Thinning Response and Growth Trends of Seeded Scots Pine Stands at the Arctic Timberline

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Varmola, M., Salminen, H. & Timonen, M. 2004. Thinning response and growth trends of seeded Scots pine stands at the arctic timberline. Silva Fennica 38(1): 71–83.

Growth patterns and reactions of Scots pine (*Pinus sylvestris* L.) to thinning in extremely harsh climatic conditions were studied in two seeded Scots pine stands located on the arctic timberline. Coniferous trees usually do not form closed stands at the timberline, but occur only in scattered tree groups. The trial was established in two stands in 1985–1986 when the trees were at an age of 47 and 56 years and an average dominant height of 6.0–6.9 m. The trial was remeasured in 1998. The thinning treatments reduced the stem number for five different levels; final density of 300, 550, 800, 1050, and 1300 stems ha^{-1} and unthinned. The experiment had a randomised block design with four replications in each stand.

The increased growing space provided by thinning accelerated diameter growth after a delay of 2–3 years. The differences between the radial growth of the thinning treatments were very clear during the whole 13- to 14-year observation period. Annual increment of the mean diameter was regularly the higher, the larger the spacing. Dominant diameter was less influenced by treatments. There were no significant differences in dominant height between any of the treatments. Both basal area and volume were regularly the greater the higher the stem number was. Even a relatively light thinning had a distinct positive effect on tree growth, i.e. not carrying out thinning resulted in a production loss of merchantable wood.

According to the results, seeded stands on the arctic timberline can grow surprisingly well in favourable conditions and reach a dominant height of 12–14 m in 100 years and a mean annual increment of 1.0–1.5 m^3 ha^{-1} y^{-1} over a rotation period of 130–160 years. Based on increment figures and thinning reactions, a spacing of ca. 1000 stems ha^{-1} can be recommended.

Keywords growth and yield, northern timberline, *Pinus sylvestris*, thinning
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Received 25 June 2003 **Revised** 24 October 2003 **Accepted** 3 December 2003

1 Introduction

Scots pine (*Pinus sylvestris* L.) forms the arctic coniferous timberline in Fennoscandia (Oksanen and Virtanen 1995). This is in complete contradiction to other parts of the circumpolar north, where the northernmost coniferous forests are composed of *Picea, Abies* and *Larix* species (Hustich 1966, Veijola 1998a). The northernmost pine stands in Finland are located at latitude 69°45', but scattered pines can be found up to latitude 70° (Hustich 1966). In northern Norway, pine forests are found even further to the north along the coast of the Arctic Ocean (Oksanen and Virtanen 1995).

In order to prevent a possible decline of the timberline, as well as to colonize new areas with forests, artificial regeneration experiments were established close to and even to the north of the Scots pine timberline already in the 1910's in Finnish Lapland. According to Pohtila and Timonen (1980), over 23 000 ha were reforested and afforested in the protection forest area between 1910 and 1977. Artificial regeneration has not been used anywhere else at corresponding conditions at high latitudes in Fennoscandia or in the circumpolar north. Lodgepole pine (*Pinus contorta* Doughl. var. *latifolia* Engelm.) has been widely planted in Sweden (569 000 ha altogether) (FAO 2001), and this has even included climatically harsh environments at high altitudes in central and northern Sweden. Lodgepole pine usually survives better and grows faster than Scots pine (Ericsson 1993, Fries 1993), but there have been serious problems with fungal diseases (Karlman 1986). Norway spruce (*Picea abies* Karst.) has been successfully planted along the coastal areas of Norway far to the north of its natural occurrence range (up to 69° latitude) (Bergan 1985). The climatic conditions are, however, totally different from those in northern Finland because of the warming effect of the Gulf Stream and the more humid climate, which corresponds approximately to the middle-boreal zone (Oksanen and Virtanen 1995).

The thinning reactions and growth patterns of artificially regenerated Scots pine in harsh climatic conditions close to the timberline have not been studied earlier. Pohtila and Timonen (1980) presented mean curves for the volume development of pine plantations in the protection forest area in Finnish Lapland. Ruha and Varmola (1997) studied the precommercial thinning reaction in naturally regenerated pine stands growing in the north and middle-boreal forest zone. They found that the diameter growth of pine reacted very slowly to thinning, not earlier than ten years after thinning.

The aim of this study was to determine the growth patterns and reactions of Scots pine to thinning in extremely harsh conditions where coniferous trees usually do not form closed stands, but occur only in scattered tree groups. The especially successful seeded stands established in the 1920's and 1930's on and beyond the arctic timberline provided an ideal opportunity to study these processes.

2 Material and Methods

Two experimental stands were chosen for this study from among the best-developed stands in connection with the inventory of artificially regenerated, seeded and planted Scots pine in the protection forest area (Pohtila and Timonen 1980). Stand 1 (lat. 69°33'39'', long. 29°10'56'', 90 m a.s.l.) is located in the Pakanajoki area, Inari (Fig. 1), where artificial regeneration was carried out on an area of 400 ha in 1921–29 and 1937–39 (Veijola 1998b) on a formerly mountain birch (*Betula pubescens* sp. *screpanowii* Hämet-Ahti) site. An area of 18 ha was first prescribed burned. Broadcast seeding was carried out on the snow cover in spring 1929. The seed originated from latitudes 67°–67 30' (Kemijärvi-Kolari), i.e. ca. 300 km southwards. In 1952 the area was cleaned lightly and all the birches were removed. At that time snow blight (*Phacidium infestans* Karst.) had infected the lower branches of about 90 per cent of the seedlings and also killed some of the small seedlings. Both snow and reindeer had broken seedlings in the area. The sapling stand was estimated as moderately good, with some gaps and a relatively low density. According to the relevant documents, the area was cleaned again in 1957.

Stand 2 (lat. 69°31'33'', long. 27°13'00'', 190 m a.s.l.) is located on the eastern slope of the Utsjoki river valley (Fig. 1). Site preparations

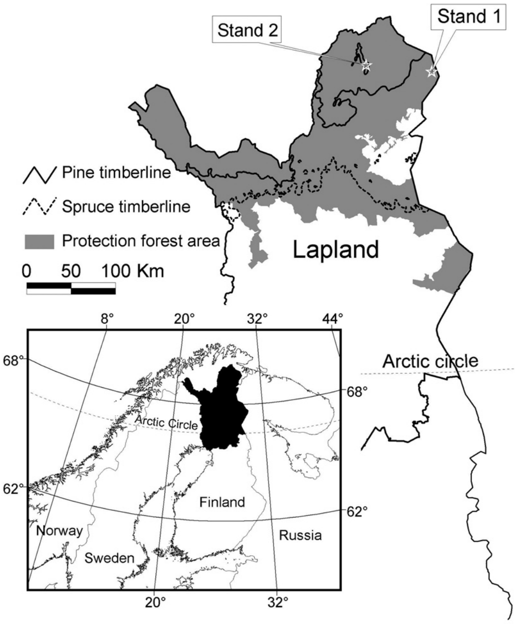

Fig. 1. Location of the two stands, protection forest area and the Scots pine and Norway spruce timberline.

and artificial regenerations were made on 175 ha in the Mierasrova area in 1939–49, 1954–55 and in 1960 (Veijola 1998b). A 27.5 ha compartment was first prescribed burned and then seeded in 1939–40. The area in question was band-seeded in 1939. No information is available about the seed origin or earlier stands, but some older trees are still present in the area. The area was most probably cleaned in 1955.

The bedrock in the area of Stand 1 consists of gneisses of the granulite complex. Stand 2 is located between a gneiss complex and granulite occurence where the bedrock is younger and consists of para- and orthogneisses. The surficial deposits in the two areas are different. The overburden in the area of Stand 1 is sand and gravel and has been formed after the last ice age as a result of ice river sedimentation. Ground moraines are dominant on the area of Stand 2 (Geological Survey of Finland, pers. comm. by J. Nenonen). The forest site type of both stands was classified as ErClT (*Ericacea-Cladinae*-type), representing dry forest land. The organic layer was only 1 cm thick in Stand 1 and 1–3 cm thick in Stand 2.

The topography was even in Stand 1, but there was a 6–10° gradient towards the west in Stand 2. According to the model of Ojansuu and Henttonen (1983), the effective temperature sum (threshold value of the daily mean temperature +5°C, standard years 1961–90) was 667 d.d. for Stand 1 and 618 d.d. for Stand 2.

The trial was established in spring 1985 (Stand 1) and in spring 1986 (Stand 2), i.e. at the age of 56 and 47 years, respectively. 40 * 40 m square plots were used as experimental units. Four blocks of six plots were laid out in as homogeneous a fashion as possible; in Stand 1 along the bank of the River Uutuanjoki and in Stand 2 according to the contour lines of the slope.

The treatments were randomised within the blocks. The thinning treatments were designed to represent all the relevant management alternatives under such extreme conditions: final density of 300, 550, 800, 1050, 1300 stems ha^{-1} and unthinned (S300, S550, S800, S1050, S1300, Unthinned).

A circular subplot located in the middle of each plot was used for tree measurements; the radius of the subplot in Stand 1 was 15.00 m and in Stand 2 11.28 m. All the trees were tallied and at least 20 sample trees were measured. Trees were tallied for the direction and distance from the centre of the plot, breast height diameter, condition and damage. Tree height, living crown limit, bark thickness at breast height as well as the height increment during the three previous five-year periods were determined on the sample trees. The radial increments during the past 15 years were measured in the tree-ring laboratory on cores taken at breast height.

The stands were remeasured in autumn 1998. The trees were tallied for breast height diameter and the sample trees measured for height and living crown limit. Five-year height increments starting at the time of thinning were measured and increment cores were taken down to the pith of the sample trees.

The experimental stands were very homogeneous with respect to dominant height and mean diameter at the time of establishment of the trial (Table 1). In Stand 1 the average dominant height was 6.93 m, with a range of 0.43 m. Stand 2 was as uniform, the respective values being 6.03 m and 0.41 m. There were slightly more variation in

Table 1. Stand variables by treatment before and after the establishment of the trial.

Before thinning	S300	S550	S800	S1050	S1300	Unthinned	Mean
Stand 1							
Stem number ha^{-1}	1707	1813	1441	1608	1916	1530	1669
Basal area, m^2 ha^{-1}	9.8	10.9	9.2	10.1	10.8	10.0	10.1
Volume, m^3 ha^{-1}	35.4	40.1	33.7	36.9	38.4	36.6	36.8
Basal area median diameter, cm	9.9	9.9	10.1	10.0	9.3	10.2	9.9
Height corresponding to basal area median diameter, m	6.10	6.21	6.24	6.18	5.97	6.18	6.15
Dominant height, m	6.94	7.03	6.85	7.12	6.69	6.95	6.93
Living crown limit, m	1.90	1.97	2.01	2.10	2.27	1.93	2.03
Stand 2							
Stem number ha^{-1}	1863	1969	1750	2006	2388	1856	1972
Basal area, m^2 ha^{-1}	12.8	13.8	10.3	13.0	16.5	13.0	13.2
Volume, m^3 ha^{-1}	43.5	47.8	34.2	43.8	57.1	44.8	45.2
Basal area median diameter, cm	10.6	10.5	9.8	10.1	10.5	10.7	10.4
Height corresponding to basal area median diameter, m	5.71	5.69	5.40	5.55	5.78	5.73	5.64
Dominant height, m	5.76	6.06	5.92	6.17	6.13	6.12	6.03
Living crown limit, m	1.63	1.78	1.59	1.70	1.80	1.67	1.69

After thinning	S300	S550	S800	S1050	S1300
Stand 1					
Stem number ha^{-1}	283	510	803	1048	1296
Basal area, m^2 ha^{-1}	2.8	4.8	6.2	7.5	8.4
Volume, m^3 ha^{-1}	11.1	18.7	23.0	27.9	30.4
Basal area median diameter, cm	11.8	11.3	10.7	10.4	9.8
Dominant height, m	7.03	7.27	7.10	6.99	6.89
Stand 2					
Stem number ha^{-1}	300	550	794	1044	1306
Basal area, m^2 ha^{-1}	3.1	4.9	5.3	7.6	10.2
Volume, m^3 ha^{-1}	10.9	17.6	18.1	26.1	35.5
Basal area median diameter, cm	11.8	11.4	10.1	10.1	10.7
Dominant height, m	6.33	6.61	6.07	6.34	6.58

the stem number and basal area between the plots before the treatments: the plots that were thinned to 800 stems ha^{-1} were slightly less dense, and those thinned to 1300 stems ha^{-1} were slightly denser.

The mean characteristics of the two stands differed slightly from each other. The dominant height was 0.80 m higher in Stand 1, but the average volume was almost 10 m^3 ha^{-1} higher in Stand 2. This was due to the larger average stem number (300 stems ha^{-1}) and slightly thicker trees in Stand 2 (Table 1). After the thinning treatments, the mean diameter and dominant height were somewhat higher in both stands, indicating that selection of remaining trees favoured larger trees.

A mixed-model ANOVA was used to determine the effect of thinning intensity on the plot characteristics. The experimental design was assumed to be randomised factorial. The dependent variables were transformed prior to ANOVA in order to homogenize the variance and normalize the distribution. Levene's test for homogeneity and Kolmogorov's statistic D compared to the normal distribution were used as criteria (SAS Institute Inc. 1994). In most cases, a logarithm transformation was applied after scaling the original variable.

After performing the necessary transformations, the dependent variables were subjected to analysis of variance using PROC MIXED in SAS version 8.2 (Littell et al. 1996). Thinning intensity

Table 2. The number of sample trees (n) and minimum, mean and maximum values of breast height diameter (DBH) under bark after thinning by treatment, used for the thinning reaction and tree-ring indices analyses. Values are calculated from radial increment bores.

Treatment	n	DBH, min.	DBH, mean	DBH, max.
Stand 1				
S300	70	6.1	10.0	15.1
S550	84	3.6	9.8	14.1
S800	88	2.4	9.3	17.1
S1050	95	3.7	9.4	14.9
S1300	95	3.9	8.9	14.7
Unthinned	119	2.8	8.9	16.8
Stand 2				
S300	79	6.4	10.5	13.8
S550	82	5.9	9.9	15.6
S800	80	4.0	8.7	15.3
S1050	79	3.3	9.2	15.2
S1300	80	4.7	9.5	15.5
Unthinned	80	4.0	9.4	17.4

was introduced as the fixed classification variable. Block factor (within stand) was introduced in ANOVA as a random intercept. The variances of the components were estimated using restricted maximum likelihood (REML). The degrees of freedom were approximated using the approach described by Kenward and Roger (1997).

The covariance structure of the block-within-stand effect was assumed to follow compound symmetry. Multiple pair-wise comparisons were made between thinning intensity classes. The significance levels for these comparisons were adjusted using the Bonferroni-adjusted t-test for multiple comparisons (Sokal and Rohlf 1981).

The following dependent variables representing the mean plot-wise values in the last measurement were analysed one at a time: dominant and median height, basal area, total volume, mean and dominant breast height diameter, living crown limit, and the mean size of pulp wood stems.

The temporal dynamics of the thinning response and growth trends were analysed by using single tree material. On the average, 80 sample trees by treatment and by experimental stand were bored at breast height down to the pith in 1998. The sample trees tended to be bigger the sparser was the spacing. However, the differences can be considered to be small (Table 2). The annual ring width data were used for the analysis of both growth variation and the thinning reaction.

The tree-ring indices were calculated from individual ring-width measurement series. The age-related growth trend was removed by dividing the ring widths by the values of negative exponential functions or descending straight lines (Fritts 1976, Cook et al. 1990). The resulting dimensionless indices were averaged to form master chronologies for the stands. ARSTAN analysis (Cook 1985, Holmes et al. 1986, Cook and Holmes 1996) was used to produce the final corrected chronologies containing a maximum of low-frequency variability (Cook 1985, Holmes et al. 1986). The dependence between prewhitened tree ring chronologies and annual temperature sums was studied with cross-correlation analysis using PROC ARIMA in SAS version 8.2 (SAS Institute Inc. 2000, 2001).

Thinning response dynamics was analysed by fitting a multilevel ANOVA to the single tree material (Table 2). Data from sequential years were analysed separately with a univariate ANOVA at each time point. The basic questions were: 1) were the plots homogeneous before the thinning treatment, and 2) what was the time lag between thinning and the statistically significant diameter growth response to thinning. For comparison, the same approach was also applied annually to the 12-year period prior to thinning. The independent variable was the width of a tree ring. In addition to block-within-stands, also plot-within-stand was introduced as a random intercept. Otherwise, ANOVA was carried out following the principles of plot-wise analysis.

3 Results

3.1 Mortality

Mortality was insignificant in all the treatments. The largest changes in stem number were caused by local reindeer herders who cut pole stems for fencing material on two of the sample plots in Stand 1. These plots, with thinning treatments of 300 and 550 stems ha^{-1}, had to be omitted from the analyses.

Table 3. Stand variables at the time of remeasurement in 1998 by treatment. Combined material. In the Bonferroni adjusted t-test for multiple comparisons, the treatments indicated by different letters differ from each other at the 5% significance level.

	S300	S550	S800	S1050	S1300	Unthinned	Mean
Stem number ha^{-1}	292	523	789	1041	1287	1562	
Dominant height, m	8.71^{a}	8.94^{a}	8.60^{a}	8.62^{a}	8.73^{a}	8.26^{a}	8.64
Height corresponding to basal area median diameter, m	8.57^{a}	8.53^{ab}	7.88^{c}	7.93^{bc}	7.93^{bc}	7.73^{c}	8.09
Basal area, m^2 ha^{-1}	5.7^{a}	8.7^{b}	10.1^{b}	12.7^{c}	14.6^{c}	16.1^{d}	11.3
Volume, m^3 ha^{-1}	25.7^{a}	39.7^{b}	43.7^{b}	55.3^{c}	63.9^{c}	68.9^{d}	49.5
Dominant diameter, cm	17.8^{a}	17.8^{a}	17.1^{a}	17.0^{a}	16.6^{a}	16.7^{a}	17.2
Basal area median diameter, cm	16.1^{a}	15.1^{a}	13.6^{b}	13.3^{bc}	12.7^{bc}	12.5^{c}	13.9
Mean size of pulp wood stems, dm^3	86.5^{a}	73.1^{a}	52.7^{b}	51.4^{b}	48.1^{b}	44.4^{b}	59.4
Living crown limit, m	2.43^{a}	2.61^{a}	2.56^{a}	2.76^{ab}	3.12^{b}	3.07^{b}	2.76

There were no dead trees on 22 of the 46 plots. The average mortality on all of the thinned plots was only 5–24 stems ha^{-1} in 13–14 years, thus indicating only occasional tree deaths. On the other hand, the number of trees on the unthinned plots decreased on the average by 131 stems ha^{-1} between the measurements. It is obvious that weak and dying trees were removed in all the thinning treatments. In treatment S550, which had a relatively high mortality, the average size of the dead trees was almost twice the size of dead trees on the unthinned plots. The volume of natural drain varied from 0.15 to 1.0 m^3 ha^{-1}, and was only 0.3–2.5 per cent of the total volume.

3.2 Stand Height

The stands were thinned when the dominant height was 6.9 m (Stand 1) or 6.0 m (Stand 2). The corresponding figures 13–14 years later in 1998 were 8.8 and 8.5 m. Stand 2 thus had somewhat better height development (current annual increment (c.a.i.) 0.15 m yr^{-1}) than Stand 1 (c.a.i. 0.12 m yr^{-1}).

There were no significant differences in dominant height between any of the treatments (Table 3). However, the dominant height and the annual increment of dominant height on the unthinned plots were among the lowest in both stands, which might be evidence of a suppressing effect of overdensity on the height increment.

The height corresponding to the basal area mean diameter was, on the average, the higher, the lower the stem number (Table 3). Spacings S300 and S550 resulted in 0.5 m higher mean heights, on the average, but this was mainly due to the low stem number, not to increased height increment.

3.3 Stand Basal Area and Volume

Basal area and volume showed very similar growth patterns. When comparing different thinning treatments, only two pairs (S550 and S800, S1100 and S1300) did not differ significantly from each other (Table 3).

The annual increment of both basal area and volume were also the higher, the higher the stem number. However, the differences between S1050, S1300 and unthinned were smaller than between the less dense spacings. In Stand 1 the current annual volume increment (c.a.i) varied from 0.7 to 1.7 m^3 ha^{-1}, and in Stand 2 from 1.2 to 2.8 m^3 ha^{-1}.

3.4 Stand Diameter

Dominant diameter was, in the same way as for dominant height, on the same level in all the treatments (Table 3). A slight increase in dominant diameter as a result of increased growing space was, however, seen, and the difference between the extreme treatments was 1.1 cm. The annul increment of dominant diameter varied in Stand 1 from 1.7 to 2.6 mm and in Stand 2 from 2.3 to 3.7

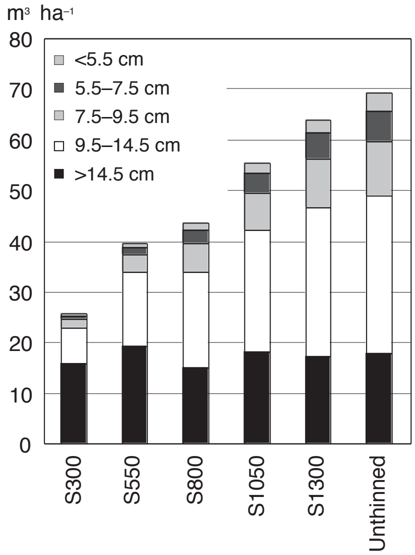

Fig. 2. Distribution of standing volumes in different dimensions by treatment at the time of remeasurement in 1998. Dimension limits are top diameters over bark.

mm; the lower value represented unthinned plots and the higher value the S300 treatment.

The basal area median diameter was the higher, the lower the stem number (Table 3). Treatments S300 and S550 differed significantly from the others, while the mean diameters between the other adjacent treatments were on the same level. The annual increment of the mean diameter was systematically the higher, the lower the spacing.

3.5 Timber Assortments and Total Yield

Both stands were at the pole stage at the time of the remeasurement, and did not contain any saw timber sized trees. In fact, saw timber production is not relevant in the timberline area but other products such as wood for reindeer fences or household use might be more important.

As was the case for total volumes, the commercial sized volumes (top diameter > 5.5 cm) were also the higher, the higher the density (Fig. 2). Only the amount of large sized timber (>14.5 cm) was at the same level irrespective of the treatment. The amount of waste wood was negligible, 0.4–3.6 m^3 ha^{-1} or 1.7–5.1 per cent.

The proportion of pulp wood stems was 98–99 per cent on all the thinned plots, and 93 per cent on the unthinned plots. There was a clear difference in the mean size of pulp stems between the lowest density treatments (S300 and S550) and all the other treatments (Table 3).

The highest total yield was reached in the S1300 treatment (Table 4). Removals at the time of the thinning varied from 13 to 29 m^3 ha^{-1}, which corresponds to a considerable drain of small sized timber in these conditions during a period of 50 years. Because mortality was negligible, the total yield in 1998 was mainly the sum of removals and standing volumes.

The highest volumes after thinning occurred on the unthinned plots (Table 1). 13–14 years later the total yield on the unthinned plots was at the same level as in the S550 and S1050 treatments (Table 4). It is obvious that even relatively light thinning had a very positive effect on tree growth, i.e. leaving stands unthinned results in a loss in total yield and especially in merchantable wood.

3.6 Green Crowns

At the time of remeasurement the living crown limits were at a height of 2.4–3.1 m (Table 3). The average crown ratio was 64 per cent in Stand 1 and 67 per cent in Stand 2. Living crowns were the longer, the sparser the density (Table 3). When expressed as crown ratios, that corresponds to a range of 59–69 per cent in Stand 1 and 61–74 per cent in Stand 2.

3.7 Growth Trends

The average radial growth indices varied from a minimum of 55 in Stand 1 to a maximum of 149 in stand 2 (Fig. 3). The variation in radial growth was very similar in both stands, except in the beginning of the 1960's when Stand 1 had a considerably better growth period. After the thinnings the radial growth variation seemed to diminish. The correlation between tree ring chronology and temperature sum was positive but statistically insignificant in both stands (r = 0.2, lag 0).

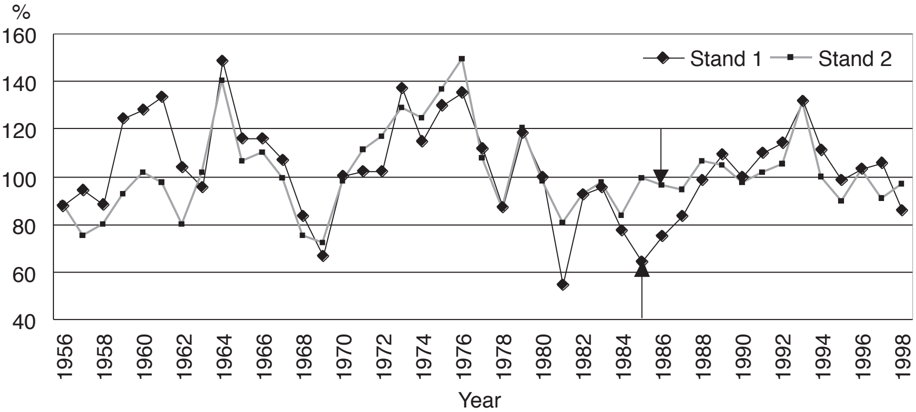

Fig. 3. Radial growth indices of the stands from 1956 to 1998. The thinning times are indicated with arrows.

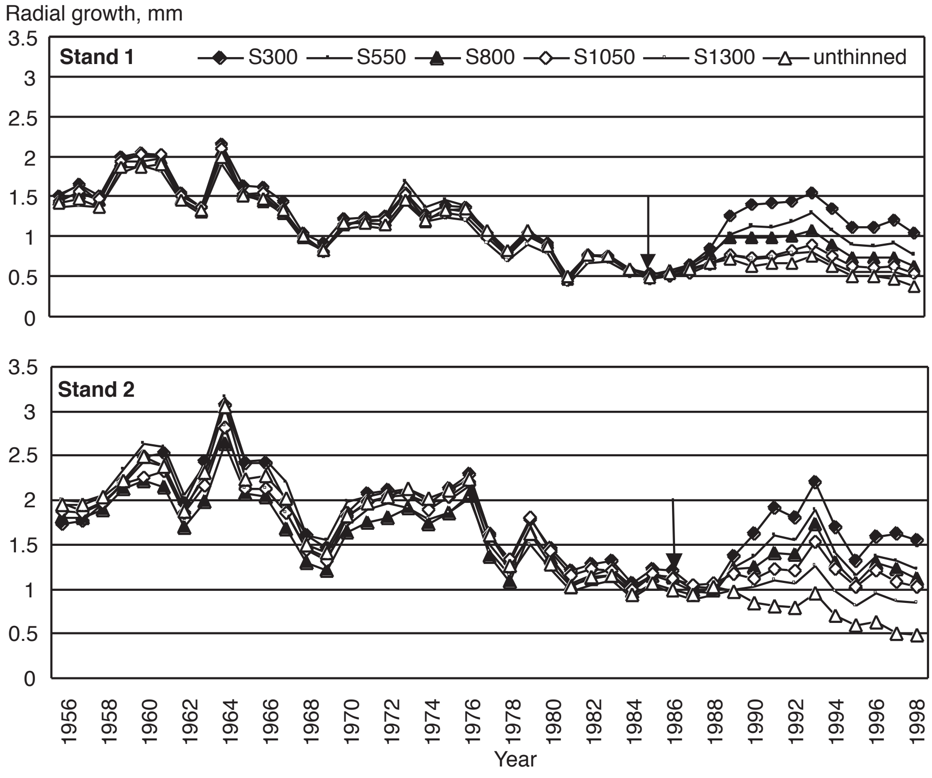

Fig. 4. Radial growth by thinning treatments in Stand 1 and Stand 2 from 1956 to 1998. The thinning times are indicated with arrows.

Table 4. Total yield in 1998 by treatment. Removal calculated from thinnings in 1985–1986, mortality as dead trees in 1998, and standing volume as living trees in 1998.

Treatment	S300	S550	S800	S1050	S1300	Unthinned
			$m^3\ ha^{-1}$			
Removal 1985–86	28.5	25.8	13.4	13.4	14.8	
Mortality	0.6	1.0	0.4	0.1	0.5	1.0
Standing volume	25.7	39.7	43.7	55.3	63.9	68.9
Total yield	54.9	66.5	57.5	68.9	79.2	69.8

Table 5. Annual radial growth (mm) from 1988 to 1998 by treatment. In the Bonferroni adjusted t-test for multiple comparisons, the treatments indicated by different letters differ from each other at the 5% significance level.

Year	S300	S550	S800	S1050	S1300	Unthinned
1988	0.93^{a}	0.86^{a}	0.90^{a}	0.85^{a}	0.80^{a}	0.85^{a}
1989	1.32^{a}	1.14^{ab}	1.11^{abc}	0.98^{bcd}	0.88^{d}	0.84^{d}
1990	1.52^{a}	1.25^{b}	1.12^{bc}	0.92^{cd}	0.87^{d}	0.73^{e}
1991	1.67^{a}	1.36^{b}	1.20^{bc}	0.99^{cd}	0.92^{d}	0.74^{e}
1992	1.62^{a}	1.37^{b}	1.20^{b}	1.02^{c}	0.93^{c}	0.73^{d}
1993	1.87^{a}	1.60^{ab}	1.41^{bc}	1.21^{cd}	1.04^{de}	0.85^{e}
1994	1.52^{a}	1.25^{ab}	1.09^{b}	0.99^{bc}	0.82^{cd}	0.66^{e}
1995	1.22^{a}	1.03^{ab}	0.90^{b}	0.83^{bc}	0.69^{c}	0.55^{d}
1996	1.35^{a}	1.13^{ab}	1.02^{b}	0.91^{bc}	0.76^{c}	0.57^{d}
1997	1.41^{a}	1.12^{b}	0.98^{bc}	0.86^{cd}	0.72^{d}	0.49^{e}
1998	1.30^{a}	1.00^{b}	0.88^{bc}	0.78^{cd}	0.67^{d}	0.44^{e}

Trees in the different treatments in both stands had very similar growth trends from the very beginning, i.e. after reaching breast height (Fig. 4), but the annual radial growth in Stand 2 was, on the average, 0.5 mm greater than in Stand 1. After thinning it took 2–3 years for the trees to react to the increased growing space as accelerated diameter growth.

Up until 1988 there were no significant differences in the annual radial growth of the sample trees between any of the treatments (Table 5). 1989 was the first year when the radial growth differed between the treatments. During 1990–92 and 1997–98 the S300 treatment had significantly higher radial growth than any of the other treatments. On the other hand, the unthinned treatment showed significantly lower radial growth than all of the other treatments between 1990–98, except in 1993. In the pair-wise comparison the adjacent treatments (S550, S800, S1050 and S1300) had similar radial growth (Table 5). The differentiation of radial growths between the treatments was, however, very clear and growth remained at different levels throughout the study period (Fig. 4) even though the absolute radial growth values were very low, ranging from 0.4 to 2.0 mm yr^{-1} only.

4 Discussion

Very few results are available about the production of pine stands in the extreme north. Ilvessalo (1970) presented yield tables for naturally regenerated pine stands between latitudes 68° and 69°30'in northern Lapland, based on over 100 permanent sample plots. Gustavsen published volume increment functions (Gustavsen 1977), as well as site index curves (Gustavsen 1980) for naturally regenerated Scots pines based on the material from the 3rd national forest inventory covering the whole country up to latitude 70°, but Vuokila and Väliaho (1980) did not find any sample plots north of latitude 68° in their material on which to calculate yield models for planted and seeded Scots pine stands.

Stand 1 followed rather closely the development of the ErClT (*Eriophorum-Cladonia*) site type (Ilvessalo 1970) and, compared to the site index curves of Gustavsen (1980), will reach a dominant height of ca. 11–12 m at the age of 100 years (Fig 5). Stand 2 had a faster height development and will most probably reach a dominant height of 13–14 m at the same age. According to Vuokila and Väliaho (1980), ErClT corresponded to the site index class H_{100} = 12, which is also the limit of productive forest land (m.a.i. over 1.0 m^3 ha^{-1} yr^{-1}) and scrub land (m.a.i. between 0.1 and 1.0 m^3 ha^{-1} yr^{-1}) (Roiko-Jokela 1980).

The length of rotation of Scots pine stands growing on dry forest land, as ErClT, in northern Lapland is long, at least 130–160 years, and Ilvessalo (1970) describes the development of natural stands up to 300 years. Based on the function of Vuokila and Väliaho (1980) for seeded Scots pine stands, the m.a.i. over the rotation period is 1.0 m^3 ha^{-1} y^{-1} for H_{100} = 12, 1.2 m^3 ha^{-1} $y^{-1}$for H_{100} = 13 and 1.5 m^3 ha^{-1} $y^{-1}$for H_{100} = 14. According to Ilvessalo (1970), naturally regenerated, unmanaged stands on ErClT produce on the average 135 m^3 ha^{-1} in 100 years, of which 36 m^3 ha^{-1} is natural removal and the maximum m.a.i of 1.2 m^3 ha^{-1} y^{-1} is reached at the age of 180 years.

The current annual volume increment in both stands exceeded the maximum c.a.i. value of ErClT, 1.6 m^3 ha^{-1} y^{-1} (Ilvessalo 1970) and in Stand 2 on unthinned plots c.a.i actually corresponded to the sub-dry *Eriophorum-Myrtillus*-site type (EMT). EMT has a maximum c.a.i. of 2.6 m^3 ha^{-1} y^{-1} at the age of 60 years and a maximum m.a.i. of 1.8 m^3 ha^{-1} y^{-1} at the rotation period of 120 years. These figures show that seeded stands on the arctic timberline can, in favourable conditions, grow surprisingly well. Based on these increment figures, the actual development of both stands and the thinning reactions, it can be estimated that a spacing of ca. 1000 stems ha^{-1} would be the most proper alternative in this phase of stand development.

The two experimental stands represented the best-developed stands in the timberline region. According to Pohtila and Timonen (1980), there were 910–1040 stems ha^{-1} growing in corresponding conditions, whilst in the two stands in question the stem number was as high as 1670–1970 stems ha^{-1} even after one or two cleanings. Both height and stand volume development were much higher than that in the seeded or planted stands, where a volume of 10 m^3 ha^{-1} was reached in 60 years (Pohtila and Timonen 1980).

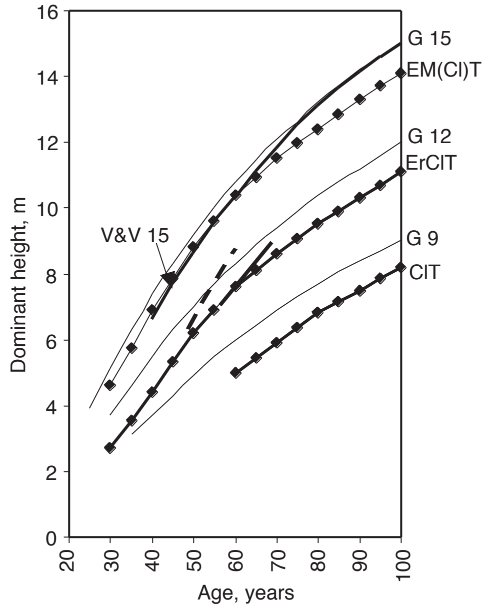

Fig. 5. Dominant height development of Stand 1 (solid line) and Stand 2 (dashed line), compared to site index curves (H_{100}) for artificially regenerated Scots pine stands in Finland (Vuokila and Väliaho 1980, V&V 15), to naturally regenerated Scots pine stands in Finland (Gustavsen 1980, G 15, G 12 and G 9), and to naturally regenerated Scots pine stands in northern Lapland (Ilvessalo 1970, EM(Cl)T, ErClT, ClT).

Temperature is the main determinant for the survival of trees near the arctic timberline. The temperature sums vary over a wide range near to the arctic timberline, thus indicating the extremely variable growing conditions (Fig. 6). For example, during the period 1956 to 1998 the minimum temperature sum for Stand 1was 443 d.d. and the maximum 979 d.d. The respective values for Stand 2 were 404 d.d. and 930 d.d. The lowest values are below the average conditions at the northernmost single treeline, and the highest values correspond to the average conditions in southern Lapland.

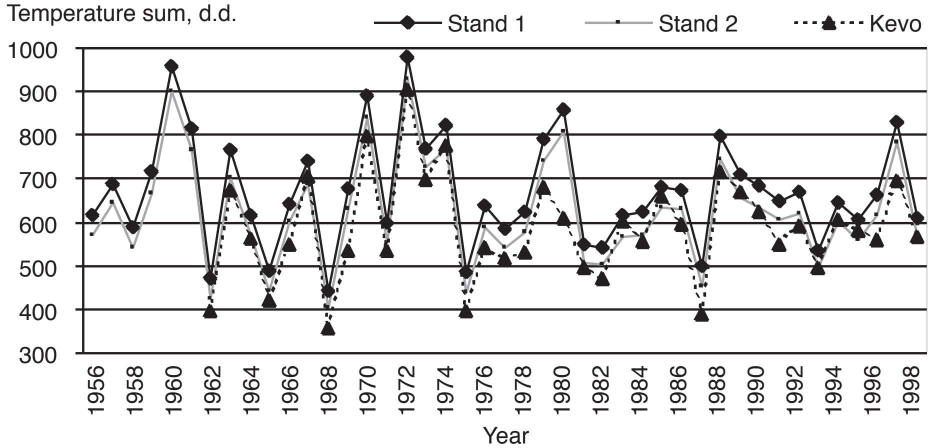

Fig. 6. Annual temperature sums for Stand 1 and 2, calculated with the model of Ojansuu and Henttonen (1983), based on observations made by the Finnish Meteorological Institute (FMI). Values for Kevo are from the nearest weather station of FMI (lat 69°45', long. 27°00', 90 m a.s.l.).

The variation in the radial growth of the trees in both stands was, however, much smaller than that in the temperature sums (see Figs. 3 and 6). This is evidence of the trees' ability to survive in extremely harsh conditions. During the observation period there was only one extremely cold summer, but no extended period of cold summers, which probably would have dramatically affected tree growth.

The response of tree growth to temperature sum was not very clear. For example, the radial growth of the trees in both stands was at its maximum level in 1964 (Fig. 3), but this year was not among the warmest at the timberline (Fig. 6). On the other hand, the well documented extremely cool summer of 1968 in Finnish Lapland resulted in low radial growth, even during the next year.

It is widely accepted that growth variation increase on moving towards the timberline (Mielikäinen et al. 1998). Comparison with radial growth indices for the whole of northern Finland (Mielikäinen et al. 1996) showed that the variation coincided well with the indices for pine in northern Finland.

The thinning reaction could be determined exactly on the basis of single tree data, and the differences in radial growth between the treatments were clear. The rapid, strong reaction was somewhat unexpected in stands located at the timberline. In a material representing the whole of Finland, pines reacted to thinning only moderately at a dominant height of 13–16 m during the first five years and the reaction was the weaker, the dryer the site (Hynynen and Arola 1999). Also Ruha and Varmola (1997) reported rather small differences in diameter growth between thinning treatments during the first ten years after precommercial thinning in naturally regenerated pine stands in northern Finland. Clear differences between all the thinning treatments ranging from 600 to 4400 stems ha^{-1} did not appear until the second decade after thinning (Ruha and Varmola 1997).

Valinger (1992) studied the thinning response in a Scots pine stand growing on a site of medium fertility (H_{100} = 24) at latitude 64° in Sweden. After the removal of 40 per cent of the basal area, the trees reacted in the form of slightly accelerated diameter growth already during the next year. From the third year on the thinned trees had ca. 50 per cent higher diameter growth compared to the unthinned stand. When applied to timberline trees, a relative increase of 50 per cent in radial growth was reached at a later stage, on the average in the sixth year after thinning.

The results show that, under favourable conditions, artificially regenerated Scots pine stands can grow surprisingly well at the arctic timberline.

It presupposes an extended warm climatic period at the time of planting or seeding but, after the trees have become established, they can survive and grow at a uniform rate. However, careful management is needed because of the severe conditions. Trees growing near their survival limit seem to respond to thinning in a similar way to those growing in more favourable conditions. The stand densities should, however, be lower because of the very limited resources for growth.

Acknowledgements

We thank Metsähallitus, the Northern Lapland District for Wilderness Management, for financial support in the remeasurements. Tauno Luosujärvi was responsible for most of the field work, and for carrying out the calculations together with Hannu Herva. We thank John Derome who revised the English.

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