning (N_{fct}). In the model, ε depicts the random error.

Table 4. Data set used in parameter[a] estimation of the model of volume removal (9).

	V_r, m^3 ha^{-1}	H_{fct}, m	D_{fct}, cm	D_r, cm	N_{fct}, N ha^{-1}	N_r, N ha^{-1}	$N_{post\text{-}pct}$, N ha^{-1}	H_{pct}, m	DD d.d.
Mean	48.6	14.1	12.5	10.7	1918	909	2083	6.4	1156
Minimum	16.1	11.5	9.6	7.7	1350	210	1483	2.0	1006
Maximum	121.6	17.9	15.8	16.6	3208	2456	4960	8.2	1290
S.D	24.9	1.7	1.4	1.8	476	423	670	1.5	108
N	74	74	74	74	74	74	70	70	74

[a] V_r is volume of the removal (pulpwood and saw wood) per hectare in first commercial thinning, H_{fct} is dominant height before the first commercial thinning, D_{fct} is stand mean diameter at breast height before the first commercial thinning, D_r is stand mean diameter of thinning removal, N_{fct} is stem number before thinning, N_r is removed stem number at the first commercial thinning, $N_{post\text{-}pct}$ is stem number after the precommercial thinning and H_{pct} is dominant height at the time of precommercial thinning. *DD* is effective temperature sum.

The thinning removal is known to depend on tree selection, i.e. thinning from below or above (Vuokila 1977, Niemistö 1994). The ratio between the mean diameters of the removal (D_r) and the stand diameter before FCT (D_{fct}) was applied to describe the type of tree selection. Thus, the higher the issued proportion, the more clearly tree selection has been made from above.

The timing and intensity of PCT affects the FCT removal. The intensity of PCT was described by the stem number after PCT ($N_{post\text{-}pct}$). The timing of PCT was described as the ratio between the dominant height at the time of PCT (H_{pct}) and the dominant height at the time of FCT (H_{fct}).

The regeneration method affects the development of a young stand, and it is also reflected in the amount of FCT removal. The effect of regeneration method was added to the model by means of a categorical variable referring to seeding. The effect of climate was added to the model by means of the temperature sum. The final multiplicative model can be expressed as:

$$V_r = a_0 \times D_{fct}{}^{a_1} \left(H_{fct} - 1.3\right)^{a_2} \times \left(\frac{N_r}{N_{fct}}\right)^{a_3} \times \left(\frac{D_r}{D_{fct}}\right)^{a_4} \times \exp\left(PCT \times a_5 \frac{N_{post-pct}}{1000}\right) \times \exp\left[PCT \times a_6 \left(\frac{H_{pct}}{H_{fct}}\right)\right] \times \exp(a_7 S) \times \exp\left(a_8 \frac{DD}{1000}\right) \times \varepsilon \quad (8)$$

where N_r is the number of removed trees, and D_r is the mean diameter of the removed trees. $N_{post\text{-}pct}$ is the number of trees after the precommercial thinning (PCT). The other symbols are the same as in Models 5 and 6.

The linearized model for the volume of FCT removal is:

$$\ln\left(V_{r,ik}\right) = a_0 + a_1 \ln\left(D_{fct,ik}\right) + a_2 \ln\left(H_{fct,ik} - 1.3\right) + a_3 \ln\left(\frac{N_{r,ik}}{N_{fct,ik}}\right) + a_4 \ln\left(\frac{D_{r,ik}}{D_{fct,ik}}\right) + PCT\left[a_5\left(\frac{N_{post-pct,ik}}{1000}\right) + a_6\left(\frac{H_{pct,ik}}{H_{fct,ik}}\right)\right] + a_7 S_k + a_8\left(\frac{DD_k}{1000}\right) + \mu_k + \varepsilon_{ik} \quad (9)$$

where ln is the natural logarithm of the issued variable. The other symbols are the same as in Models 5, 6 and 8. PCT = 1 if precommercial thinning is carried out, otherwise the value is 0.

The data of the model for the thinning removal consisted of the measurements which were carried out at the time of FCT. The data were restricted to the stands representing cases where FCT is actual according to the common practice in Finnish forestry. Thus, only the plots with a dominant height less than 19 m, and densities over 1400 trees per hectare before FCT, and 600–1400 trees per hectare after FCT, were included in the data (Table 4).

2.6 Estimation of Model Parameters

The parameters of the models were estimated using the Mixed procedure of SAS software (SAS Institute Inc. 1999, Littell et al. 1996) applying the method of restricted maximum likelihood (REML). Variables were included in the models if the p value was less than 0.05 (5% risk level).

The stand was used as a random factor in

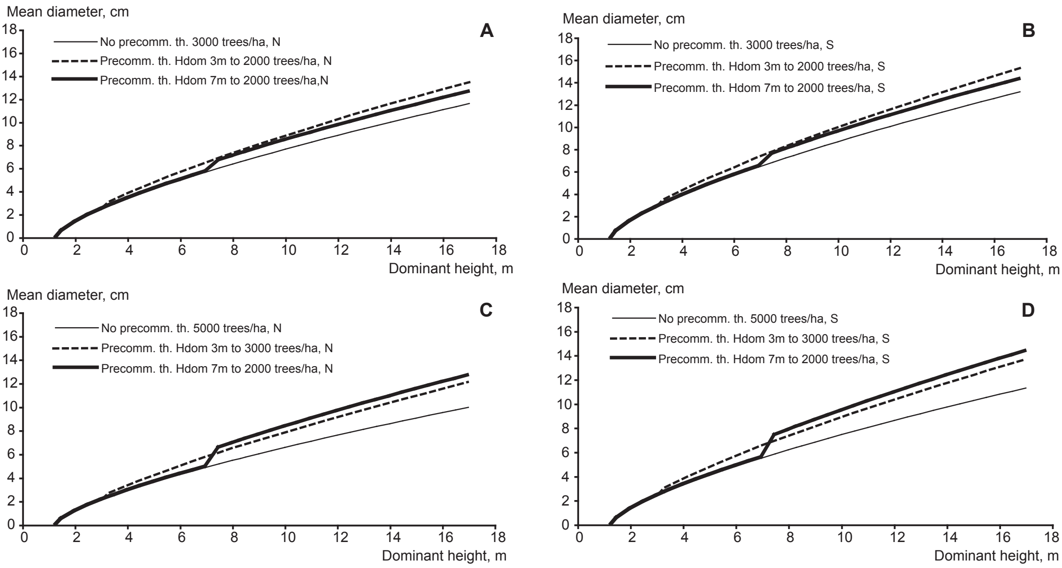

Fig. 3. Diameter development (Eq. 4) by dominant height in Scots pine stands with different initial stand densities (A, B – 3000 trees per hectare and C, D – 5000 trees per hectare), regeneration methods (seeded (*S*) or natural (*N*)) and the effect of precommercial thinning and its timing and intensity with different dominant heights.

the models. In addition, for the diameter model (Model 4) the measurement time nested within the experiment was the repeated covariance parameter. Different random parameters were tested in the mixed model formulation for diameter using the Akaike's Information Criterion and Likelihood Ratio test. It was first assumed that both the experiment and the plot nested within the experiment were random parameters. However, tests showed that plot nested within experiment random parameter could be discarded ($p > 0.1000$).

In the model for FCT removal (Model 9), the variance estimates for experiment were not statistically significant ($p = 0.1509$), but due to the experimental design the variance component structure was maintained in the model. There was more variance at the plot level than at the experiment level.

The reliability of the models was tested in terms of the mean (bias) and standard deviations (RMSE) of the residuals (observed-estimated). The estimated values and residuals for each plot were calculated after transformation back to the arithmetic scale, using only the fixed part of the model. A bias correction (half of the estimated error variance) was added to the estimates at the arithmetic scale.

3 Results

3.1 Stand Diameter Development

Precommercial thinning (PCT) considerably enhanced the diameter development (Eq. 4, Fig. 3). For example, the stand mean diameter of a naturally regenerated managed stand (PCT at 3-m height) was 15% (1.5 cm) greater than that of the unmanaged stand at the stage of the first commercial thinning (H_{dom} = 14 m) (Fig. 3a). Furthermore, the timing of PCT had a major effect on the diameter development (Table 5, Fig. 3a). The difference in mean diameter between a stand with early PCT (H_{dom} = 3 m) and that with a late PCT (H_{dom} = 7 m) was 6% (0.6 cm) at the time of FCT (H_{dom} = 14 m) (Fig 3a). Intensive PCT enhanced the diameter development (Table 5). If the PCT was carried out at the 3 m (H_{dom}) stage to a density of 2000 trees per hectare in a seeded stand, the diameter at a dominant height of 14 m was 16% (1.8 cm) greater than with a density of 3000 trees per hectare after PCT.

High stand density slows down the diameter development (Table 5). In an unmanaged seeded stand with an initial density of 3000 trees per hectare, the mean diameter at a stand height of

Table 5. Statistics for diameter model (Model 4), the model for the volume of the growing stock at the time of FCT (Model 6) and the model for thinning removal at FCT (Model 9).

Mean diameter (Eq. 4)				Total volume (Eq. 6)				Thinning removal (Eq. 9)			
Parameter	Variable	Value	SD	Parameter	Variable	Value	SD	Parameter	Variable	Value	SD
a_0	*const.*	0.8285	0.04764	a_0	*const.*	–10.0581	0.2356	a_0	*const.*	–0.5092	0.4613
a_1	$\ln(N_{ini}/1000)$	–0.05002	0.01202	a_1	$\ln(D_{fct})$	2.0619	0.05664	a_1	$\ln(D_{fct})$	0.6851	0.207
a_2	$\ln(H–1.3)$	0.7057	0.01352	a_2	$\ln(H_{fct}–1.3)$	0.8073	0.03737	a_2	$\ln(H_{fct}–1.3)$	1.2151	0.2287
a_3	$\ln(N/1000)$	–0.247	0.00745	a_3	$\ln(N_{fct})$	1.0612	0.02138	a_3	$\ln(N_r/N_{fct})$	1.0162	0.06269
a_4	*timing of PCT*[a]	–0.03316	0.008657	a_4	$DD/1000$	–0.1567	0.04815	a_4	$\ln(D_r/D_{fct})$	2.496	0.2072
a_5	*intensity of PCT*[b]	0.1114	0.01428					a_5	$N_{post\text{-}pct}/1000$	0.1028	0.02277
a_6	*Seeding*	0.1246	0.0382					a_6	H_{pct}/H_{fct}	–0.6306	0.1328
a_7		—	—					a_7	*Seeding*	0.1562	0.05207
a_8		—	—					a_8	$DD/1000$	0.4486	0.2043
σ^2_k		0.003065	0.001508	σ^2_k		0.000261	0.000150	σ^2_k		0.002854	0.002764
σ^2_e		0.008885	0.000484	σ^2_e		0.000618	0.000079	σ^2_e		0.009739	0.001873
bias		–0.002	cm	*bias*		0.055	m^3ha^{-1}	*bias*		0.180	m^3ha^{-1}
RMSE		0.991	cm	*RMSE*		4.803	m^3ha^{-1}	*RMSE*		5.323	m^3ha^{-1}

[a] Timing of PCT was described in the model as $\ln(H_{pct} – 1.3)$ $[\ln((H – 1.3) / (H_{pct} – 1.3))]$. [b] Intensity of PCT was described as N_r / N_{pct} $[\ln((H – 1.3)/(H_{pct} – 1.3))]$.

14 meters is 16% (1.6 cm) greater than that of an unmanaged stand with an initial density of 5000 trees per hectare. (Fig. 3b, 3d).

In seeded stands the diameter development was faster than that in naturally regenerated stands; the difference being ca. 13% (Table 5, Fig 3c, 3d).

Model behaviour was tested with the help of the residual analysis. The means and standard deviations of the residuals of Model 4 were calculated for 2 cm diameter classes (Fig. 4A), and for 2 m dominant height classes (Fig. 4B). The model resulted in a slightly biased behaviour with respect to stand mean diameter. In stands with a mean diameter over 18 cm the model tends to overpredict mean diameter. However, these kinds of stand have usually passed the stage of the first commercial thinning, and are therefore outside the range of intended application area of the model. The average bias in the diameter development model was negligible, –0.002 cm.

3.2 Stand Volume at the Time of the First Commercial Thinning

The total volume at the time of the first commercial thinning was strongly dependent on the timing of FCT and stand density (Fig. 5). According to the model (Eq. 6), the volume of the growing stock in a stand with a density of 3000 trees ha^{-1} is 150 m^3ha^{-1} at the dominant height of 12 m. The increase of the dominant height by four meters (H_{dom} 16 m) results in a double stand volume (ca. 300 m^3ha^{-1}).

The means and standard deviations of the residuals of Model 6 were calculated for 50 m^3ha^{-1} volume classes of estimated removal (Fig. 6A), for 2 cm diameter classes (Fig. 6B) and for 2 m dominant height classes (Fig. 6C). There were no serious trends in the model residuals with respect to these variables. The mean bias of the Model 6 was 0.06 m^3ha^{-1} (Table 5).

3.3 Volume of the Thinning Removal

The volume of the merchantable thinning removal of FCT was strongly affected by the timing of FCT, depicted as the dominant height and stand mean diameter (Eq. 9, Table 5). The late FCT at

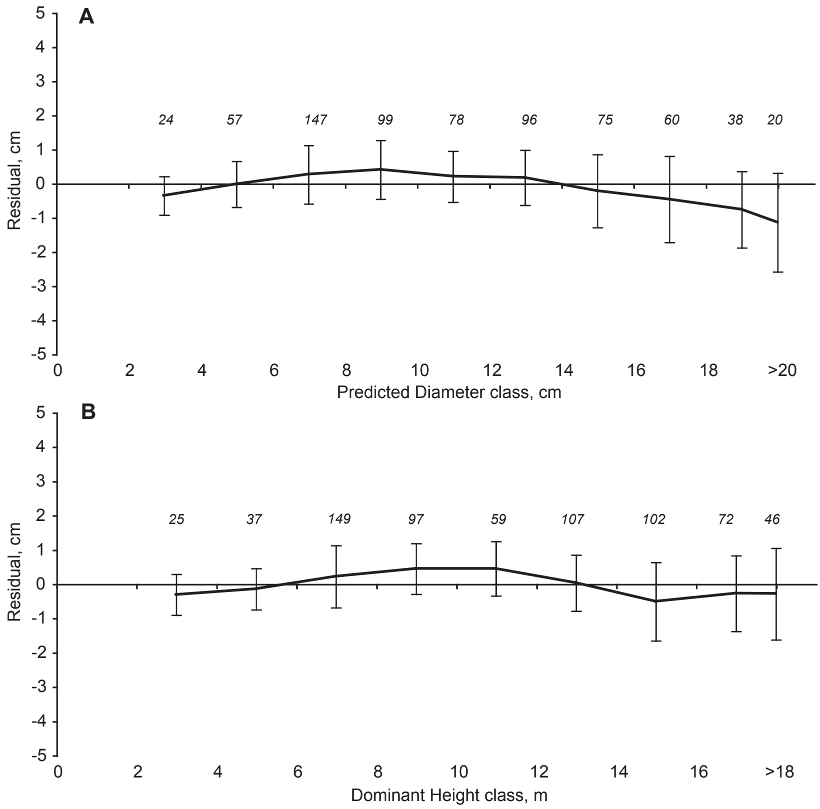

Fig. 4. Class-wise residual means and standard deviations of the residuals in the modelling data with respect to the estimated mean diameter at breast height in 2 cm diameter classes (A), and stand dominant height in 2 m height classes (B). Residuals are presented at an arithmetic scale. In transformation from a logarithmic to an arithmetic scale, bias correction was performed for the model (Eq. 4). Numbers above the line represent the number of observations per class.

a height of 16 meters resulted in a removal of 99 m^3ha^{-1}, whereas the removal in an early thinning (H_{dom} = 12 m) was 45% less (55 m^3ha^{-1}) (Fig. 7A, 7C).

Thinning intensity and thinning type also affected the removal (Table 5). For example, thinning to a density of 900 trees per hectare led to a 19 m^3ha^{-1} higher removal than FCT to a density of 1100 trees per hectare at a dominant height of 14 m. Thinning (H_{dom} = 14 m) from above increased the removal by 26 m^3ha^{-1} compared to thinning from below to a density of 1100 trees per hectare.

The timing of PCT affected the removal of FCT (Table 5). According to the model, the earlier the timing of PCT, the larger is the removal in FCT,

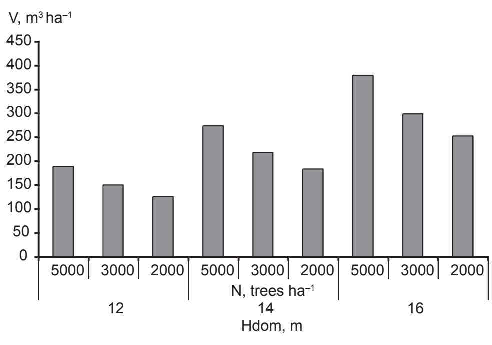

Fig. 5. Predicted total volume before the first commercial thinning in Scots pine stands (1200 d.d.) (Eq. 6) with varying dominant height and stand density. The stand diameter at the time of thinning was calculated using the diameter model (Eq. 4).

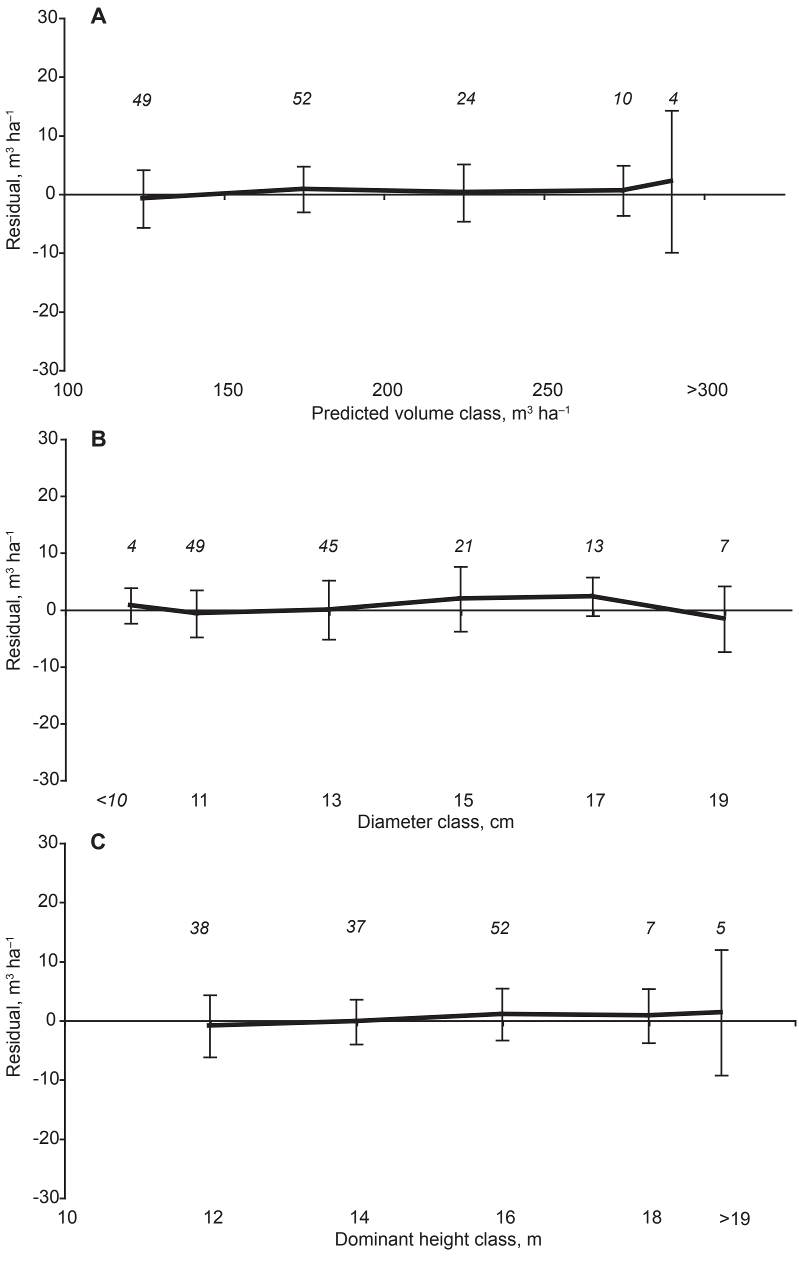

Fig. 6. Class-wise residual means and standard deviations of the residuals in the modelling data with respect to the estimated total volume in 50 m^3ha^{-1} volume classes (A), stand diameter in 2 cm classes (B), and dominant height in 2 m classes (C). Residuals are presented at an arithmetic scale. In transformation from a logarithmic to an arithmetic scale, bias correction was performed for the model (Eq. 7). Numbers above the line represents the number of observations per class.

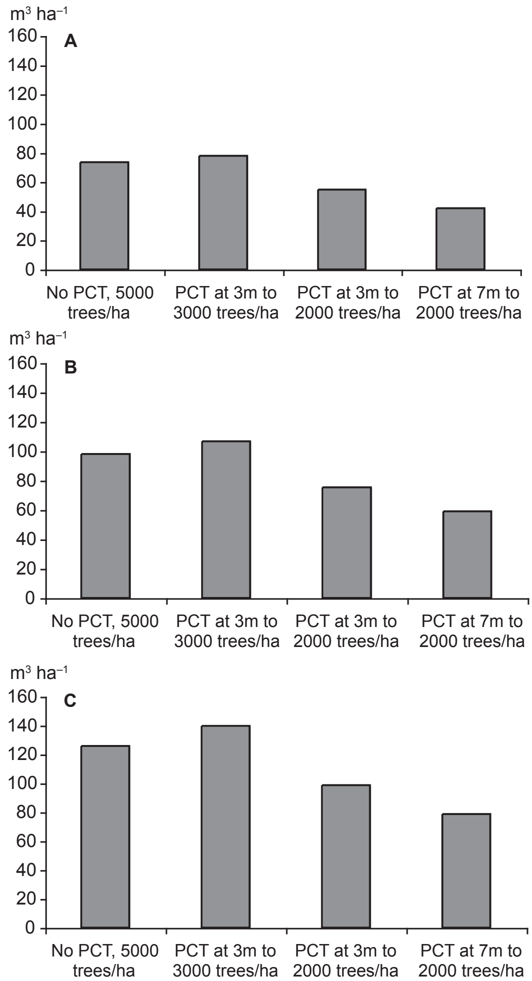

Fig. 7. Predicted volume of the first commercial thinning removal in seeded stand (Eq. 9) with varying timing of first commercial thinning, and with varying precommercial thinning (PCT) treatment. A) First commercial thinning (FCT) at 12-m dominant height, B) FCT at 14 m, and C) FCT at 16 m. The stand diameter at the time of thinning was calculated using the diameter model (Eq. 4). The temperature sum was 1200 d.d., and the stem number after the first commercial thinning was 1100 trees per hectare. The mean diameter of removed trees was similar to the mean diameter of the stand before thinning.

if the treatment intensities are kept constant. The difference in FCT removal between the stands with PCT at H_{dom} 3 m, instead of 7 m, was 28% (16 m^3ha^{-1}) (Fig. 7B).

A low PCT intensity increases the removal in FCT. The difference between PCT to a density of 3000 trees per hectare and to 2000 trees per hectare was 30% (32 m^3ha^{-1}) in FCT removal (Fig. 7B). The largest FCT removal can be achieved when PCT is performed at an early stage, but leaving the stand comparatively dense (Fig. 7A, 7B, 7C).

Artificial regeneration (seeding) increased the FCT removal by approximately 17% compared to the case with natural regeneration (Table 5). Improved growing conditions, in terms of a higher temperature sum, increased the FCT removal as well. For example, the difference in the FCT removal was 9% higher when the temperature sum increases from 1000 d.d. to 1200 d.d. at a density of 5000 trees per hectare.

The means and standard deviations of the residuals of Model 9 were calculated for 20 m^3ha^{-1} volume classes of estimated removal (Fig. 8A), for 1 cm diameter classes (Fig. 8B) and for 1 m dominant height classes (Fig. 8C). The mean bias of the Model 9 was 0.18 m^3ha^{-1}. The model had a slight tendency for overestimation with thinning removals over 110 m^3ha^{-1}.

4 Discussion

This study addresses the effects of young stand management on the diameter development, on the yield of total volume and merchantable wood removal at the first commercial thinning. The analysis was based on extensive permanent sample plot data collected from Scots pine stands. The study material covered a large variation in initial stand densities, as well as a wide range of timing and intensity of precommercial thinning. As a result of the analysis, a model was developed for depicting the overall pattern related to stand diameter increment, including the response to precommercial thinning. The models were also developed in order to assess the total volume of the growing stock at the time of the first commercial thinning, and the volume of merchantable

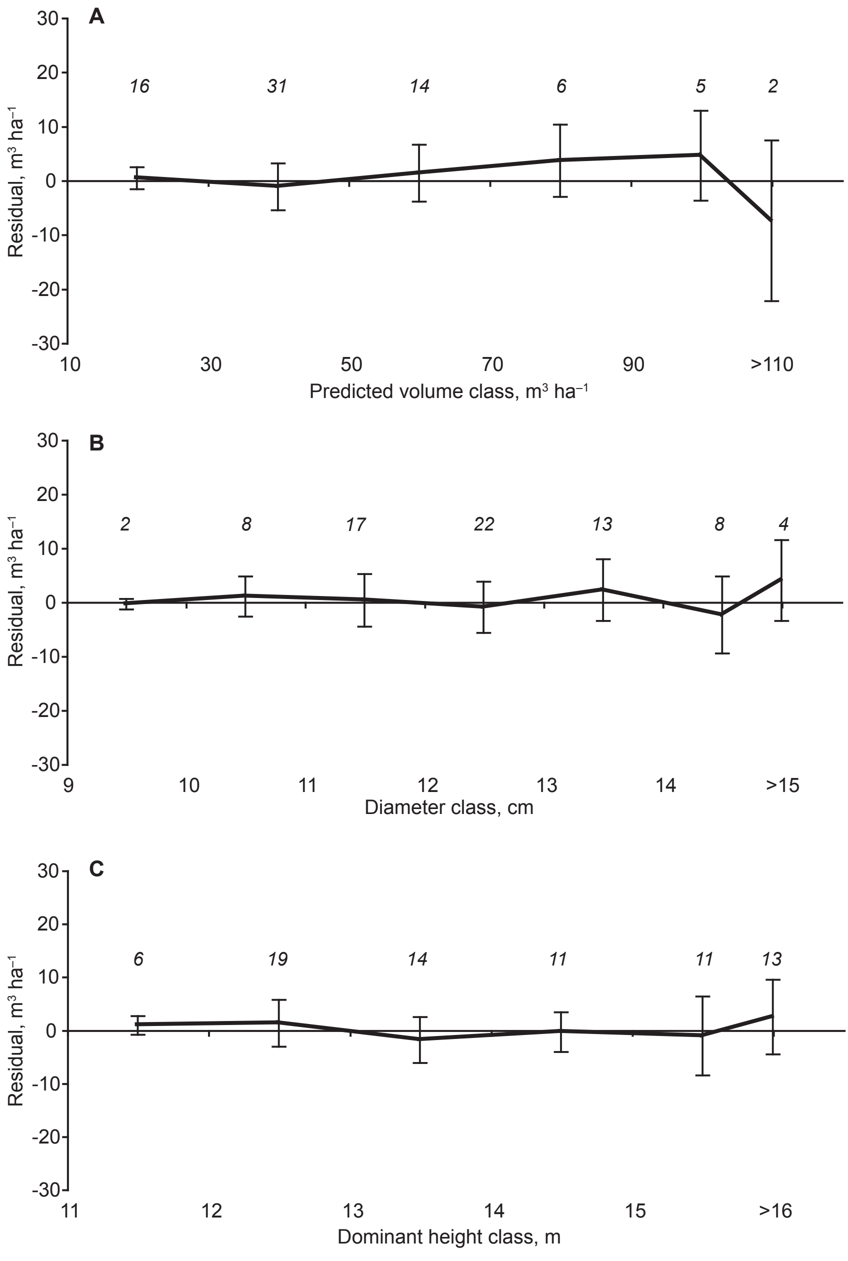

Fig. 8. Class-wise residual means and standard deviations of the residuals in the modelling data with respect to the estimated timber volume in 20 m^3ha^{-1} volume classes (A), stand diameter in 1 cm classes (B), and dominant height in 1 m classes (C). Residuals are presented at an arithmetic scale. In transformation from a logarithmic to an arithmetic scale, bias correction was performed for the model (Eq. 9). Numbers above the line represents the number of observations per class.

wood of the FCT removal.

There are some restrictions related to the study material, which should be kept in mind when interpreting the results. The study area covers Southern and Central Finland, and the results cannot be generalized to Northern Finland because of the obvious differences in tree growth and structure of the stands. The sites in the experiments were all classified as the *Vaccinium* forest stand type, which corresponds to a typical site for Scots pine. Furthermore, the experiments were located in pure or almost pure Scots pine stands and therefore the results can only be generalized to Scots pine stands, and not mixed stands. Due to the imbalanced modelling data with respect to PCT treatments in the stands with the dominant height less than 3 m, the applicability of the model for diameter development (Eq. 4) is restricted to stands in which precommercial thinning has been carried out later than at 3-meter dominant height.

The study addresses only the stem diameter growth response to PCT. However, it is known that management practices that increase stem growth also promote branch development (Kellomäki and Tuimala 1981, Kellomäki et al. 1992, Agestam et al. 1998). This, in turn, impairs stem quality from the point of view of high quality saw timber production. The development of stem quality is a relevant issue especially in the management of Scots pine. Thus, both quantity and quality aspects are taken into account in the practical recommendations for the management of Scots pine stands. The effects of PCT on wood quality have not been addressed in this study.

The results concerning the stand growth response to PCT are in line with earlier studies. The response of diameter growth is greatest in stands with an intensive and early PCT, as reported earlier by Varmola (1996), Ruha and Varmola (1997), Varmola et al. (1998), Varmola and Salminen 2004. Similar results on the growth response to precommercial thinning have also been reported in studies in Canada by Tong and Zhang (2005) for jack pine, by Johnstone (2005) for lodgepole pine, by Fleming et al. (2005) for black spruce, and by Pothier (2002) for balsam fir.

The regeneration method was found to affect the growth rate of young Scots pine stands. In seeded stands, the stand mean diameter at a given dominant height was greater than that in naturally regenerated stands. This result is in accordance with our recent study of young Scots pine stands in Finland (Huuskonen and Miina, manuscript). Varmola (1996) suggests that the above-mentioned difference in mean diameter can be explained by the more homogeneous stand structure of seeded stands compared to naturally regenerated stands. The regeneration method still had an effect on the timber yield at the first commercial thinning stage. Artificial regeneration (i.e. seeding) enhanced the timber yield by approximately 17% compared to natural regeneration. These results are in agreement with the findings of Varmola (1996), who compared the results of his study in cultivated stands with older studies in naturally regenerated stands (Vuokila 1972 and 1976).

The total volume at the time of first commercial thinning was affected by the timing and stand structure. The removal of commercial wood in first commercial thinning was found to be affected by its timing, intensity, and thinning type. Late timing of first commercial thinning strongly increased the thinning removal. Similar results have been reported by Hynynen and Saramäki (1995), Hynynen and Arola (1999) and Huuskonen and Ahtikoski (2005), who also emphasized that, from the silvicultural point of view; delayed FCT is possible only in managed stands where precommercial thinnings have been carried out.

Early timing and low intensity of precommercial thinning resulted in high FCT removals. Varmola (1982) noted that early thinning to 1000 stems per hectare before a dominant height of 4 m resulted in the same volume as thinning to 2000 trees per hectare at a dominant height of 6–7 m. Salminen and Varmola (1990) also reported that a higher growing stock resulted in a higher total volume. In recent studies in Canada, precommercial thinning was reported to have positively affected merchantable stem volume production (Tong and Zhang 2005, and Johnstone 2005). In contrast, Fleming et al. (2005) found that cleaning improved black spruce growth, but precommercial thinning resulted in only a slight increase in mean tree size but a larger reduction in merchantable stand volume. Pothier (2002) also found that precommercial thinning did not increase the merchantable wood volume at maturity but, on the other hand, he found that thinning improved the yield composed of large diameter trees (≥15.1 cm), while obviously the effect of the treatments on wood volume depends on the minimum usable diameter in question.

In this study, a modelling approach was applied to describe the overall pattern in the stand response to precommercial thinning. The model for diameter development enables assessment of the effects of the timing and intensity of precommercial thinning in young stands. Models 4, 6 and 9 include driving variables that are easily measurable and commonly known characteristics of young stands. Thus, the information required in using these models is commonly available in practical forest management databases.

The models for the volume of the growing stock and thinning removal at FCT (Eq 6 and 9) are designed to be used as a tools for comparing the effects of different young stand management practices (e.g. timing and intensity of precommercial thinning) on the merchantable wood removal of FCT. The model for removal is the most reliable in stands with an initial stand density of more than 1400 trees per hectare, a density after first commercial thinning that is in line with current management practices (600–1400 trees per hectare), and the timing of first commercial thinning at the latest at a dominant height of 19 m.

In conclusion, there are considerable possibilities to affect the development of young Scots pine stands through management practices. This study provides new tools for assessing the management responses of diameter development, total volume and volume of FCT thinning removal.

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