Multilevel Modelling of Height Growth in Young Norway Spruce Plantations in Southern Finland

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Height development of Norway spruce (*Picea abies* (L.) Karst.) transplants was studied on 22 sites prepared by disc trenching or mounding. At the age of 4–9 years the plantations were surveyed using a multistage sampling design. For every planted spruce on a plot, the past annual height increments were measured as far into the past as possible. Multilevel mixed linear modelling was used to analyse the variation in growth at different levels (year, stand, cluster, plot, tree) and the effects of climatic and site characteristics on height growth. The within-plantation variation in height growth was higher on mounded sites than on disc-trenched sites. The mean temperature and the precipitation sum of the summer months affected height growth positively. Soil characteristics measured from undisturbed soil did not explain the height growth of seedlings on mounded sites, whereas on disc-trenched sites, the depth of the organic layer and the soil temperature had a positive effect and the depth of the eluvial horizon a negative effect. The modelling approach used proved to be a useful method for examining the sources of variation in development of young plantations.

Keywords *Picea abies*, Norway spruce, container seedlings, mounding, disc trenching, height growth, intra-level correlation, variance-component model

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1 Introduction

In Finland about 150 million forest tree seedlings are planted annually (Finnish Statistical… 2002). In the 1990's, the proportion of Norway spruce (*Picea abies* (L.) Karst.) seedlings increased at the expense of Scots pine (*Pinus sylvestris* L.). Nowadays, nearly 60% of the transplants are spruce seedlings. Simultaneously, three- to four-year-old bare-root spruce seedlings have been replaced by younger and smaller container seedlings. About 90% of the spruce seedlings planted today are one- to two-year-old container seedlings. Use of smaller seedlings has become possible because almost all regeneration areas are prepared mechanically (Finnish Statistical… 2002).

Disc trenching and patch scarification (scalping) are lighter methods of site preparation, which are used when pine is regenerated, naturally or artificially, on poor and medium fertile sites. Both of these methods of site preparation have also been used when spruce is planted. The main idea in disc trenching and patch scarification is to expose the mineral soil and to reduce competition from vegetation. In recent years, mounding has increasingly been used as a method of site preparation in spruce plantations on fertile sites in southern Finland. Traditionally, mainly paludified and waterlogged sites have been (ditched and) mounded. Mounds made by an excavator are capped with mineral soil and contain a double organic layer underneath. As in lighter methods of site preparation, mounding also reduces competition by other vegetation, but it enhances soil temperature more and makes nutrient release more favourably (Örlander et al. 1990, Sutton 1993). Today, about 20% of the total site preparation area is treated with mounding (Finnish Statistical… 2002).

The long-term effects of site-preparation on plantation establishment and growth of pine and spruce seedlings are rather well known in northern Fennoscandia (e.g. Örlander et al. 1990, 1998, Hansson and Karlman 1997, Mäkitalo 1999). However, research on spruce has largely been based on three- to four-year-old bare-root transplants, which have now been phased out. The development of plantations established on regeneration areas with small container seedlings and site-prepared with modern methods is rather poorly known.

According to inventories of young spruce plantations in southern Finland, the survival rate of small, one- to two-year-old container seedlings planted on mounded sites is high, and their height development is rapid (Schildt 2000, Saksa et al. 2002). These results suggest that plantations established with container seedlings usually do not have a stagnation phase in height development just after planting, i.e. planting shock, as often happens with older bare-root seedlings (Heikinheimo 1941, Björkman 1953). This difference, however, has so far not been verified by scientific studies.

Growth of spruce forests in Finland is more dependent on the temperature sum of the growth season than on the precipitation (Henttonen 1990, Miina 2000). However, on drought-prone sites precipitation also has a significant effect on growth (Mäkinen et al. 2001). Fine soil texture generally indicates good water and nutrient availability to trees, but mainly the nitrogen content of the humus layer correlates with growth of both pine and spruce (Tamminen 1991, 1993, Nohrstedt and Jacobson 1994). On clearcut areas, nitrogen availability to seedlings is dependent on the organic matter content and its mineralization (Örlander et al. 1990, Smolander et al. 2000). Site preparation alters soil temperature and density, as well as water relations and nutrient availability, thus affecting plantation establishment markedly (Örlander et al. 1990).

In forest regeneration, the aim is to reach a high rate of survival and rapid early development of planted seedlings as well as low variation in tree size within the stand. Within-stand variation in juvenile growth is a result of differences in competition from vegetation such as weeds and broadleaves, as well as differences in soil properties and pests (e.g. Kuuluvainen et al. 1993, George et al. 1997, Groot 1999, Bell et al. 2000, Heiskanen and Viiri 2005). When the early development of seedlings is modelled, tree height and height growth are the attributes that are most applicable for evaluating the response of seedlings to, e.g. site conditions and regeneration methods (e.g. Örlander et al. 1998, Mäkitalo 1999).

When several annual increments are measured from a seedling, this will result in longitudinal data, i.e. the autocorrelation associated with repeated measurements are nested within individual trees (e.g. Henttonen 1990, Miina 2000).

The annual increments of trees can be cross-classified, for example, according to growing years. Therefore, the individual observations are generally not completely independent. Furthermore, the response variable is measured at the lowest hierarchical level, but the explanatory variables are measured at all existing levels. Multilevel modelling techniques must be applied to such data and are especially valuable in those situations where data are unbalanced or missing, i.e. every level has not the same number of observations. In a general context, multilevel modelling has been covered by, e.g. Searle (1971), Goldstein (1995), Hox (1995) and Snijders and Bosker (1999) and in the forestry literature by, e.g. Lappi (1986), Gregoire et al. (1995) and Hall and Bailey (2001).

The aim of this study was to apply multilevel regression modelling to the hierarchical, longitudinal and cross-classified data collected on the height growth of young Norway spruce plantations regenerated with container seedlings. Climatic and soil characteristics as well as site-preparation method were used as explanatory variables in the regression models.

2 Material and Methods

2.1 Tree Variables

The study material consisted of 22 Norway spruce plantations in southern Finland (Table 1). The plantations were located 6753–6877 km from the Equator and 3469–3520 km from the Greenwich meridian, and altitude varied between 85 and 140 m a.s.l. The plantations were established in spring of 1993, 1994, 1997 or 1998 using one- or two-year-old container seedlings. On 8 plantations, the soil was mounded and on 14 plantations it was disc trenched a year before planting. All plantations were growing on forest soil of medium fertility classified as *Myrtillus* site type in the Finnish system of classification (Cajander 1949). The plantations surveyed were a random sample from similar plantations owned by UPM-Kymmene Forest Corp. (Valkeakoski, Finland). According to the records, the original planting density varied between 1500 and 2000 seedlings per ha; but as this was not known exactly, it was not possible to analyse the survival rates of seed-

Table 1. The main characteristics of the plantations.

Site	Site preparation	Planting year	Age of planted seedlings (a)	Number of planted spruce in 2001 (ha^{-1})	Mean height (± SD) of spruce in 2001 (cm)
1	Disc trenching	1993	1	1100	112 ± 34
2	Disc trenching	1993	1	1450	130 ± 44
3	Disc trenching	1993	1	1466	147 ± 37
4	Disc trenching	1993	1	1350	117 ± 42
5	Disc trenching	1993	2	1500	124 ± 26
6	Disc trenching	1993	2	1433	156 ± 44
7	Disc trenching	1993	2	866	143 ± 47
8	Disc trenching	1997	2	1142	61 ± 12
9	Disc trenching	1997	2	1266	64 ± 15
10	Disc trenching	1997	-[a)]	1150	70 ± 14
11	Disc trenching	1998	2	1183	73 ± 12
12	Disc trenching	1998	2	1450	53 ± 10
13	Disc trenching	1998	2	1194	67 ± 13
14	Disc trenching	1998	2	1416	60 ± 9
15	Mounding	1993	2	1222	201 ± 66
16	Mounding	1994	2	1650	162 ± 67
17	Mounding	1994	-[a)]	1600	123 ± 28
18	Mounding	1997	-[a)]	1366	64 ± 17
19	Mounding	1997	2	844	70 ± 15
20	Mounding	1998	2	1533	49 ± 12
21	Mounding	1998	2	1333	52 ± 11
22	Mounding	1998	2	1366	66 ± 12

[a)] Unknown

lings from these data.

Tree and soil characteristics were measured in the field during a short period late in the summer of 2001 when weather conditions were relatively stable and shoot elongation had ceased. A total of 4 clusters, including 3 sample plots each, i.e. 12 sample plots altogether, were systematically placed within each plantation (Table 2). Because the size of plantations varied greatly (0.5–19.2 ha), clusters were located evenly along the longest diagonal of the plantation or on small plantations, along the two rectangular diagonals. The size of the circular sample plot was 50 m^2 and contained up to 9 planted, healthy, undamaged spruce seedlings (on average, 4.5 trees per plot/900 trees per ha). Total height and past annual height increments were measured from branch whorls as far into the past as possible from every planted spruce. On average, it was possible to record four annual height increments per seedling. The position of the planted spruces was classified as: 1) higher position if the tree was growing on the top of a mound and 0) other. On each plot, the number and median height of broadleaves which were more than 0.5 times the mean height of planted spruces were determined.

2.2 Soil Variables

At the same time as the tree measurements were made, the thickness of organic and eluvial layers (O and E horizon) were measured from an undisturbed spot as near as possible to the centre of each cluster (Table 2). From the same spot, the surface-penetration resistance of mineral soil below the organic layer was measured in the range 0–4.5 kg cm^{-2} (Pocket penetrometer, Eijkelkamp,

Table 2. Characteristics of the predicted variable and predictors in the whole study material, N is the number of observations at year, stand, cluster, plot or tree level.

Variable	Disc-trenched sites			Mounded sites		
	N	Mean ± SD	Range	N	Mean ± SD	Range
At tree × year level:						
Height increment (cm a^{-1})	2619	20.6 ± 13.6	1–119	1384	23.7 ± 17.4	1–103
Tree height (cm)	2619	78 ± 42	14–292	1384	75 ± 55	13–330
At tree level:						
Proportion of high position of trees	658	0.04	-	360	0.05	-
At plot level:						
Number of broadleaves (ha^{-1})	152	3312 ± 2694	0–15995	80	6048 ± 4221	400–18595
Median height of broadleaves (cm)	150	141 ± 47	62–319	80	188 ± 101	89–800
At cluster level:						
Organic layer (cm)	56	4.7 ± 1.5	1.1–7.9	26	5.5 ± 1.6	3.1–9.4
Eluvial layer (cm)	42	6.0 ± 3.1	1.8–17.5	22	8.4 ± 3.2	2.8–16.5
Proportion of particles < 0.06 mm	54	0.26 ± 0.1	0.06–0.66	26	0.23 ± 0.1	0.02–0.43
Soil temperature (°C)	52	14.1 ± 1.6	10.8–18.9	23	13.6 ± 1.1	11.1–14.9
Soil water content (%)	50	20.9 ± 12.0	2.9–65.3	20	21.1 ± 10.2	5.3–46.2
Electric conductance (mS cm^{-1})	49	2.5 ± 3.2	0.8–22.8	21	2.3 ± 2.2	1.2–11.2
Penetration resistance (kg cm^{-2})	53	2.1 ± 0.8	0.8–5.1	26	2.3 ± 0.8	0.7–3.8
Soil organic content (%)	52	5.8 ± 2.7	1.2–13.0	25	4.0 ± 2.5	2.0–13.6
At stand × year level:						
Time since planting (a)	64	5.1 ± 2.5	1–9	36	4.3 ± 2.2	1–9
At year level:						
Mean temperature from May to September (°C)	5	13.1 ± 0.6	12.5–13.6	5	13.1 ± 0.6	12.5–13.6
Precipitation sum from May to September (mm)	5	303 ± 68	221–371	5	303 ± 68	221–371

Giesbeek, The Netherlands). Volumetric soil-water content was measured using a ThetaProbe and soil electronical conductance and temperature using a SigmaProbe EC1 (Delta-T Devices Ltd., Cambridge, UK). All these measurements were made from a 10 cm thick layer beginning about 2 cm below the mineral soil surface downwards. In this study, replicated measurement of the temporal course of soil conditions on planting spots was not possible, so only those variables describing average site conditions that were easy to measure and could be collected only once were measured. Immediately after these in situ soil measurements, a soil sample of about one litre was taken from the same measurement layer. From the soil samples, the content of fine soil particles less than 0.06 mm in diameter was determined by dry sieving and the content of organic matter as loss on ignition at 550 C° was measured gravimetrically in the laboratory.

Means of soil characteristics were calculated according to stand (22 plantations) and site-preparation treatment (disc trenching and mounding). Between-treatment differences in mean soil characteristics of plantations were studied by analysis of variance. At plantation level, only the thickness of the E horizon differed significantly ($p = 0.011$) between disc-trenched (5.9 ± 2.0 cm) and mounded sites (8.7 ± 2.2 cm). For other soil characteristics, $p > 0.264$.

2.3 Climatic variables

In the study area, the effective temperature sum (threshold 5 °C) varied (1961–1990) between 1000 and 1300 d.d. (Solantie and Drebs 2000). Monthly mean air temperatures and precipitation sums from the years 1997–2001, measured at the meteorological stations nearest to the studied plantations, Mikkeli (61°41´N, 27°12´E, 101 m a.s.l.) and Valkeala (60°54´N, 26°56´E, 99 m a.s.l), were used to describe the annual growth conditions. From these climatic data the total precipitation and mean air temperature in the summer months (May to September) were calculated and used as explanatory variables in the height-growth models. The climatic variables of the above-mentioned two meteorological stations were averaged.

2.4 Model Formulation

The multilevel model for height growth that was prepared here can be written in the following general form:

$$\begin{aligned} \ln(ih_{ijklt}) = f(X,\beta) + u_t + u_i + u_{ij} + u_{ijk} + u_{ijkl} + v_{ijklt}, \\ v_{ijklt} = \rho v_{ijklt-1} + e_{ijklt} \end{aligned} \qquad (1)$$

where

$\ln(ih_{ijklt})$ = the logarithmic height increment (cm)
$f(\cdot)$ = the fixed part of the model
X = a vector of fixed predictors
β = a vector of fixed parameters

Subscripts i, j, k, l and t refer to stand i, cluster j, plot k, tree l and year t, respectively. u_t, u_i, u_{ij}, u_{ijk}, u_{ijkl} and e_{ijklt} are independent and identically distributed random between-year, between-stand, between-cluster, between-plot, between-tree effects and error term with a mean of 0 and constant variances of σ_{yr}^2, σ_{st}^2, σ_{cl}^2, σ_{pl}^2, σ_{tr}^2 and σ_e^2, respectively. v_{ijklt} is an autocorrelated within-tree error term which was assumed to arise from a first-order autoregressive process with a mean of 0 and constant variance of $\sigma_v^2 = \sigma_e^2 / (1 - \rho^2)$. Based on the normal probability plots and the Kolmogorov-Smirnov statistics, the logarithmic transformation of height increment resulted in a normal distribution of the residuals. The variances of the random effects and the parameters of fixed predictors were estimated using the maximum likelihood method of the computer software PROC MIXED in SAS/STAT (SAS Institute Inc. 1999).

First, in order to find the average height growth pattern during the first 9 years after planting, the model was fitted to the whole data set using only time since planting as a predictor. Second, the separate models were fitted for disc-trenched and mounded sites. Using the variances of the hierarchical levels, several kinds of intra-level correlation coefficient were calculated (e.g. Snijders and Bosker 1999). After that, more predictors (e.g. climatic and soil variables, the characteristics of competing broadleaves and tree height, as well as their transformations) were tried as predictors in the reference models. The requirements were that all the predictors added to the models had to be logical and significant at the 0.05 level and that no systematic errors were observed in residuals.

For example, the number and median height of broadleaves were found to correlate positively with the height growth of spruce seedlings, and therefore the characteristics of competing broadleaves were not used as predictors in the models. Third, the data sets from both disc-trenched and mounded areas were combined again, and the final growth models were fitted using the different sets of predictors.

In the models used, the explained variance R^2 was defined as the proportional reduction in the value of the total residual variance due to including new fixed predictors into the reference model. The explained variance R^2 was calculated as follows: $R^2 = 100 \times (1 - \sigma^2_{\text{total}} / \sigma^2_{\text{total,ref}})$. When height-growth predictions were calculated in the original scale, owing to the logarithmic transformation, the correction factor (i.e. the half of the total residual variance) was added to the model prediction.

3 Results

Time since planting (*TSP*) and its squared transformation (TSP^2) described the pattern of height growth well during the first nine years after planting. No obvious pattern could be found that would indicate systematic trends in the residuals as a function of time since planting.

In the separate height-growth models (reference models), the largest proportion of the total variance was located at the within-tree level: 71% on disc-trenched sites and 65% on mounded sites (Table 3). The proportion of tree-level variance was about three times higher on mounded sites (16%) than on disc-trenched sites (5%). On the contrary, the proportion of stand-level variance on disc-trenched sites (10%) was twice as high as on mounded sites (5%). The rest of the total error variance (14%) was situated at the year-, cluster- and plot- levels.

The intra-level correlation coefficients were higher on disc-trenched sites than on mounded sites (Table 4). For example, the intra-tree correlation that expresses the likeness of trees in the same stand (i.e. ignoring between-year and within-tree variation) was estimated to be 0.41 on disc-trenched sites and 0.17 on mounded sites.

The separate growth models for disc-trenched and mounded sites indicated that height development of spruce seedlings was more rapid on mounded than on disc-trenched sites. On disc-

Table 3. Estimates of the parameters, variance components and fitting statistics of the reference height growth models (Eq. 1) for disc-trenched and mounded sites.

Variable	Disc-trenched sites	Mounded sites
Intercept	1.6183	1.3556
Time since planting (a)	0.3369	0.4874
(Time since planting)^2	–0.0176	–0.0264
σ_{yr}^2	0.0171[a)]	0.0130[a)]
σ_{st}^2	0.0352	0.0155[a)]
σ_{cl}^2	0.0174	0.0091[a)]
σ_{pl}^2	0.0117	0.0184
σ_{tr}^2	0.0184	0.0473
σ_{v}^2	0.2403	0.1951
σ_{total}^2	0.3401	0.2984
ρ	0.1406	–0.0162[a)]
N[b)]	5, 14, 56, 152, 658, 2620	5, 8, 27, 80, 360, 1385
Bias (cm a^{-1})	–0.6	0.1
Bias% (%)	–3.0	0.4
RMSE (cm a^{-1})	11.5	12.9
RMSE% (%)	54.1	54.7

[a)] Not significant at the 0.05 level
[b)] N, number of years, stands, clusters, plots, trees and height growth observations

Table 4. Intra-level correlation coefficients on disc-trenched and mounded sites according the variance component estimates of the reference height growth models in Table 3.

Similarity of	Disc-trenched sites	Mounded sites
trees in a plot	0.39	0.28
trees in a cluster	0.37	0.12
trees in a stand	0.41	0.17
plots in a cluster	0.60	0.33
plots in a stand	0.55	0.36
clusters in a stand	0.67	0.63

trenched sites, the thickness of the organic layer ($p=0.0004$) and the soil temperature ($p=0.0002$) had a positive effect and the thickness of E horizon ($p=0.0126$) a negative effect on height growth, whereas on mounded sites, none of the soil characteristics was a significant predictor ($p>0.05$). The negative regression coefficient of the E horizon was partly due to multicollinearity, i.e. a positive correlation (0.4) between the thickness of the O and E horizons (Table 5). With both site-preparation treatments, the mean temperature and the precipitation sum for the summer months increased height growth significantly ($p<0.0001$).

The proportion of transplants growing at relatively high positions was low on both mounded (5%) and disc-trenched sites (4%). The position of planted spruce was not a significant predictor in the models. On disc-trenched sites, no effect of the age of the transplants (one- or two-year-old) on the post-planting height growth was found in this material.

The reference model fitted to the modelling data set was almost unbiased, and its relative RMSE was 58% (Table 6). Of the total variance, 62% was situated at the within-tree level while year-, stand-, cluster-, plot- and tree-levels each accounted for 5–12% of the total variance unexplained by time since planting.

The more rapid development of height growth on mounded sites was accounted for in Model 1 by adding the dummy variable for mounding (Table 6). This decreased the stand-level residual variance (σ_{st}^2); but compared to the reference model, the proportional reduction in the prediction error was less than 5%. According to Model 1, annual height increments progressed from 8 cm a^{-1} in the first growing season, reaching about 29 cm a^{-1} on disc-trenched sites and 44 cm a^{-1} on mounded sites in the 9th year (Fig. 1). At the age of 5 years, the average height growth was about 5 cm a^{-1} higher on mounded sites than on disc-trenched sites.

Using the tree height (Model 2) and climatic characteristics (Model 3) as predictors increased the proportion of explained variance to 18 and 23%, respectively. The thickness of the organic and eluvial layers and the soil temperature explained the height growth only on disc-trenched sites (Model 4). These soil characteristics decreased both the stand- and cluster-level residual variance and increased R^2 to 26%.

Table 5. Significant ($p<0.05$) correlations among the soil characteristics.

	Penetration resistance (kg cm^{-2})	Eluvial layer (cm)	Soil water content (%)	Electric conductance (mS cm^{-1})
Soil temperature (°C)			–0.442 $p=0.000$	0.254 $p=0.034$
Organic layer (cm)		0.411 $p=0.001$		
Proportion of particles <0.06 mm	–0.245 $p=0.031$			
Soil organic content (%)	–0.248 $p=0.032$		0.420 $p=0.000$	

Table 6. Estimates of the parameters, variance components and fitting statistics of the height growth models (Eq. 1). Models 1–4 are estimated by including step by step new predictors to Reference model. The number of observations is 3237 in all models.

Variable	Reference model	Model 1	Model 2	Model 3	Model 4
Intercept	1.5289	1.5223	–0.02148	–4.0560	–5.5567
TSP	0.3988	0.3732	0.2674	0.2643	0.2643
TSP^2	–0.0227	–0.02077	–0.02018	–0.02027	–0.02028
Mounding*TSP		0.04613	0.03358	0.03256	0.03143
Mounding					1.4990
$\ln(h)$			0.5004	0.4962	0.4963
Temp				0.2795	0.2800
Prec				0.001356	0.001364
Disc*O					0.08699
Disc*SoilTemp					0.08777
Disc*E					–0.02417
σ_{yr}^2	0.0210 a)	0.0180 a)	0.0157 a)	0.0	0.0
σ_{st}^2	0.0438	0.0311	0.0154	0.0144 a)	0.0061 a)
σ_{cl}^2	0.0178	0.0179	0.0138	0.0140	0.0093
σ_{pl}^2	0.0176	0.0177	0.0094	0.0095	0.0097
σ_{tr}^2	0.0319	0.0330	0.0	0.0	0.0
σ_{v}^2	0.2195	0.2178	0.2336	0.2335	0.2336
$\sigma_{\mathrm{total}}^2$	0.3516	0.3355	0.2879	0.2714	0.2587
ρ	0.1350	0.1288	0.1131	0.1160	0.1173
–2Log likelihood	4752.3	4738.8	4627.4	4609.1	4589.0
R^2 (%)	0.0	4.6	18.1	22.8	26.4
Bias (cm a^{-1})	0.1	–0.2	0.1	–0.2	–0.1
Bias% (%)	0.3	–0.7	0.5	–0.8	–0.3
RMSE (cm a^{-1})	13.3	12.7	11.1	10.5	10.2
RMSE% (%)	57.8	54.4	48.2	44.9	44.2

a) Not significant at the 0.05 level
TSP, time since planting (yrs); *Mounding* and *Disc*, dummy-variables for mounding and disc trenching, respectively; *h*, tree height in the beginning of the growing season (cm); *Temp* and *Prec*, mean monthly temperature (°C) and sum of monthly precipitation (mm), respectively, from May to September during the growing season; *O*, *SoilTemp* and *E*, organic layer (cm), soil temperature (°C) and eluvial layer (cm), respectively, measured in autumn 2001

4 Discussion

In the present study, each plantation was treated either by disc trenching or by mounding. It is possible that part of the between-treatment differences were explained by the differences in the site productivity, though the soil characteristics measured (Table 2) showed no systematic differences (excluding the E horizon) between disc-trenched and mounded sites. Apparently the site-preparation method was not selected initially according to the soil characteristics of the regeneration area, because e.g. soil-water content or thickness of organic layer did not differ between the disc-trenched and mounded sites.

Due to possible differences in site productivity between disc-trenched and mounded sites as well as the use of a few older plantations that were mounded, the results of this study are only tentative. Instead of this inventory data, only balanced data from an experimental design could have enabled statistical comparison of site preparation treatments. However, the multilevel modelling approach allowed us to study the effects of soil and climatic characteristics on the height growth of Norway spruce on disc-trenched and mounded sites. In the models, variation in height growth that was not explained by the explanatory variables was accounted for by random variables at different levels.

The effect of mounding on the height growth of spruce seedlings was positive. However, in

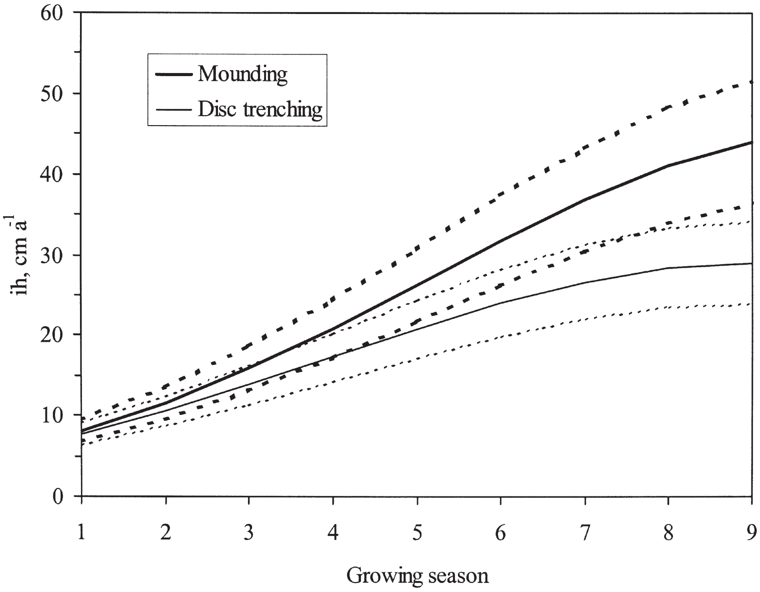

Fig. 1. Post-planting height increment of Norway spruce (ih, cm a^{-1}) on mounded and disc-trenched sites according to Model 1 in Table 6. Dashed lines indicate the between-stand variation around the model prediction (i.e. the fixed part ± σ_{st}).

our data the characteristics measured from undisturbed soil, which were significant predictors of height growth on disc-trenched sites, did not explain the height growth on mounded sites. As has also been found in other studies, disc trenching compared with mounding can have only a modest effect on height growth and pine-weevil damage in Norway spruce seedlings (Kinnunen 1999, Löf 2000).

On disc-trenched sites, the thickness of the O layer had a positive effect on height growth, which might be an indication that site fertility is better with a thicker O layer. In Norway spruce stands, the O layer tends to thicken in more fertile soils, while in Scots pine stands, thin O layers occur in both low and high fertility soils (Tamminen 1993). In general, the thickness of the O and E horizons varies more with soil texture than with tree species (Aaltonen 1941). On mounded sites, the thickness of the O layer (measured from undisturbed pots) had no effect on height growth.

According to previous studies (e.g. Örlander et al. 1990, 1998, Nordborg 2001), the better seedling height growth with mounding is evidently due to improved growing conditions in the mounds (e.g. higher soil temperature, better aeration and drainage, quicker mineralization of nutrients). In our study, the soil conditions (water content, temperature and electrical conductivity) were measured only once from undisturbed spot; not from the soil in the planting spot. Therefore, these soil data described average site characteristics rather than the actual temporal growing conditions and their effects on the height growth of seedlings growing on mounds. Furthermore, the other soil characteristics measured describe static site properties (soil horizons, texture, organic matter), which remain virtually unchanged over time, e.g. due to weather or soil preparation.

In the present data, competition from broadleaves did not explain variation in height growth; actually, the responses of spruce in terms of height growth were slightly positive. An explanation for the positive correlations may be that the number and median height of broadleaves served more as a measure of site conditions than a measure of competition between spruce and broadleaves.

The warm and rainy summer months promoted the height growth of spruce seedlings on both disc-trenched and mounded sites. In several Fennoscandian studies, high temperature and precipitation have been found to increase the diameter growth of spruce (e.g. Eklund 1957, Bergan 1987, Henttonen 1990, Miina 2000, Mäkinen et al. 2001).

As expected, the tree-level contributed more to variability than the plot-level did, and the plot-level contributed more than the cluster-level. Most of the variation (about 60–70%) in height growth was due to within-tree variation. High within-tree variation in the height-growth data meant that the growth curves of individual trees did not exactly follow the average growth curve estimated with the fixed part of the model. High within-tree variation is partly due to measurement errors but also due to the fact that the annual growth of trees varies from year to year according to the complex interaction of several factors (micro-climatic and -site conditions, competition by weeds and other trees, etc), which are difficult to take into account in modelling (see e.g. Kuuluvainen et al. 1993).

According to the models, mounding enhanced the height development of spruce transplants on surveyed upland sites; but at the same time, variation in height growth between trees increases, probably due to variation in growing conditions between planting spots/mounds. Therefore in future studies, the growing conditions on planting spots/mounds must be measured in more detail. In addition, to compare methods of site preparation, balanced data from experimental designs are required.

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References

Aaltonen, V.T. 1941. Die finnischen Waldböden nach den Erhebungen der zweiten Reichswaldschätzung. Communicationes Instituti Forestalis Fenniae 29(5). 71 p. (In Finnish with German summary).

Bell, F.W., Ter-Mikaelian, M.T. & Wagner, R.G. 2000. Relative competitiveness of nine early-successional boreal forest species associated with planted jack pine and black spruce seedlings. Canadian Journal of Forest Research 30(5): 790–800.

Bergan, J. 1987. Effects of temperature on annual ring growth of different Norway spruce provenances planted at various altitudes at 69° N. Meddelelser fra Norsk institutt for skogforskning 40(3): 1–46.

Björkman, E. 1953. Om orsakerna till granes tillväxtsvårigheter efter plantering i nordsvensk skogsmark. Norrlands Skogsvårdsförbunds Tidskrift: 285–316. (In Swedish).

Cajander, A.K. 1949. Forest types and their significance. Acta Forestalia Fennica 56. 71 p.

Eklund, B. 1957. The annual ring variations in spruce in the centre of northern Sweden and their relation to the climatic conditions. Meddelanden från Statens skogsforskningsinstitut 47(1): 1–63. (In Swedish with English summary).

Finnish Statistical Yearbook of Forestry 2002. SVT, Agriculture, forestry and fishery 2002:45. 378 p.

George, E., Seith, B., Schaeffer, C. & Marschner, H. 1997. Responses of Picea, Pinus and Pseudotsuga roots to heterogeneous nutrient distribution in soil. Tree Physiology 17: 39–45.

Goldstein, H. 1995. Multilevel statistical models. 2nd ed. Arnold, London. 178 p.

Gregoire, T.G., Schabenberger, O. & Barrett, J.P. 1995. Linear modelling of irregularly spaced, unbalanced, longitudinal data from permanent-plot measurements. Canadian Journal of Forest Research 25: 137–156.

Groot, A. 1999. Effects of shelter and competition on the early growth of planted white spruce (Picea glauca). Canadian Journal of Forest Research 29(7): 1002–1014.

Hall, D.B. & Bailey, R.L. 2001. Modeling and prediction of forest growth variables based on multilevel nonlinear mixed models. Forest Science 47(3): 311–321.

Hansson, P. & Karlman, M. 1997. Survival, height and health status of 20-year-old Pinus sylvestris and Pinus contorta after different scarification treatments in a harsh boreal climate. Scandinavian Journal of Forest Research 12: 340–350.

Heikinheimo, O. 1941. Metsänistutusmenetelmistä. Metsätieteellisen tutkimuslaitoksen julkaisuja

29(4): 1–63. (In Finnish with German summary).

Heiskanen, J. & Viiri, H. 2005. Effects of mounding on damage by the European pine weevil in planted Norway spruce seedlings. Northern Journal of Applied Forestry. (In press).

Henttonen, H. 1990. Variation in the diameter growth of Norway spruce in Southern Finland. University of Helsinki, Department of Forest Mensuration and Management, Research Notes 25. 88 p. (In Finnish with English summary).

Hox, J.J. 1995. Applied multilevel analysis. 2nd ed. TT-Publikaties, Amsterdam. 118 p. ISBN 90-801073-2-8.

Jonsson, B. 1999. Stand establishment and early growth of planted Pinus sylvestris and Picea abies related to microsite conditions. Scandinavian Journal of Forest Research 14: 425–439.

Kinnunen, K. 1999. Tukkimiehentäin tuhojen kemiallinen ja mekaaninen torjunta. Metsätieteen aikakauskirja 4/1999: 687–695. (In Finnish).

Kuuluvainen, T., Hokkanen, T.J., Järvinen, E. & Pukkala,T. 1993. Factors related to seedling growth in a boreal Scots pine stand: a spatial analysis of a vegetation-soil system. Canadian Journal of Forest Research 23(10): 2101–2109.

Lappi, J. 1986. Mixed linear models for analyzing and predicting stem form variation of Scots pine. Communicationes Instituti Forestalis Fenniae 134. 69 p.

Löf, M. 2000. Influence of patch scarification and insect herbivory on growth and survival in Fagus sylvatica L., Picea abies L. Karst. and Quercus robur L. seedlings following a Norway spruce forest. Forest Ecology and Management 134: 111–123.

Mäkinen, H., Nöjd, P. & Mielikäinen, K. 2001. Climatic signal in annual growth variation in damaged and healthy stands of Norway spruce [Picea abies (L.) Karst.] in southern Finland. Trees 15(3): 177–185.

Mäkitalo, K. 1999. Effect of site preparation and reforestation method on survival and height growth of Scots pine. Scandinavian Journal of Forest Research 14(6): 512–525.

Miina, J. 2000. Dependence of tree-ring, earlywood and latewood indices of Scots pine and Norway spruce on climatic factors in eastern Finland. Ecological Modelling 132(3): 259–273.

Nohrstedt, H-Ö. & Jacobson, S. 1994. Relationship between nutrient concentrations in soil and current year needles. SkogForsk. Redogörelse 7. 18 p.

Nordborg, F. 2001. Effects of site preparation on soil properties and on growth, damage and nitrogen uptake in planted seedlings. Acta Universitatis Agriculturae Sueciae Silvestria 195: 1–11.

Örlander, G., Gemmel, P. & Hunt, J. 1990. Site preparation: a Swedish overview. FRDA Report 105. 61 p.

— , Hallsby, G., Gemmel, P. & Wilhelmsson, C. 1998. Inverting improves establishment of Pinus contorta and Picea abies – 10-year results form a site preparation trial in Northern Sweden. Scandinavian Journal of Forest Research 13: 160–168.

Saksa, T., Särkkä-Pakkala, K. & Smolander, H. 2002. Työkalu metsänuudistamisen laatutyöhön. Metsätieteen aikakauskirja 1/2002: 29–34. (In Finnish).

SAS Institute Inc. 1999. SAS OnlineDoc®, Version 8. SAS Institute Inc., Cary, NC.

Schildt, J. 2000. Mätästys ja istutus ovat kuusen uudistamisessa ylivoimainen yhdistelmä. Metsä 5: 10–11. (In Finnish).

Searle, S.R. 1971. Linear models. John Wiley & Sons Inc., New York. 532 p.

Smolander, A., Paavolainen, L. & Mälkönen, E. 2000. C and N transformations in forest soil after mounding for regeneration. Forest Ecology and Management 134: 17–28.

Snijders, T. & Bosker, R. 1999. Multilevel analysis. An introduction to basic and advanced multilevel modeling. SAGE Publications Inc., London, 266 p. ISBN 0-7619-5889-4.

Solantie, R. & Drebs, A. 2000. On temperature conditions in Finland during the vegetational period 1961–90 considering the effect of the underlying surface. Finnish Meteorological Institute, Reports 2000:1. 38 p. ISBN 951-697-521-6. (In Finnish with English summary).

Sutton, R.F. 1993. Mounding site preparation: a review of European and North-American experience. New Forests 7: 151–192.

Tamminen, P. 1991. Expression of soil nutrient status and regional variation in soil fertility of forested sites in southern Finland Folia Forestalia 777. 40 p. (In Finnish with English summary).

— 1993. Estimation of site index for Scots pine and Norway spruce stands in South Finland using site properties. Folia Forestalia 819. 26 p. (In Finnish with English summary).

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