Individual-tree Basal Area Growth Models for Scots Pine, Pubescent Birch and Norway Spruce on Drained Peatlands in Finland

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Models for individual-tree basal area growth were constructed for Scots pine (*Pinus sylvestris* L.), pubescent birch (*Betula pubescens* Ehrh.) and Norway spruce (*Picea abies* (L.) Karst.) growing in drained peatland stands. The data consisted of two separate sets of permanent sample plots forming a large sample of drained peatland stands in Finland. The dependent variable in all models was the 5-year basal area growth of a tree. The independent tree-level variables were tree dbh, tree basal area, and the sum of the basal area of trees larger than the target tree. Independent stand-level variables were stand basal area, the diameter of the tree of median basal area, and temperature sum. Categorical variables describing the site quality, as well as the condition and age of drainage, were used. Differences in tree growth were used as criteria in reclassifying the a priori site types into new yield classes by tree species. All models were constructed as mixed linear models with a random stand effect. The models were tested against the modelling data and against independent data sets.

Keywords *Betula pubescens*, forest drainage, growth, mires, mixed models, sites, *Picea abies*, *Pinus sylvestris*

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1 Introduction

In Finland, the area of peatlands and paludified forests drained for forestry up to 1991 was 6 million ha (Aarne 1993). In the beginning of the 1980s, the percentage of the growing stock and the total volume which was in peatland forests was 18 % and 22 %, respectively (Paavilainen and Tiihonen 1987). The proportions are probably increasing because most drained peatland stands are about to reach or have just reached the commercial size. Drained peatland stands differ from those growing on mineral soils because of the skewed age- and size distributions and clumped spatial distribution of the trees (Hökkä and Laine 1988, Hökkä et al. 1991, Miina et al. 1991). Furthermore, drainage causes long-term changes in site properties. Because these factors most probably influence tree growth, specific growth models taking them into account should be applied when growth predictions for drained peatlands are made. For the purposes of timber management planning, the need for accurate predictions of growth is evident because drained peatlands represent such a large proportion of the total forest land.

At stand level, post-drainage growth has been examined in several Finnish studies since the 1920s (Lukkala 1937, Heikurainen 1959, Huikari et al. 1967, Heikurainen and Seppälä 1973, Laine and Starr 1979, Keltikangas et al. 1986, Penttilä 1990). Site quality indices in terms of the relative post-drainage timber productivity of peatland site types in different parts of the country were defined by Heikurainen (1959). A common method has been to evaluate the timber production potential of different sites on the basis of the relative growth rate (growth expressed as a function of present stand volume) of stands.

Tree-level growth analyses have become more common during the last decades. In Finland, Saramäki (1977) constructed growth and yield tables for pubescent birch (*Betula pubescens* Ehrh.) stands growing on drained peatlands in northern Finland with stand-level equations, but also derived tree-level growth equations. Sites were classified on the basis of stand dominant height development. In Sweden, Hånell (1984, 1988) developed a site type classification for peatlands on the basis of individual-tree basal area growth models for Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst.) and pubescent birch (*Betula pubescens*). To obtain the post-drainage forest productivity of the distinguished sites, stand-level equations were developed and used to simulate stand development after drainage. In Canada, Payandeh (1973) used both tree- and stand-level approaches when studying the post-drainage growth of black spruce (*Picea mariana* (Mill.) B.S.P.) stands. The pattern of response of annual tree ring growth of black spruce following drainage has been analyzed by Dang and Lieffers (1989). In Finland, spatial individual-tree growth models for Scots pine growing on drained peatland have been developed by Miina et al. (1991), Miina (1994, 1996) and Penner et al. (1995).

When growth models are applied to forest management planning systems and used primarily for inventory updating, the models should meet specific requirements (Burkhart 1993). The input variables should be common and easy to measure. The models should describe growth in a simple and logical way. Furthermore, the models should be unbiased, which requires that the modelling data be a representative sample of the forests where the models will be applied. Distance-independent individual-tree growth models are most commonly used. Most forest management planning systems in Finland operate with the MELA growth simulator (Siitonen et al. 1996). The growth models in MELA for drained peatland stands have been constructed using inventory data collected from drained peatlands (Keltikangas et al. 1986). A common basic model is applied to stands growing in mineral soil sites and peatlands, but in the peatland growth models, specific parameters related to site and its post-drainage succession are incorporated (Ojansuu et al. 1991).

In this study, individual-tree basal area growth models for Scots pine, Norway spruce and pubescent birch (hereafter pine, spruce and birch, respectively) were constructed to substitute for the present models in MELA. Simultaneously, the present peatland site type classification was reformed with the aim of determining a reasonable number of yield classes that significantly differ from each other in terms of tree growth.

2 Materials

2.1 Modelling Data

The modelling data consisted of two separate inventory data sets covering the whole area where forest drainage has been applied in practical forestry (Fig. 1a). For southern Finland and southern parts of northern Finland, the permanent sample plots of the 8th National Forest Inventory (NFI8) were used. For northern Finland, a special set of permanent growth plots (SINKA) was used (see Penttilä and Honkanen 1986, Mielikäinen and Gustavsen 1993).

The NFI8 plots were established in 1985 to produce information concerning changes in the Finnish forests. The remeasurement was carried out in 1990. The plot establishment is based on systematic sample tracts. Each tract contains a cluster of 3 to 4 plots, and the distance between tracts is 16 km.

The SINKA plots were established in 1984–88 in order to produce data for stand- and tree-level growth models for drained peatlands (Penttilä and Honkanen 1986). The first remeasurement was done in 1988–1994 following a period of 5 growing seasons on each plot. The plots have been sampled by stratified systematic sampling from those NFI7 plots that were located on drained peatlands. Sampling units were stands that were in satisfactory silvicultural condition (i.e., not underproductive according to the definitions given in the NFI field guide (Valtakunnan metsien... 1977)) and homogeneous with respect to site and stand developmental stage (Penttilä and Honkanen 1986). Birch-dominated stands were sampled only in the southern parts of northern Finland and spruce-dominated stands in Lapland.

The NFI8 sample plot was composed of two circular plots: a greater plot with a radius of 9.77 m and a smaller plot with a radius of 5.64 m superimposed on the greater plot. All trees with dbh exceeding 10.5 cm were measured in the area of greater radius and trees with dbh of 4.5–10.5 cm in the area of smaller radius. If the dbh

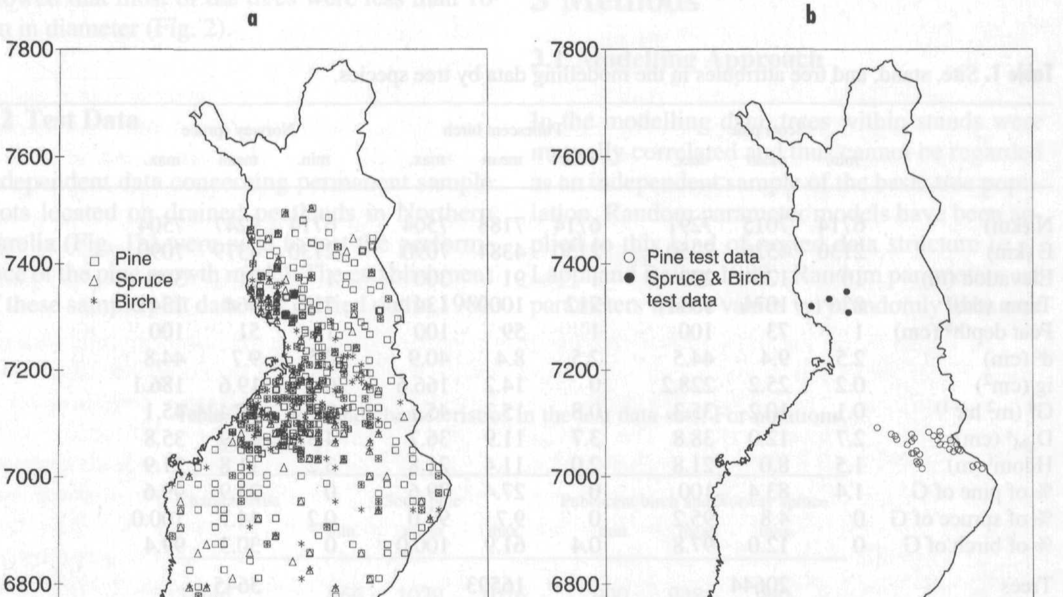

Fig. 1. Location of the modelling data (a) and test data (b) by tree species.

was less than 4.5 cm, only a limited number of selected trees were measured. The SINKA sample plot was composed of three circular subplots located 40 m apart. The size of the subplots was adjusted according to the stand density. The whole SINKA plot contained approximately 100 tally trees. The minimum diameter at breast height was 4.5 cm if the stand was past pole stage, and 2.5 cm otherwise.

Some plots were deleted from both data sets due to the following reasons. All accepted plots were classified as productive forest land and located on drained peatland. Plots where any cutting or drainage treatments had taken place during the period of 5 growing seasons were omitted. Plots including parts of more than one stand and plots with severe or complete damage were left out. Furthermore, small sapling stands or sapling stands with an overstorey were excluded. Altogether, the data sets consisted of advanced sapling stands, pole stands of non-commercial size, thinning stands and mature stands.

Several site attributes indicating the drainage condition were recorded: the phase of post-drainage succession according to Sarasto (1957), the time passed since drainage, previous ditch cleanings or complementary ditchings and their estimated dates and suggestions for improvement ditching measures. The site type classification was based on Huikari's (1952, 1974) extensive classification system. The thickness of the peat layer was measured down to 1 meter. Previous stand treatments (≤ 5 yrs) were recorded. It was not possible to detect whether fertilization treatments had been carried out.

All tally trees of which dbh was recorded on both occasions were included in the data. Sample tree data were not used because of the low number of sample trees and small area of the sample plots in the NFI8 data. For pine, spruce and birch, separate data files were formed by combining both the NFI8 data and SINKA data in such a way that a stand was included if at least one tree of the species of interest was growing in the stand. Due to the overall occurrence of different tree species on drained peatlands, the number of pine and birch stands and trees was considerably greater than that of spruce (Table

Table 1. Site, stand, and tree attributes in the modelling data by tree species.

	Scots pine			Pubescent birch			Norway spruce		
	min.	mean	max.	min.	mean	max.	min.	mean	max.
N (km)	6714	7015	7291	6714	7188	7504	6714	7247	7504
E (km)	2130	4526	7250	2130	4384	7090	2130	4379	7090
Elevation (m)	10	126	270	1	91	300	1	91	300
Tsum (dd)[a]	826	1074	1341	712	1000	1341	712	964	1341
Peat depth[b] (cm)	1	73	100	1	59	100	1	51	100
d[c] (cm)	2.5	9.4	44.5	2.5	8.4	40.9	0.5	9.7	44.8
ig (cm^2)	0.2	25.2	228.2	0	14.2	166.6	0	19.6	186.1
G[d] ($m^2\ ha^{-1}$)	0.1	10.2	35.3	0.8	15.3	45.1	0.7	15.4	45.1
D_{gM}[e] (cm)	2.7	12.0	38.8	3.7	11.9	36.7	4.3	13.9	35.8
Hdom[f] (m)	1.5	8.0	21.8	2.0	11.4	21.8	3.2	11.8	21.9
% of pine of G	1.4	83.4	100	0	27.4	99.6	0	23.9	99.6
% of spruce of G	0	4.8	95.2	0	9.7	99.0	0.2	44.7	100.0
% of birch of G	0	12.0	97.8	0.4	61.9	100.0	0	30.3	99.4
Trees		20644			16593			5645	
Stands		555			503			382	

[a] average temperature sum, degree days, with threshold value +5 °C
[b] peat depth measured up to 100 cm
[c] tree diameter at breast height
[d] stand basal area
[e] diameter of the tree of median basal area
[f] average height of 100 thickest trees per hectare

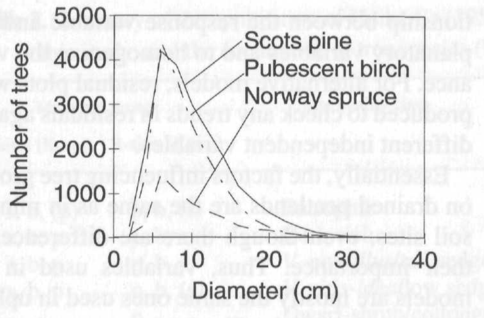

Fig. 2. Diameter distribution of the trees in the modelling data by tree species.

1). Pine stands and birch stands were most common in Ostrobothnia, while spruce stands were more evenly distributed around the country (Fig 1a).

Plotwise stand attributes at the first measurement occasion were calculated on the basis of tree tally. Means indicated that the data sets consisted of stands with low stocking (Table 1). Diameter distributions for different species showed that most of the trees were less than 10 cm in diameter (Fig. 2).

2.2 Test Data

Independent data concerning permanent sample plots located on drained peatlands in Northern Carelia (Fig. 1b) were used to test the performance of the pine growth model. The establishment of these sample plot data was carried out in 1981 following a similar procedure that was used later when the SINKA stands were established. The remeasurements were done in 1986 and 1991. Altogether, 2644 pines in 32 stands with 3 plots in each stand were used for testing. With respect to the average stand characteristics, the stands were rather similar to those in the modelling data: i.e., young stands with low stocking (Table 2).

To test the spruce and birch models, tree growth data from thinning experiments established in drained peatland stands in southern Lapland (Fig. 1b) in 1986–1991 were used. In the experiments, 3–5 different thinning treatments, including control, were arranged in a randomized block design. Two of the stands were in the phase of first commercial thinning and two in the phase of second commercial thinning. These sets of data consisted of 2640 spruces and 1857 birches in 48 plots representing four different stands (Table 2). Compared to the modelling data, these stands were, on average, more stocked.

3 Methods

3.1 Modelling Approach

In the modelling data, trees within stands were mutually correlated and thus cannot be regarded as an independent sample of the basic tree population. Random parameter models have been applied to this kind of nested data structure (e.g., Lappi and Bailey 1988). Random parameters are parameters whose values vary randomly from unit

Table 2. Mean stand characteristics in the test data sets. For notations, see Table 1.

Characteristic	Scots pine			Pubescent birch and Norway spruce		
	min.	mean	max.	min.	mean	max.
Tsum	966	1029	1076	900	948	990
G (m^2 ha^{-1})	0.7	7.6	22.3	11.3	19.1	25.8
D_{gM} (cm)	4.7	10.3	20.6	8.0	15.1	28.3
Hdom (m)	3.8	8.4	14.5	10.8	13.9	18.1
Stands		32		4		4
Trees		2644		1857		2640

to unit. In this study, between-stand differences in tree growth were accounted for by a random stand effect. This variance component model can be described by the following equation:

$$y_{ij} = b_1 x_{1ij} + b_2 x_{2ij} + \ldots + b_p x_{pij} + u_j + \varepsilon_{ij} \qquad (1)$$

where y_{ij} is the value of the response variable for the ith tree in the jth stand, $b_1, \ldots, b_p$ are fixed parameters, $x_{1ij}, x_{2ij}, \ldots, x_{pij}$ $(x_{1ij} \equiv 1)$ are the values of the explanatory variables for the ith tree in the jth stand, u_j a random stand variable (error), and ε_{ij} a random tree variable (error). All u's and ε's are assumed to be independent of each other and follow the normal distribution, with zero expectation and variances σ_u^2 and σ_e^2. The fixed part is composed of the explanatory variables $x_{1,\ldots,p}$ as well as their estimated coefficients $b_{1,\ldots,p}$. Variation not accounted for by the fixed part is expressed by the random part and decomposed between the two random parameters u_j and ε_{ij}.

In estimating the fixed and random effects, restricted maximum likelihood (REML) estimates produced by the MIXED procedure in the SAS statistical software (SAS 1992) were used. Two variance terms were estimated: the variance component σ_u of the random stand effect and the component σ_e of the random tree effect (random error). In the SINKA data set, the data structure was actually three-level (trees within plots within stands) because all stand characteristics were produced for the sub-plots. Thus, the random stand effect was a combination of plot effect and stand effect, although it will hereafter be called stand effect.

The explanatory variables in the fixed part were either measured or estimated tree, stand and site attributes. They were added to the model on the basis of several criteria. The MIXED procedure produced tests to determine whether the coefficients of the alternative explanatory variables deviated from zero as a guide for evaluation. Depending on whether the variable was explaining growth at tree level or stand level, a reduction in the variances of the random error or random stand effect was detected (see, e.g., Penner et al. 1995). The value of –2 × log-likelihood was used as an indicator of the overall goodness-of-fit measure of the nested model. Transformations were made in order to linearize the relationship between the response variable and explanatory variables and to homogenize the variance. For alternative models, residual plots were produced to check any trends in residuals against different independent variables.

Essentially, the factors influencing tree growth on drained peatlands are the same as in mineral soil sites, even though there are differences in their importance. Thus, variables used in the models are mostly the same ones used in upland site growth models. The basic assumption was that tree growth is determined by growth factors related to the quantity and quality of living tree biomass, site quality and other environmental factors, and that they all act multiplicatively (Baule 1917, Jonsson 1969). Hence, the logarithm of the basal area growth of a single tree was used as the response variable. It was chosen because it is widely used and because basal area growth models are unbiased in relation to tree volume growth. Growth was calculated as the difference between tree basal areas (cm^2) in successive measurements. Before taking logarithms, 1 cm^2 was added to the basal area growth of every tree. This was done to permit the logarithmic transformation for trees whose basal area growth was coded as 0.

At tree level, basal area growth was explained by tree diameter. Age is commonly used to characterize the phase of development of trees or stands. Due to the unstable relationship between tree age and size on drained peatlands, neither tree nor stand ages were measured in the field. Thus, tree diameter summarized both the quantity and quality of the growing biomass.

Other independent tree, stand, and site attributes were used to describe the competitive status of a tree and the average growing conditions in the stand and site.

Variables related to the drainage properties of the site are characteristic of peatland growth models. In order to indirectly assess each site's drainage condition, the site was evaluated by two dummy variables indicating whether the condition of drainage had recently been affected by any improvement ditching measures, or whether alternative improvement ditching methods needed to be carried out in the near future. In addition, the time since drainage was classified according to four categories: 0–5, 6–10, 11–25,

Table 3. Summary of the application of Huikari's (1952, 1974) classification of forested peatland site types used in this study, and the occurrence of tree species (b = birch, p = pine, s = spruce) in different sites.

Main site group		Site quality class	Code (this study)	Trophic class
K-sites (Korpi)	R-sites (Räme)			
s, b, (p)	p, b, (s)	Eutrophic	KI, RI	Eutrophic
s, b, p	p, b, s	Herb-rich	KII, RII	Mesotrophic
s, b, p	p, b, s	*V. myrtillus*/tall sedge	KIII, RIII	Oligo-mesotrophic
s, b, p	p, b, (s)	*V. vitis-idea*/low sedge	KIV, RIV	Oligotrophic
-	p	Dwarf-shrub/cottongrass	RV	Poor oligotrophic/ombrotrophic
-	p	*S. fuscum*	RVI	Ombrotrophic

and over 25 years. Using these classes, it was possible to account for the temporal trends in tree growth due to the specific growth increase pattern of trees responding to drainage.

3.2 Site Classification

The site type classification used in data collection was based on Huikari's (1952, 1974) extensive system. According to Huikari (1974), the classification reflects differences in average tree growth after drainage. Pristine peatland sites are divided into three 'main site groups' on the basis of the composition of the field vegetation species: 1. Sites dominated by *Vaccinium myrtillus*, *V. vitis-idaea* and other species which typically occur in spruce- and/or birch-dominated peatland stands (*Korpi* in Finnish); 2. Sites dominated by dwarf shrubs (*V. uliginosum*, *Ledum palustre*, *Betula nana*) and other species that are most common in pine-dominated peatland stands (*Räme*); and 3. Treeless sites (*Neva*). Based on the composition of ground vegetation, Huikari further distinguished five 'site quality classes' for the first main group and six for the others to reflect the differences in site nutrient status. The site quality classification is closely related to the more widely used trophic classification. Penttilä (1990) has proposed the correspondence of these two classifications (see also Paavilainen and Päivänen 1995). Huikari (1952) also gave supplementary definitions for a more detailed classification.

In the following, the 'main site groups' are termed K- and R-sites ('K' for *Korpi* and 'R' for *Räme*). (In NFI routines, treeless sites that have become tree-covered following drainage are included in either K- or R-sites depending on the species composition of the ground vegetation and the dominating tree species). Site quality classes are referred to by the Roman numerals I-VI. The possible combinations of the 'main site groups' and the site quality classes, as well as the occurrence of the tree species in different sites, are given in Table 3. Altogether, the total number of a priori sites was 10 (4 K-sites and 6 R-sites). When sites were reclassified during the model construction, the leading principle was to keep the number of yield classes low, because it is difficult to apply too many classes to management planning systems.

4 Results

4.1 Growth Models

At tree level, the logarithm of basal area growth was explained by tree diameter and basal area in the beginning of the growing period. For pine and birch, logarithmic transformation was made for tree diameter in order to linearize the relationship (Tables 4 and 5). For spruce, the square root of tree diameter was used (Table 6).

At tree level, between-tree competition was accounted for by the total basal area of trees larger than the target tree (BAL). For all tree species, high BAL resulted in the significantly

Table 4. Model for the basal area growth (ig, cm^2 in 5yrs) of Scots pine. For notations, see Table 1.

Response variable ln(ig + 1)

Variable		Coefficient	std. error	p-value
Intercept		−1.24500576	0.16012220	0.0000
g[a]		−0.00186652	0.00011498	0.0000
BAL[b]		−0.00891664	0.00392539	0.0231
$(\mathrm{BAL})^2$		−0.00152785	0.00014132	0.0000
ln(G)		−0.24680408	0.02625567	0.0000
$(\mathrm{Tsum} \times d^{0.5})^{0.5}$		0.06914986	0.00497900	0.0000
Site p1	(0/1)[c]	−0.61149979	0.10818864	0.0000
Site p2	(0/1)	0.30142512	0.05305042	0.0000
Site p1 × ln(d)		0.66433889	0.07410497	0.0000
p2 & 4 × ln(d)		0.31461604	0.06257624	0.0000
p3 × ln(d)		0.38896748	0.05878569	0.0000
Time (0–5 yrs since drainage)	(0/1)	−0.23774480	0.08343985	0.0044
Time (11–25 yrs)	(0/1)	0.09396252	0.02977907	0.0016
Good drainage	(0/1)	0.15556923	0.02829060	0.0000
No thinning	(0/1)	−0.12766472	0.03452112	0.0002
No *S. fuscum*/flarks	(0/1)	0.25821529	0.06924475	0.0002
Variance components				
σ_u^2		0.16889356	0.00870556	0.0000
σ_e^2		0.33184759	0.00336283	0.0000

[a] tree basal area (cm^2)
[b] total basal area of trees larger than the target tree (m^2/ha)
[c] denotes a dummy variable

lower growth of a tree. The relationship was described with a linear and quadratic component for pine and birch, while the linear component was insignificant for spruce. At stand level, a stand attribute indicating the level of stocking – stand basal area, median diameter – served as a broad measure of competition. In stands with high basal area (after logarithmic transformation), pine growth was significantly lower (Table 4). The diameter of the tree of the median basal area had a similar effect on the growth of spruce (Table 6). Neither of these indicators of competition was significant in explaining the growth of birch. For spruce, the greater proportion of spruce of the total basal area showed up as lower growth. For birch, both the proportion of birch and the proportion of spruce of the total basal area had a similar decreasing effect on growth (Tables 5 and 6).

In all models, tree growth was higher with a higher temperature sum, but for birch the linear coefficient was considerably lower than for conifers. For pine and spruce models, the temperature sum was included as an interactive effect with the square root of tree diameter. Thus, the slope of the relationship between tree growth and tree diameter varied according to the average growing conditions. The immediate proximity of sea coast as defined by Ojansuu and Henttonen (1983) significantly increased the growth of birch.

A stand-level dummy variable indicating the need for complementary ditching or ditch cleaning was included in all models. Stands with good drainage conditions had a higher level of growth. Previous ditch cleanings or complementary ditchings did not affect growth significantly. Thinning treatment during the past 5 yrs, indicated by

Table 5. Model for the basal area growth of pubescent birch. For notations, see Tables 1 and 4.

Response variable ln(ig + 1)

Variable		Coefficient	std. error	p-value
Intercept		–0.02517417	0.18499226	0.8918
g		–0.00173410	0.00015860	0.0000
BAL		–0.04153247	0.00341583	0.0000
$(BAL)^2$		–0.00028995	0.00011052	0.0087
Tsum		0.00071201	0.00018916	0.0001
G_s[a]		–0.00265387	0.00084260	0.0016
G_b[b]		–0.00421752	0.00058577	0.0000
Sea index[c]		0.00867079	0.00227142	0.0001
Site b1	(0/1)	–0.08261346	0.04883984	0.0908
Site b1 & 4 × ln(d)		1.29994635	0.02829603	0.0000
b2 × ln(d)		1.25433569	0.03089656	0.0000
b3 × ln(d)		1.33101593	0.03106435	0.0000
b5 × ln(d)		1.19105053	0.0306634	0.0000
Time (0–5 yrs since drainage)	(0/1)	–0.18653365	0.08558892	0.0293
Time (11–25)	(0/1)	0.07412365	0.03001742	0.0135
Good drainage	(0/1)	0.12915862	0.02956094	0.0000
No thinning	(0/1)	–0.21468275	0.03548466	0.0000
Variance components				
σ_u^2		0.16697506	0.00934985	0.0000
σ_e^2		0.43568523	0.00494602	0.0000

[a] proportion of spruce of total basal area (%)
[b] proportion of birch of total basal area (%)
[c] proximity of sea coast as presented in Ojansuu and Henttonen (1983)

a dummy variable, significantly increased the growth of trees of all species.

The effect of time since drainage was different for each species. Stands drained less than 6 yrs earlier had the lowest level of growth for all species (Tables 4–6). For pine and birch, the highest growth rate occurred in stands that were drained 11–25 years earlier. In age classes 6–10 years since drainage and more than 25 years since drainage, the level of growth was equal, so these classes were combined. For spruce, there were no significant differences among the other age classes (Table 6).

A dummy variable related to the supplementary definitions of the site (Huikari 1952, 1974) and indicating the significant occurrence of either *Sphagnum fuscum* hummocks or flarks or both resulted in a significantly lower growth rate for pine. Peat thickness was tested for all tree species both as a continuous variable and a dummy variable using several different threshold values, but it was not significant in any of the models.

In all models, the random stand effect was significant, indicating that the level of growth varied randomly from stand to stand. The variance of the random stand effect was greatest for spruce and lowest for pine.

4.2 Yield Classes

The yield classes were defined after the other independent variables had been included in the models. The classes were formed on the basis of the site types that were initially identified for yield classification (see Table 2). In addition, ideas proposed in recent literature concerning

Table 6. Model for the basal area growth of Norway spruce. For notations, see Tables 1, 4 and 5.

Response variable ln(ig + 1)

Variable		Coefficient	std. error	p-value
Intercept		–0.58803177	0.23238229	0.0114
g		–0.00069729	0.00018861	0.0002
$(BAL)^2$		–0.00062162	0.00007297	0.0000
$(Tsum \times d^{0.5})^{0.5}$		0.05357616	0.00735395	0.0000
D_{gM}		–0.01480889	0.00554127	0.0076
G_s		–0.00732456	0.00079733	0.0000
Site s1	(0/1)	0.14520852	0.04759067	0.0023
Site s1 & 2 × $(d)^{0.5}$		0.31576897	0.07907760	0.0001
s3 × $(d)^{0.5}$		0.21092505	0.07891453	0.0075
Time (> 5 yrs since drainage)	(0/1)	0.26072199	0.11949977	0.0292
Good drainage	(0/1)	0.13043157	0.04174418	0.0018
No thinning	(0/1)	–0.27073405	0.05129760	0.0000
Variance components				
σ_u^2		0.20301884	0.01572177	0.0000
σ_e^2		0.35791851	0.00719921	0.0000

the classification of peatland sites (Reinikainen 1988, Laine 1989, Eurola and Huttunen 1990, Eurola et al. 1995) were utilized.

Several tests with different combinations of a priori sites resulted in a system that was specific to each species. Plotting observed growth against diameter curves for each a priori site suggested that not only the intercept but also the slope of the relationship varied. Consequently, a specific yield class was distinguished if either the intercept or the slope differed significantly from the others.

For pine, four different yield classes were defined (Table 7). Yield classes p1 and p2 had a different intercept compared to the others (dummies indicated by variables site p1 and site p2 in Table 4). Different slopes were determined for yield classes p1 and p3, while yield classes p2 and p4 had equal slopes.

For birch, the K-sites were divided into two yield classes: b1 included sites KI–KII, and b2 sites KIII–KIV (Table 7). Only yield class b1 had a different intercept (dummy variable site b1 in Table 5). Classes b2, b3 and b5 all had different slopes, while the slope was equal for classes b1 and b4.

For spruce, only three yield classes (s1–s3) were formed (Table 7). For yield class s1, the intercept was higher than for s2 and s3 (Table 6). Yield class s3 had a lower slope than the others.

5 Model Validation

In the final models, there was no discernible trend between the residuals ($y - \hat{y}$, in log-scale) and tree diameter (Fig. 3) or any other independent variable. The great variation in mean residuals in the largest diameter classes (> 25 cm) was assumed to be due to the low number of observations. The bias of the models in the modelling data was estimated as the difference between the observed growth and the growth predicted by the fixed part of the models. Relative bias was estimated by dividing the absolute bias by the predicted growth. Before making the exponential transformation for the predicted growth, a variance correction term $((\sigma_u^2 + \sigma_e^2)/2)$ was added to the intercept.

The average bias for the models at the original

Table 7. Yield classes for different tree species. For initial sites, see Table 2.

Tree species	Yield class	Initial sites
Scots pine	p1	K-sites
	p2	RI–RII
	p3	RIII–RIV
	p4	RV–RVI
Pubescent birch	b1	KI–KII
	b2	KIII–KIV
	b3	RI–RII
	b4	RIII
	b5	RIV
Norway spruce	s1	KI–KII, RI–RII
	s2	KIII, RIII
	s3	KIV, RIV

Table 8. Estimated average absolute and relative bias of the models in the modelling data. Standard errors given in parentheses are biased downwards due to the correlated observations.

	Tree species		
Bias	Scots pine	Pubescent birch	Norway spruce
Absolute (cm^2/5yrs)	–1.9933 (0.0938)	–1.3053 (0.0843)	–2.1686 (0.1857)
Relative	–0.0632 (0.0042)	–0.0591 (0.0207)	–0.0854 (0.0080)

scale of growth was –1.99, –1.31, and –2.17 cm^2/5 yrs for pine, birch and spruce, respectively (Table 8). For pine, there was virtually no trend in bias as a function of tree diameter. For birch, the bias showed a slight negative trend as tree diameter exceeded 15 cm (Fig. 4). For spruce, this trend was even more evident. On the average, the bias was lower when the constant variance correction was applied than in the noncorrected predictions. Overall, the models produced slight overestimates of growth in the modelling data. Due to the unsatisfactory performance of the constant correction term, an alternative procedure was tried in an effort to reduce the bias. First, the noncorrected predictions were estimated as a function of tree diameter in the modelling data. Then, the estimated bias was corrected to zero with a correction term which was calculated for each 2-cm diameter class for all models as follows:

$$Mean\ \exp(y) = c \times Mean\ \exp(\hat{y}) \qquad (2)$$

To test the pine model in an independent data set, a new version was estimated, where the time

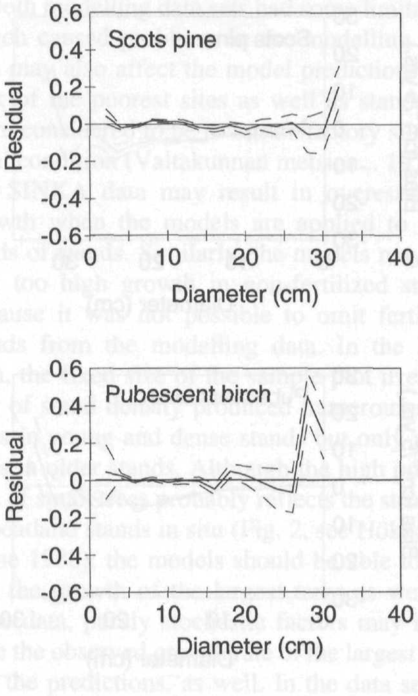

Fig. 3. Mean residuals (in log-scale) of the models as a function of tree diameter (dashed lines indicate the standard error of the mean).

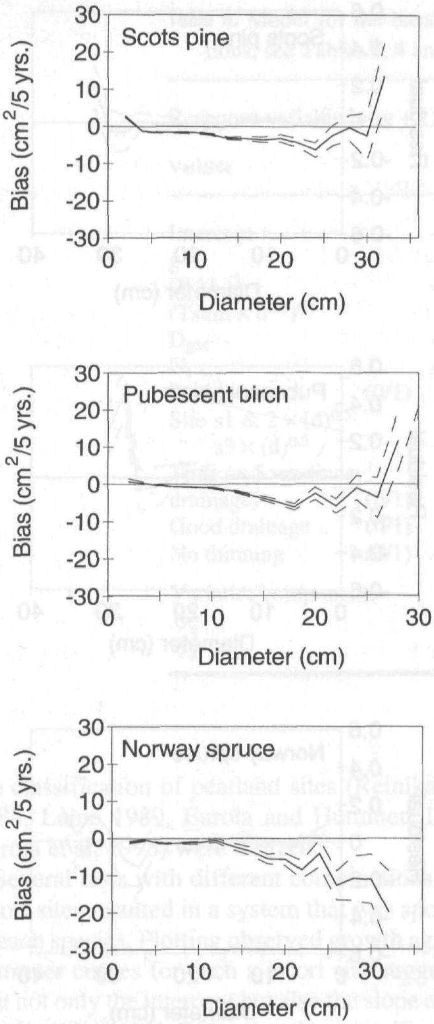

Fig. 4. Estimated mean bias of the models as a function of tree diameter in the modelling data (dashed lines indicate the standard error of the mean).

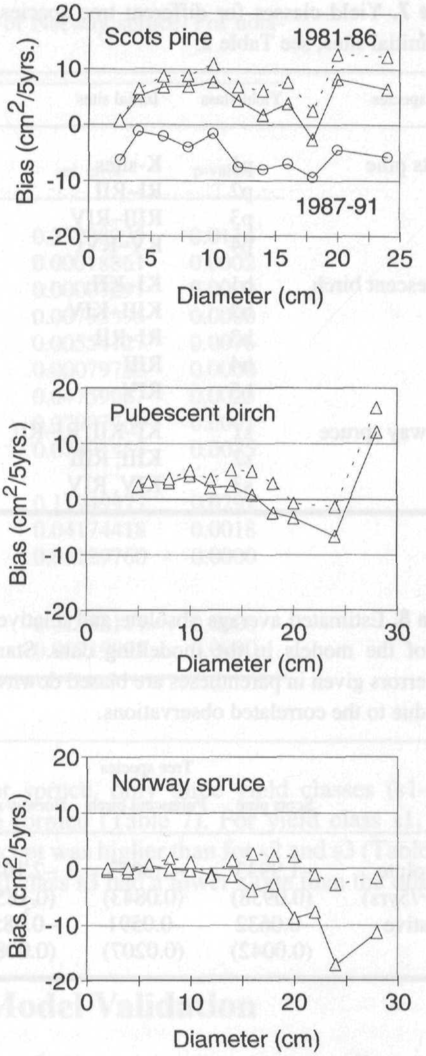

Fig. 5. Estimated mean bias of the models as a function of tree diameter in the independent test data sets using constant variance correction (solid lines) or a correction term for each 2-cm diameter class (see Eq 2, dashed lines). For Scots pine, bias was estimated for two successive 5 yr. periods.

since drainage was excluded because it was not known for the test data. Using tree, stand and site attributes recorded at the time of plot establishment in 1981, basal area growth for the following two growth periods (1–5, 6–10 yrs) was predicted. Bias (with a constant correction term) was estimated for both periods and was expressed as a function of the initial diameter. The average bias in the test data was positive for the first period and negative for the second period (5.766 and –4.216 cm^2/5yrs with standard errors of 0.324 and 0.299, respectively). No trend in bias as a function of tree diameter was detected (Fig. 5). For the first growth period, diameter-dependent correction was also tested. The result was slightly lower estimates of growth, which was practically the only difference between the two models, because neither showed clear bias as a function of tree diameter. The positive bias (underestimated growth) in the first period may be explained by the large proportion of fertilized plots in the test data. Consequently, the levelling out of the fertilization effect together with the regressive development of drainage conditions in several stands may explain the negative bias in the second period.

Models for birch and spruce were used in a similar manner to predict growth in the test data. The average bias in basal area growth for birch was 1.79 cm^2/5 yrs (s.e. 0.361), and –2.72 cm^2/5 yrs (s.e. 0.385) for spruce. When expressed as a function of tree diameter, the birch model produced both under- and overestimates of growth (Fig. 5). The spruce model was almost unbiased up to 15 cm, but produced overestimates for the larger trees. Using diameter-dependent correction for birch and spruce improved the predictions in this respect. The trend in mean bias as diameter increased became slightly smaller for birch and was completely removed for spruce. However, one should be careful when interpreting the results, because the test data are actually composed of two good-growing young stands and two older stands with lower growth rates.

6 Discussion

Models constructed to predict tree growth in growth simulators should give reliable forecasts of stand development in the future. Thus, the main emphasis in this study was to develop logical and simple models based on a large objective random sample of trees and stands. Compared to the earlier growth models for trees growing on drained peatlands, the new models are expected to produce more accurate growth predictions, because they account for, e.g., inter-tree competition more explicitly. Furthermore, specific models for birch are now availabe (c.f. Ojansuu et al. 1991).

Both modelling data sets had some limitations which caused problems in the modelling work and may also affect the model predictions. The lack of the poorest sites as well as stands that were considered to be in unsatisfactory silvicultural condition (Valtakunnan metsien... 1977) in the SINKA data may result in overestimated growth when the models are applied to these kinds of stands. Similarly, the models may predict too high growth in non-fertilized stands, because it was not possible to omit fertilized stands from the modelling data. In the NFI8 data, the fixed size of the sample plot irrespective of stand density produced numerous small trees in young and dense stands but only a few trees in older stands. Although the high proportion of small trees probably reflects the structure of peatland stands in situ (Fig. 2, see Hökkä and Laine 1988), the models should be able to predict the growth of the largest trees as well. In these data, purely stochastic factors may influence the observed growth rate of the largest trees and the predictions, as well. In the data sets of pine, birch and spruce, 96, 98, and 94 % of the trees were under 21 cm in diameter, respectively. In estimating the models, the shape of the growth curve is determined mainly by the small trees within a narrow diameter range, and the models may be biased for the larger trees.

One possibility to reduce the trend in bias could be to express the tree-level variance as a function of tree diameter instead of using a constant value. Furthermore, the constant correction term is improper, if the assumption of normally distributed errors is violated, which may be the case here. In general, the residual variances were fairly large, which resulted in large correction terms for the exponential transformation. With a smaller correction, less biased predictions could be obtained especially for pine and birch. The estimated biases in both modelling data and test data suggested that predictions given by the spruce model should be corrected by diameter classes in order to avoid negatively biased (too high) growth predictions for trees greater than 15 cm in diameter.

The nested data structure was accounted for in the model construction by the mixed linear model technique. By separating tree, plot and stand levels, unbiased tests for the independent variables were produced. The models have the standard advantages of random parameter models. If any measurements of the response variable are available, the models can be calibrated into specific stands and more accurate predictions can be obtained (Lappi and Bailey 1988).

Relatively high residual variances suggested that additional tree-level explanatory variables could be considered. It is obvious that the growth potential of a tree is not fully indicated by the diameter, because the correlation between tree age and size in drained peatlands is complicated by the interrelationship between the initial size of the tree and its response to drainage. However, age characteristics have been shown to correlate with the post-drainage growth rate of trees (Seppälä 1969, 1976, Hånell 1988, Miina 1994). For birch, the biological age could be used in models, because birch trees usually initiate after drainage. For conifers, Huikari et al. (1967) used the so-called 'economical age', which was determined as a function of tree diameter at the time of drainage and its post-drainage growth rate. In addition to the variables that were related to competition, the growth potential of a tree could be better evaluated if a variable indicating the amount of living crown were available (Hynynen 1995a).

The observed nonlinear effect of BAL on growth may be explained by the uneven size-distribution of trees in drained peatland stands (Hökkä and Laine 1988, Hökkä et al. 1991). The low values of BAL in uneven-sized stands result from the biggest trees, which occur one by one with a low total number per hectar. These do not compose a uniform canopy layer, which could affect the growth of smaller trees considerably. As BAL increases, an increasing number of trees form a more even canopy layer, and the decreasing effect on growth becomes more apparent. The results showed that in well-stocked stands stand-level competition (as indicated by high basal area or D_{gM}) limits the growth of pine and spruce. Increasing site occupancy appeared not to limit the individual tree growth of birch probably because the birch data were most concentrated in small trees and stands with low stocking.

When the models are applied in growth simulators, specific self-thinning models are needed to prevent unrealistic development of stocking (see Hynynen 1993). In drained peatlands, the pattern of self-thinning may differ from that observed in mineral soil stands because the size and spatial distribution of trees is uneven and the factors limiting tree growth are partly different from those on mineral soils (Hökkä et al. 1996, Penner et al. 1995).

According to Seppälä (1969), the development of diameter growth of spruce and pine as a function of time since drainage can be described by nonlinear curves which have a phase of growth increase, a peak point and a phase of growth decline. Applying a continuous nonlinear function for the relationship in these data would have required accurate determination of the year of drainage. Since this was not possible for all the data, drainage age classes were used. This may have resulted in underestimating the growth rates during the period 11–15 yrs after drainage, because the peak of the growth response generally occurs at that time (Seppälä 1969, Miina 1994). In the models for pine and birch, the temporal growth trend was described by three drainage age classes with different growth levels. For spruce, there were similar kinds of differences between the age classes, but only those stands that had been drained less than 6 yrs earlier had a significantly lower level of growth. This may be due to insufficient data.

As Heikurainen and Kuusela (1962) and Seppälä (1969) have shown, the growth response to drainage varies according to tree size and age, site quality, and geographical location. In the models constructed in this study, complicated interactive effects were not included because simple formulations were expected to result in more realistic and stable models. Furthermore, the cross-sectional data did not support the determination of causal relationships over time. The stands were mostly concentrated in age class 11–25 yrs since drainage. The structure and quality of stands drained in the 1980s and 1950s may differ considerably, because generally the best stands tend to become drained first. Furthermore, ditching technique has changed considerably since the 1950s. Thus, the interactions might have led to erroneous interpretations. Dummy variables indicating previous thinning treatments and the condition of drainage may also include components that are not related to thinning response or to the water regime of the site. One may suspect that the higher growth rate in thinned stands comes partly from the fact that thinnings had been carried out in stands that naturally grow better. Similarly, the best sites and well-growing stands may have drainage networks in good condition.

A variable indicating the need for complementary ditching makes it possible to adjust growth predictions according to the current drainage condition of the site. However, it may cause problems in long-term simulations because its application in the future need to be predicted somehow. This could be overcome, e.g., by constructing a probabilistic model to predict when this variable should be taken into use.

The development of 3–5 yield classes by species was basically a reclassification of the a priori K- and R-sites of different site quality (Huikari 1952) according to the observed differences and similarities in tree growth. Evaluating sites in terms of productivity is one purpose of site type classification. To develop a comprehensive site type classification system for drained peatlands, other aspects should be included as well. However, if sites are classified in practice according to Huikari (1952), the corresponding yield class can be determined and used in model applications.

The yield classes for pine (p1–p4) and birch (b1–b5) were rather similar with respect to the initial sites that were included in each yield class. For these species, K-sites (yield classes p1 and b1–b2) differed significantly from R-sites. Yield classes p2 and b3 included a homogeneous group of originally treeless or sparsely forested composite mire sites RI–RII with high timber production potential when drained. Sites RIII and RIV are of medium productivity and formed one yield class for pine (p3) and two for birch (b4, b5). Sites RV and RVI are poor pine-growing sites giving only a modest growth response to drainage. For spruce, the 'site quality classes' (trophic levels) reflected differences in growth, and no significant difference was observed between K-sites and R-sites.

Evaluating the relevance of the yield classes to the recent discussion on the classification of drained peatlands is difficult, because tree species have not been considered in other proposals. Eurola and Huttunen (1990) and Eurola et al. (1995) have emphasized the need to distinguish spruce-birch mires which correspond to the K-sites. Laine (1989) has emphasized the differences between forested and initially sparsely forested composite types and differences in site nutrition among the seven peatland forest types. The initial K-sites and the three spruce yield classes cover three of Laine's (1989) peatland forest types. Only one pine (p1) and two birch yield classes (b1, b2) were separated from the initial K-sites in this study. The *Vaccinium myrtillus* type II and *V. vitis-idaea* type II, as defined by Laine (1989), correspond quite closely to sites RI–RII and RIII–RIV, respectively, which were included in this study as yield classes p2 and p3 for pine and b3–b5 for birch. Laine's (1989) dwarf shrub type and *Cladina* type correspond to sites RV and RVI, which formed the poorest yield class site for pine (p4).

Because the effect of thinning treatment and stand drainage condition was included through simple dummy variables, there remains a need to develop separate models to describe the temporal thinning response (e.g., Hynynen 1995b) as well as the response to ditch network maintenance in drained peatland stands. Both measures are common practices in the management of drained peatlands and have a considerable impact on further stand development.

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