Models for predicting growth and yield in drained peatland stands in Finland

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MODELS FOR PREDICTING GROWTH AND YIELD IN DRAINED PEATLAND STANDS IN FINLAND

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Academic dissertation

To be presented, with the permission of the Faculty of Agriculture and Forestry of the University of Helsinki, for public criticism in Auditorium M II, Metsätalo, Unionikatu 40 B, Helsinki, on 24 October 1997, at 12 o'clock noon.

Distant-independent individual-tree models were constructed to predict tree basal area growth and tree height for Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst.), and pubescent birch (*Betula pubescens* Ehrh.) growing on drained peatlands. Forest inventory sample plots were used as the data. Variation in tree growth and height was explained by stand, site and tree attributes. Yield classes reflecting differences in growth were defined by species on the basis of *a priori* site types. Separate models were developed for predicting the growth response of Scots pine to different ditch network maintenance methods with a data set collected from experimental stands. The mixed linear models technique was applied in model estimation in order to account for the spatial correlations of the observations in the data sets. The models were applied to a growth simulator to predict the future forest development on drained peatlands. Examples of stand simulations with varying stand and site conditions were given for both the drainage of a pristine peatland and for improvement ditching.

Preface

This study was carried out at the Rovaniemi Research Station of the Finnish Forest Research Institute, which I wish to thank for providing me with excellent working facilities. The idea of this study originated in the need to further develop the peatland growth models of the MELA system, which, when taken into practice, led me into the interesting world of growth modelling.

I am most grateful to Dr. Juha Lappi for his patient and encouraging guidance throughout. I thank Ms. Virpi Alenius (M.Sc.), Dr. Jari Hynynen, Dr. Risto Ojansuu, and Mr. Hannu Salminen (M.Sc.) for inspiring discussions and methodological advice which I received. I wish to thank Professor Juhani Päivänen for his valuable support in the final stages, as well as for his comments on the manuscripts. I am also grateful to Mr. Timo Penttilä (M.Sc.) and Dr. Martti Varmola for their support and comments on my work. I acknowledge Professor Kari Mielikäinen and Assistant Professor Björn Hånell for revising the thesis.

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Finally, I thank my wife Pirkko and my daughters Eeva and Katri for the patience and understanding they have shown especially during the past year. I dedicate my thesis to them.

Rovaniemi, September 1997

Hannu Hökkä

Contents

List of original papers

The thesis is based on the following original papers, referred to according to their Roman numerals:

I   Hökkä, H., Alenius, V, and Penttilä, T. 1997. Individual-tree basal area growth models for Scots pine, pubescent birch and Norway spruce on drained peatlands in Finland. Silva Fennica 31(2): 161-178.
II   Hökkä, H. 1997. Height-diameter curves with random intercepts and slopes for trees growing on drained peatlands. Forest Ecology and Management. (Accepted).
III Hökkä, H. 1997. Predicting the initial growth response of Scots pine to ditch network maintenance with an individual-tree diameter growth model. (Submitted to Canadian Journal of Forest Research)

List of symbols

BAL   basal area of trees larger than the target tree, m^2ha^{-1}
dd   average temperature sum, degree days ($>+5°C$)
d   tree diameter, cm
D   stand arithmetic mean diameter, cm
D_{gM} diameter of the tree of median basal area, cm
G   stand basal area, m^2ha^{-1}
h   tree height, m
H   stand arithmetic mean height, m
N   number of stems, ha^{-1}
v   tree volume, m^3
V   stand volume, m^3ha^{-1}

Definitions

Birch means pubescent birch, *Betula pubescens* Ehrh.

Complementary ditching means an improvement ditching method in which new ditches are dug between the old ditches

Ditch cleaning means an improvement ditching method in which old ditches are deepened to their original depths

Drainage age of a drained peatland site means the time (in years) elapsed since the drainage of the site

Forest land means forest sites which are capable of supporting 1 m^3ha^{-1} average annual growth of stands in a 100-year rotation period

Improvement ditching means all actions taken to improve the impaired water regime in previously drained peatlands; also called *ditch network maintenance*

Main site type means either spruce mire or pine mire according to Huikari's (1952, 1974) definitions

Pine means Scots pine, *Pinus sylvestris* L.

Pristine peatland is a peatland that has not been drained

Pine mire means sites dominated by dwarf shrubs (*Vaccinium uliginosum, Ledum palustre, Betula nana*) and other species that are most common in pine-dominated peatland stands (*Räme* in Finnish)

Site quality class refers to Huikari's (1952, 1974) six classes for site fertility

Spruce means Norway spruce, *Picea abies* (L.) Karst.

Spruce mire means peatland 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)

Stand characteristics refers to attributes such as mean diameter or basal area calculated plotwise on the basis of tree measurements in the plot

1. Introduction

11. Peatland forestry in Finland

Forested peatlands occupy large land areas in the boreal regions and thus form a considerable timber resource (Jeglum et al. 1983, Päivänen 1997). However, the inherent timber production capability of peatland sites is poor compared to mineral soil sites because it is limited by the excess water in the soil. In more southern regions as well, poor drainage of mineral soil and organic sites may limit the growth of stands (Allen and Campbell 1988). Using proper management practices, the water regime can be made more favorable for trees, and the timber production potential of peatland sites can be increased.

In Scandinavia, the Baltic countries, and Russia forest drainage has been widely applied to forested peatlands and to some extent to treeless peatlands in order to increase tree growth (Päivänen 1997). In Finland, this has been a successful means of increasing the total timber resources in the country (Päivänen 1997). A total area of 6 mill. ha of peatlands and paludified mineral soils had been drained for forestry purposes by 1992 (Aarne 1993). In the beginning of the 1980s, peatland stands (drained and undrained combined) comprised 18 % and 22 % of the total volume and growth of all forests, respectively (Paavilainen and Tiihonen 1987). In Sweden, for example, the corresponding proportion of growth was 17 % and the area drained was 1.5 mill. ha of the total of 10 mill. ha of shallow and deep peatlands (Hånell 1990). Almost all peatland forestry in Finland is concentrated on drained sites; undrained peatlands have only a marginal role. The opposite is the case in, e.g., Canada and the northern parts of the USA, where undrained peatland stands are commonly managed by cuttings but without any drainage treatments (Jeglum et al. 1983).

Following drainage, the management practices applied to peatland and mineral soil sites are fairly similar in Finland. Both precommercial and commercial thinnings are carried out to minimize self-thinning and select the crop trees before the final cutting. Site water and nutrient regimes are important factors influencing tree growth in drained peatlands, because the storages of potassium and phosphorus in peat are low (Paarlahti et al. 1971, Kaunisto and Paavilainen 1988, Laiho 1997), and impaired drainage may lead to re-paludification of the site. By affecting these factors, management treatments may influence tree growth on peatlands directly or indirectly. In operational forest management, fertilization has been a common management practice on peatlands, and the maintenance of ditch network systems has been substituted for the drainage of pristine peatlands. It is recommended that ditch network maintenance be carried out immediately after commercial thinning in order to compensate for the rise in groundwater table level and to avoid permanent damage to the ditches.

Because most of the Finnish drainage work took place during the 1960s and 1970s, the trees in the stands are achieving or have just achieved the minimum commercial size. This is generally the phase of highest growth rate and the time for the first commercial thinning and repairing of the ditch network. The information needs in practical forestry reflect this situation. Proper management of thinning stands presumes specific management schedules; accurate predictions concerning the further development of present stands in long-term forest scenarios are needed, and the basis for the selection of stands for ditch network maintenance treatment should be identified. In Sweden, forest drainage has been

done less intensively since the 1930s, and more than half of the total volume is in mature stands at present (Hånell 1985). Accordingly, methods of regeneration of high-productive peatland stands have been the main focus in recent Swedish studies (Hånell 1991, 1993). In Canada and the northern USA, research has been focused on the development and management of undrained peatland stands (e.g., Haavisto et al. 1988).

12. Earlier growth and yield studies on drained peatlands

Drainage of a peatland changes the whole ecosystem in several respects. Because of this, growth studies have had varying aims and approaches. In addition to tree- and stand-level analyses, attention has also been paid to temporal growth dynamics. Generally, the magnitude of the response and the effect of different factors on the response has been studied from the very beginning. According to Tanttu (1915), assessments of tree growth response to drainage were made in Russia as early as the 1890s. Even though the results were more or less descriptive, it was concluded that site quality, distance to the ditch, peat thickness, and tree size influenced the response of a tree to drainage.

Later, more accurate tree analyses were done to determine the pre- and post-drainage development of selected sample trees (e.g., Multamäki 1923). At stand level, Lukkala (1929) compared the periodic growth of stands before and after drainage on the basis of the reconstructed stand development of sample plots established in the Jaakkoinsuo area. Stand volume growth was shown to increase considerably after drainage. In Sweden, Malmström (1928) used information on site hydrology and ground vegetation to explain variation in the productivity of different sites in Degerö Stormyr.

In Finland, estimates of the post-drainage timber productivity of peatland sites were given by Heikurainen (1959). Site quality indices ranging from 0 to 10 were derived for peatland site types on the basis of the average relative growth rate of stands (5-yr growth expressed as a function of the current stand volume) and their geographical location. The index was a rough estimate of the average post-drainage volume growth and served as a tool for rating peatland sites in terms of timber productivity in practical forest drainage work. The relative growth rate of stands has commonly been used as a basis when different site types have been compared in several Finnish studies thereafter (e.g., Seppälä 1969, Heikurainen and Seppälä 1973, Laine and Starr 1979, Keltikangas et al. 1986, Penttilä 1990). Keltikangas et al. (1986) also investigated the stability of the relative growth rate as a function of time since drainage by comparing the growth of stands drained in various decades.

Seppälä (1969, 1976) made a detailed tree-level study of the response of pine and spruce to drainage. The effects of tree species, tree age, site quality, and time on the growth response were demonstrated in tabular and graphic form. Pine was shown to respond immediately to drainage, while spruce needed several years before responding. For both species, the youngest trees in the most fertile sites showed the fastest and highest response.

Heikurainen and Kuusela (1962) applied regression analysis when the effect of drainage on the height growth of the sample tree data of Heikurainen (1959) was studied. It was shown that the shortest and youngest trees responded most to drainage. Huikari et al.

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(1967) constructed regression models to predict the stand volume growth from the site type, stand volume, stand age, species mixture, and geographical location with data collected from northern Finland. Because the best stands were selected, the equations cannot be generally applied to predict growth on drained peatlands.

In Canada, Payandeh (1973) used multiple regression analysis in evaluating the effect of drainage on black spruce (*Picea mariana* (Mill.) B.S.P.) stands drained 40 years earlier. At tree level, growth equations were derived for the annual diameter and height growth both before and after drainage. At stand level, equations were derived for the average annual growth percentage of diameter, height, basal area, and volume. Growth was expressed as a function of several tree, stand and site characteristics. It was concluded that young trees with large initial diameter and large crowns growing on better sites, and young stands with low initial stocking growing on better sites responded most. At tree level, the length of the growth response period of black spruce has been studied by Dang and Lieffers (1989).

In the southeastern USA, the effect of drainage on the growth of loblolly pine (*Pinus taeda* L.) on poorly drained mineral soils and wetlands has been assessed as a change in the site index following the drainage (e.g., Klawitter and Young 1965, Terry and Hughes 1975).

Saramäki (1977) derived regression equations for birch growing in drained peatland sites in northern Finland to predict the height, basal area, and volume growth percentage of individual trees based on tree age, size, vigour, and competion. At stand level, the volume and basal area growth percentage of stands was predicted by stand age, stand volume, dominant height, and the average length of the growing season. Stand-level equations were then applied to construct yield tables for birch. Thinning models for the same species were later developed by Niemistö (1991) on the basis of stand-level regression equations derived from thinning experiment data.

Hånell (1984, 1988) made a comprehensive growth study of drained peatlands in Sweden. Numerous tree- and stand-level regression equations were constructed to predict the post-drainage development of pine, spruce and birch. The analysis was based on increment core data collected from old drainage areas. Stand-level equations were derived and used in a growth simulator to determine the post-drainage yield in different sites when the composition of tree species and geographical location varied. A classification scheme for undrained sites was defined on the basis of the expectable yield after drainage.

Miina et al. (1991) and Miina (1994) developed spatial individual-tree growth models for pine growing on a drained poor peatland. Competition indices were used together with tree and stand characteristics to describe the growth of the target tree. Simultaneously, using the distance to the nearest ditch as an independent variable, the variation in growth caused by the ditch openings, as well as that caused by the varying depth of the ground water table level, was accounted for (Miina 1994, Miina and Pukkala 1995). The models were used to study the effect of different thinning methods and clustering of trees on stand volume growth, and to develop optimal thinning schedules for pine stands in drained peatlands (Miina 1996a, 1996b). Penner et al. (1995) studied the effect of competition, as indicated by stand basal area and different competition indices, on single tree growth of pine with a spatial growth model.

13. Aims of the study

Several growth studies conducted in drained peatlands in Finland have produced valuable information on tree growth and its dependence on different growth factors. However, they have been somewhat scattered and have not given conclusive results for the whole country and for all the relevant tree species: i.e., pine, spruce, and birch.

In Finland drained peatlands form a remarkable timber resource which is under intensive utilization and management in practical forestry. This resource can be used on a sustainable basis only when management planning and decision making are based on reliable information about the present status of the forests and forecasts concerning future timber resources. Growth models are generally used as tools to forecast future forest resources in growth simulators such as MELA (Siitonen et al. 1996). In general, growth models should give unbiased and reasonable predictions concerning stand development on the basis of various input data, and they should be applicable to the management planning system. In drained peatland forests, valid forecasts presume that simulators are using models that are specifically derived for drained peatlands. Previously, the MELA growth simulator has used specific models for drained peatlands, but only a few properties of drained peatland stands and sites have been accounted for (Ojansuu et al. 1991).

The aims of this study were: to develop a new set of individual-tree growth models to describe the effect of different growth factors, as well as stand and site management, on the growth of pine, spruce, and birch in drained peatland sites with commonly measured site, stand, and tree attributes (study I), and to specifically quantify the growth response of pine to different ditch network maintenance methods, and to construct a model for simulator use (study III). To give a reliable basis for tree volume calculations, height-diameter models had to be developed for the same species (study II). This approach will allow the models to serve as the basis in growth simulators when growth forecasts of the most common tree species in drained peatland stands are made.

2. Materials and methods

21. Basal area growth models and height-diameter models

The data for the basal area growth models (I) and for the height-diameter models (II) consisted of two 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 north Finland, the permanent sample plots of the 8th National Forest Inventory (NFI8) were used. For northern Finland, permanent growth plots (SINKA) were used (see Penttilä and Honkanen 1986, Mielikäinen and Gustavsen 1993). Due to the more intensive sample in the SINKA data, the northern parts of Finland were more represented.

a)

  Pine
  Spruce
  Birch

b)

  Pine test data
  Spruce & Birch
  test data
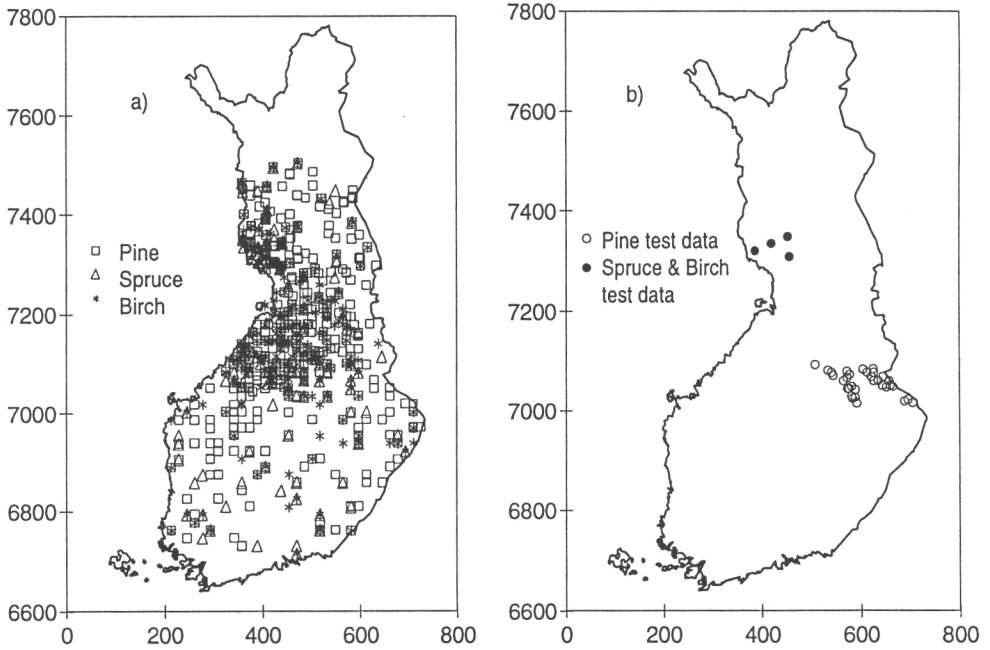
Figure 1.(a-c). Location of the data used in studies I-III.

c)

The NFI8 plots were established in 1985, and a remeasurement was carried out in 1990. The plot establishment was based on systematic sample tracts. Each tract contained a cluster of 3 to 4 plots, the distance between tracts being 16 km. The NFI8 sample plots were 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 diameter exceeding 10.5 cm were measured in the area of greater radius, and trees with diameter of 4.5 - 10.5 cm in the area of smaller radius. If the diameter was less than 4.5 cm, only a limited number of selected trees were measured.

The SINKA plots were established in 1984 - 88 (Penttilä and Honkanen 1986) for the purpose of studying the growth of peatland forests. The first remeasurement was done in 1988 - 1994 following a period of 5 growing seasons on each plot. The plots were sampled by stratified systematic sampling from those 7th National Forest Inventory

sample plots that were located on drained peatlands. Sampling units were stands that were considered to be in satisfactory silvicultural condition and homogeneous with respect to site and stand developmental stage. Birch-dominated stands were sampled only from the southern part of northern Finland and spruce-dominated stands from northern Finland. 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 age, and 2.5 cm otherwise.

The NFI8 data and the SINKA data were combined to form one data set for each tree species. All tally trees the diameter of which was recorded in both measurements were used as the basal area growth model data (I). Sample tree data were not used because of the low number of sample trees and small area of sample plots in the NFI8 data. For the height-diameter models (II), only sample tree data were used because both diameter and height measurements were needed. From the SINKA data, only one sample plot out of three from each stand was chosen, in order to give more emphasis to the NFI8 data. Considerably smaller data sets were thus available for the height-diameter models than for the basal area growth models.

The number of pine and birch stands and trees was considerably greater than that of spruce (Table 1) in both modelling data (I, II). The data sets for both the basal area growth models (I) and height-diameter models (II) consisted of advanced sapling stands, pole stands of non-commercial size, thinning stands and mature stands, all located on drained peatland sites that were classified as forest land. On the basis of the measurements in the field, stand characteristics were calculated for each plot. The means showed that the data sets mainly originated from stands with low stocking (Table 2).

Table 1. Number of stands and trees in different data sets by species   (P = pine, B = birch, S = spruce).

| Study | | Species | | |
		P	S	B
I	Stands	555	382	503
	Trees	20644	5645	16593
Test data	Stands	32	4	4
	Trees	2644	2640	1857
II	Stands	458	131	279
	Trees	3450	769	2133
III	Stands	9		
	Trees	1995		

Table 2. Mean tree, stand and site characteristics in different studies, by tree species (for notations, see Table 1).

| Study | Species | Stand characteristics | | | |
		d	G	D_{gM}	dd
I	P	9.4	10.2	12.0	1074
	S	9.7	15.4	13.9	964
	B	8.4	15.3	11.9	1000
Test data	P	7.6	7.6	10.3	1029
	B/S	11.8/13.3	19.1	15.1	948
II	P	11.2	11.8	11.9	1004
	S	11.8	17.1	14.9	1015
	B	10.4	15.4	12.2	1017
III	P	10.8	8.9	11.2	1045

22. Test data for basal area growth models

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 sample plots were laid out in 1981 following a procedure similar to that used later when the SINKA stands were set up. The remeasurements were done in 1986 and 1991. Altogether, 2644 pines in 32 stands with 3 plots in each stand were included in the data. With respect to the average stand characteristics, the stands were rather similar to those in the modelling data (Table 2).

To test the spruce and birch models, the data from four thinning experiments established in 1986 - 1991 in mixed stands of spruce and birch on drained peatlands in northern Finland were used (Fig. 1b). In the experiments, 3 - 5 different thinning treatments, including a 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. The total number of plots was 48. Compared to the modelling data, these stands were more stocked (Table 2).

23. Growth model for improvement ditching

The data used in constructing the growth model for improvement ditching consisted of nine field experiments that were set up in 1982 - 85 in drained poor pine mires considered to be in need of improvement ditching (Fig. 1c, Table 1). The experimental design included the following treatments: ditch cleaning, complementary ditching, a combination of ditch cleaning and complementary ditching, and untreated control (Ahti and Päivänen 1997). The number of replicates varied in the different experiments from one to five. Within each experiment, permanent sample plots representing different treatments were delimited from ditch to ditch.

In each plot, 20 - 25 trees belonging mostly to the dominant canopy layer were cored and calipered in 1989 or 1990 in order to determine the annual growth rates. At the time of the core sampling, the age of treatment varied between 5 and 8 years. The annual diameter growth of the sample trees within a 13-year period (5 years prior to and 8 years after the treatment) or an 8-year period after the treatment were used in the growth response analysis. As in studies I and II, the stands were understocked and characterized by small average size of trees at the time of the set up of the experiments (Table 2).

24. Approach and assumptions

241. Growth models

Several factors related to site conditions, tree vigor, inter-tree competition, stand management, and annual climatic variation influence the growth of a tree in a stand. Common tree, stand, and site attributes, such as tree diameter, stand basal area, and site quality classes, have been used to describe the effect of these factors on tree growth in growth models (Vanclay 1994). Excluding the drainage treatment to which the site is subjected, the factors influencing tree growth in drained peatlands and in mineral soil sites are essentially the same. It can be assumed that in drained peatlands, the 'site factor' includes two components: nutrition, which is more or less constant over time (or changes take place slowly), and moisture, which is expected to cause temporal variation in growth due to the ditching treatment.

The factors affecting tree growth on drained peatlands can thus be grouped as follows: those determining the basic level of growth of stands and trees, and those that are related to the growth response to the treatment. When constructing the models, both of these aspects can be accounted for by deriving a basic growth equation and by adding a description of the growth response to the treatment.

In studies I and III, basic growth models were constructed, in which different growth factors, as indicated by various stand, plot and tree attributes, were assumed to influence growth in a multiplicative manner (Jonsson 1969). The models were linearized with a logarithmic transformation. At plot level, tree growth was expressed as a function of the tree's diameter, and this relationship was allowed to vary randomly from plot to plot in terms of the intercept and slope. Variation in intercept and slope was modelled by assuming these parameters to be composed of a fixed mean function and random plot effects with mean zero and constant variance. The mean was expressed as a function of stand and site characteristics (stand characteristics were calculated for each plot). Thus, differences in both the growth rate and pattern in relation to tree diameter were accounted for.

The random parameter model approach (Lappi 1986) was used in model construction in order to account for the correlations that arose from the hierarchically structured data. It also made it possible to study the decomposition of the residual variance at different levels of hierarchy. In study I, tree and plot levels were distinguished, while in study III, four hierarchical levels - stand, plot, tree, and the successive growths of the same tree - were distinguished.

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Since the growth response of a tree is a change in growth over time, detailed modelling of the response was limited by the data available. In study I, the temporal dimension was obtained from stands of varying drainage ages; i.e., no information on tree-level response was available. Thus, the growth response was defined at stand level as a change in site productivity and was expressed as a function of time. The use of cross-sectional data to determine changes over time in the basal area growth models (I) was based on the assumption that, on the average, stands follow a similar pattern in their post-drainage development. Thus, recently drained stands represented the immediate growth dynamics after drainage, and the same pattern of growth was assumed to have taken place in areas drained much earlier. However, this assumption may not be valid in all respects because the sample was concentrated in areas drained 10 - 20 years ago, while stands with higher or lower drainage ages were not as well represented. It was further assumed that annual climatic variation did not influence growth significantly, because the five successive growing seasons between the measurements varied from stand to stand; in all, 10 different growing seasons were represented in the data.

In study III, the actual time series of the annual diameter growth of sample trees permitted detailed modelling of the growth response. This presupposed that annual climatic variation, as well as local differences in climate, were accounted for in the model.

Factors affecting growth were grouped according to their contribution to the basic growth or to the growth response (Section 3). Within these groups, factors related to site, and those related to tree vigor and competition, were further distinguished. Site factors caused variation among stands (and plots), and tree vigour influenced tree growth within a stand. Competition may exist at both levels.

242. Height-diameter models

To provide a basis for tree volume calculations in growth simulators, either height growth models or static height models were needed. Since height growth data for the whole country were not available, height-diameter models were constructed for each species. Because of the great variability of peatland stands and the considerable change in stand structure following drainage, it was considered essential to make the height-diameter models flexible so that they can be applied to different stand structures.

In the models, tree height was assumed to depend on tree diameter according to the following height formula, the exponent c being specific to each species:

$$ln(h_{ij} - 1.3) = a_j - b_j d_{ij}^{-c} + e_{ij} \tag{1}$$

where h_{ij} = height of tree i in plot j
$\quad\quad a_j$ = intercept for plot j
$\quad\quad b_j$ = slope for plot j
$\quad\quad d_{ij}$ = diameter of tree i in plot j
$\quad\quad e_{ij}$ = random error

Another basic assumption was that height-diameter curves vary randomly from stand to stand with respect to both intercept and slope (Lappi 1997); tree, stand and site

characteristics were then used to explain this variation. As in the growth models, the random parameter model approach was used in the analysis.

3. Results

31. Factors affecting tree growth on drained peatlands

311. Basic level of growth

3111. Site factors

In the basal area growth models (I), the site quality classification system of Huikari (1952, 1974) was applied. Using the main site types and site quality classes that Huikari (1952) has defined to characterize peatland vegetation, it was possible to distinguish 6 - 10 *a priori* sites, depending on the species. Variation in the growth rate and growth pattern among these sites was studied by detecting differences in both the intercept and slope of the relationship between tree growth and tree diameter among plots.

For all species, sites of different fertility, as indicated by the site quality classes, showed differences in growth. For pine and birch, the differences in growth between pine mires and spruce mires were significant. From the *a priori* sites, four, five, and three yield classes were formed for pine, birch, and spruce, respectively (I). Birch appeared to show the most variation in growth as indicated by the yield classes, even though pine covered the widest range in site quality. In study III, meso-oligotrophic pine mire sites differed from poor oligotrophic and ombrotrophic sites. Huikari (1952, 1974) has also given supplementary definitions for more detailed classification. These definitions refer to site conditions that reflect poorer or better site quality in terms of timber production. In study I, sites showing either a dominance of *Sphagnum fuscum* hummocks in the ground vegetation or extreme moisture in the substrate as indicated by the occurrence of flarks, or both, showed a lower average growth of pine.

The average temperature sum was used in studies I and III to express growth as a function of the geographical location. The growth of birch was less dependent on the temperature sum than that of conifers. For pine and spruce, the temperature sum influenced the slope between growth and tree diameter (I). Peat thickness (expressed with continuous values down to 1 m depth) correlated negatively with the growth of pine in study III, while no trend was observed with any of the three tree species in study I. In the immediate proximity of the sea coast, as indicated by a variable defined by Ojansuu and Henttonen (1983), the basal area growth of birch was higher (I). In study III wider ditch spacing showed up as lower diameter growth of pine in the control treatment.

The average productivity of sites drained more than 15 yrs earlier may be affected by the present status of the site drainage (Heikurainen 1980). This effect was assessed in the field as a need for improvement ditching. A dummy variable showing lower growth was used to refer to sites where such measures were suggested (I).

3112. Tree vigor and competition

Tree size was used as an indicator of tree status and vigor in studies I and III. The logarithm of tree diameter and tree basal area were used in study I to explain the basal area growth of pine and birch. Basal area growth increased with increasing tree diameter until the negative component related to tree basal area caused a decrease in growth. For spruce, the square root of the tree diameter gave a better fit than logarithmic transformation. In study III, the logarithm of the tree diameter and the second power of the logarithmic diameter were used correspondingly to explain the annual diameter growth of pine.

The effect of inter-tree competition on basal area growth was accounted for at plot and tree levels in study I. Plot basal area and the diameter of the tree of median basal area decreased the growth of pine and spruce, respectively, while neither of these influenced the growth of birch. At tree level, the basal area of trees larger than the target tree (BAL) decreased the individual-tree growth of all species. The relationship was nonlinear, suggesting that BAL was more important in decreasing the growth of small trees. If plot-level competition had been reduced by a thinning treatment during the past five years, the growth of all species was higher (I).

In study III, the diameter growth of pine was lower in plots where the basal area was higher. No tree-level measure of competition was applied, but the plot basal area explained the slope between tree diameter and diameter growth. The basal area changed the relationship in such a way that in well-stocked plots growth was strongly allocated to the biggest trees. Thus, this effect served also as a tree-level measure of competition.

The basal area growth of birch and spruce was influenced by the mixture of other species in the stand as indicated by the proportion of spruce or birch of the total plot basal area (I). Both species showed higher growth in mixed than in pure stands.

312. Growth response to the drainage treatment

3121. Site factors

In the basal area growth models (I), the effect of site treatment on growth was accounted for by expressing the average growth rate of stands as a function of time since drainage. Stand-level categorical variables were used, referring to drainage age classes 1 - 5, 6 - 10, 11 - 25, and >25 years since drainage (I). It was shown that the basal area growth of all species was at the lowest level during the first 5-year period after drainage. For pine and birch, growth was higher for the second 5-year period, and the highest growth was found between 11 and 25 years since drainage. After 25 years had passed, the growth rate was equal to the period 6 - 10 years after drainage. There were differences in growth among the drainage age categories for spruce as well, but only the youngest age class differed significantly from the others.

The diameter growth models for improvement ditching showed that pine responded immediately and increased its growth continuously for the whole study period (III). In the models, the temporal response was expressed as a continuous nonlinear function of time. The magnitude of the growth response varied according to the different treatments, with

ditch cleaning giving the lowest average response and the combination of ditch cleaning and complementary ditching giving the greatest response. A higher response to ditch cleaning was obtained for plots with narrower ditch spacing.

3122. Tree vigor and competition

The effects of tree vigor and competition on the growth response to improvement ditching in study III were modelled by expressing the response as a function of the initial tree diameter and plot basal area. This was possible because the temporal change in growth was described with a continuous function. It turned out that the largest trees responded most to all improvement ditching treatments. Plot basal area also had a significant increasing effect on the response to ditch cleaning and complementary ditching, while no effect on the response to the combination treatment was found. Thus, inter-tree competition, as indicated by plot basal area, did not limit the response. As a result, the effect of improvement ditching on the growth response was different depending on the method applied, the initial tree size, and the initial plot basal area.

32. Factors affecting tree height

The shape of the height-diameter curve may be different for different species, as determined by the value of the exponent c in Equation 1. On the basis of the sum of squared residuals produced by alternative parameter values, the appropriate values were determined to be 0.3, 0.4 and 0.7 for spruce, pine and birch, respectively. Thus, the curves were most linear for spruce, while more non-linear curves were obtained for pine and birch. Consequently, the range in predicted heights for small trees was narrower for spruce than for the other species.

For all species, the most important stand and site characteristics explaining variation in the intercept of the height-diameter curves were the diameter of the tree of median basal area (D_{gM}), the plot basal area, and the north coordinate. For birch, plot basal area was substituted for the basal area of birch in the plot. In more stocked stands the intercepts were higher. At high elevations the intercept was lower for birch. A dummy variable which had value 1 if the stand had been thinned during the past five years increased the intercept for pine and birch. For pine, a dummy variable referring to Huikari's (1952) site quality classes 2 - 4 produced higher intercepts than classes 1, 5, and 6.

For all species, variation in the slope was explained by tree diameter and D_{gM}. For birch and pine, plot basal area also explained the slope. The slope was steeper in stands where the average size of the trees was larger.

Because tree-level variance of birch and pine appeared to be non-constant, a variance function was applied to account for the change in variance as a function of tree diameter.

4. Examples of stand-level simulations

41. Basis for calculations

411. Drainage of a pristine peatland site

To predict the effect of drainage of a pristine peatland site on stand development, the basal area growth models (I) and height-diameter models (II) were used simultaneously in the MELA growth simulator (Siitonen et al. 1996). As a starting point, a sample stand was described with a diameter distribution in which trees were divided into 1-cm diameter classes. Tree heights were predicted from the diameters and the corresponding stand and site characteristics (II). Tree volumes were obtained from stem curve models as a function of tree species, diameter and height (Laasasenaho 1982). Single tree volumes in each diameter class were multiplied by the number of trees in the class, and the stand volume was calculated by adding up the volumes in each diameter class. Basal area growth models were then applied to predict the basal area growth of each tree (= diameter class) for the following five-year period. Tree diameters were then updated and new heights and volumes and subsequent stand characteristics predicted. To predict self-thinning, the MELA growth simulator used the respective models derived for stands growing in mineral soil sites (Hynynen 1993).

Fertilization of drained peatlands has been a common management practice during the past decades, and the modelling data also included fertilized stands because it was not possible to omit them (I). In order to avoid growth predictions that were too high for non-fertilized stands, the effect of fertilization on growth in the modelling data was estimated. The total area of peatlands which were under the influence of fertilization during the data collection was obtained from fertilization statistics. Estimates concerning the distribution of fertilization among different site types have been given by Keltikangas et al. (1986). The growth response of pine, birch, and spruce to the fertilization treatment in different yield classes and in different parts of the country was estimated on the basis of results obtained from numerous fertilization experiments conducted by the Finnish Forest Research Institute. Using this information, the relative basal area growth without fertilization was calculated by species and site types separately for northern and southern Finland. Depending on the tree species, yield class, and location, growth in nonfertilized stands was estimated to be 0 - 14 % lower than the average in the modelling data.

Before the basal area growth models (I) and height-diameter models (II) were applied in MELA, they were calibrated with the sample tree data of the 8th National Forest Inventory to give unbiased estimates on growth and height with respect to tree diameter, geographical location, and site quality.

Only one initial stand representing one site for each species in northern (1050 dd°C) and southern (1200 dd°C) Finland was simulated for a 50-year period following drainage. The pine and birch stands were located in a tall-sedge pine fen (Laine and Vasander 1990) which corresponded to yield classes p3 for pine and b4 for birch (I). The spruce stand was located in a *Vaccinium myrtillus* spruce swamp (yield class s2). These are typical of sites which have been subjected to drainage treatments in practice. The spruce stand was generated on the basis of the average diameter distributions and stand characteristics given by Gustavsen and Päivänen (1986) for pristine peatland stands in Finland (Fig. 2a, Table

3). The site type chosen for pine and birch was a sparsely forested composite type which was not studied by Gustavsen and Päivänen (1986). Thus a low-stocked stand with reversed J-shaped diameter distribution and low initial basal area was produced for pine, and a slightly denser and more even-sized stand for birch (Fig. 2a, Table 3). No stand management was carried out during the simulation period, and for the sake of simplicity, only pure stands were simulated. The condition of drainage was assumed to be satisfactory for 30 and 40 years following drainage in pine mires and spruce mires, respectively. No ingrowth was assumed.

Table 3. Stand characteristics at the time of drainage in stands used in simulating stand development after the drainage of a pristine peatland site.

Stand	dd	N	V	G	D	H
Pine	1200	1260	13.9	3.9	9.8	6.0
	1050	1260	13.0	3.9	9.8	5.6
Spruce	1200	2300	66.7	14.0	12.5	9.5
	1050	2300	61.2	14.0	12.5	8.9
Birch	1200	1660	14.4	4.1	8.2	6.8
	1050	1660	13.4	4.1	8.2	6.2

412. Improvement ditching

To simulate the effect of improvement ditching on the growth of pine, a new version of the prediction model given in study III was derived, in which the year effects were estimated as random at stand level and ditch spacing was not used to explain the growth response to ditch cleaning. Because the growth response to improvement ditching varied according to initial tree diameter and initial stand basal area, three stands with different diameter distributions and basal areas (Fig. 2b) were simulated in two locations representing southern (1200 dd$^{\circ}$C) and northern Finland (1050 dd$^{\circ}$C). The site type chosen was an oligo-mesotrophic pine mire (tall-sedge pine fen). The development of the non-ditched stands was simulated with the common basic growth model of the treated stands without the growth response (see III): i.e., no time-dependent decrease in the growth of the untreated stand was assumed. Since the data in study III covered only the initial response, the simulations were limited to the first 15 years. The simulation step was one year. Tree heights were predicted with height models for pine (II). The corresponding volumes were predicted as a function of diameter and height using the following volume equation for pine derived by Laasasenaho (1982):

$$ln(v) = -3.32176 + 2.01395 \cdot ln(d) + 2.07025 \cdot ln(h) - 1.07209 ln \cdot (h-1.3) \qquad (2)$$

Stand volumes were obtained by adding up the volumes in each diameter class. No ingrowth or self-thinning was assumed for the simulation period.
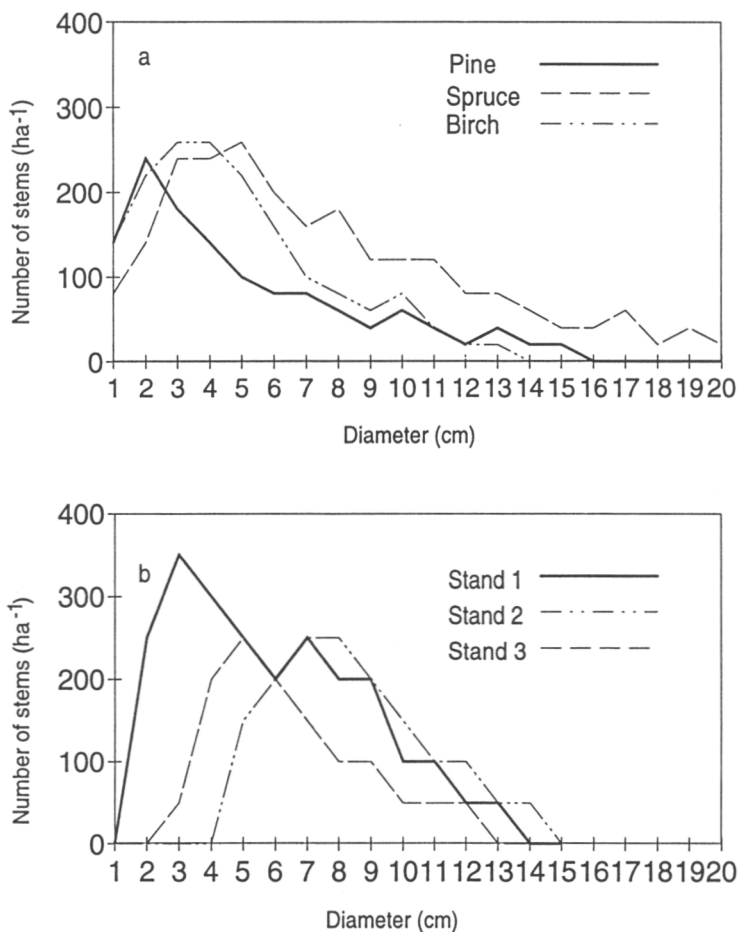
Figure 2.(a-b). Diameter distributions of pine, spruce, and birch stands used in simulating the post-drainage development of a pristine peatland (a), and three pine stands used in simulating the effect of improvement ditching on stand volume development (b).

42. Effect of climatic region and tree species on post-drainage stand development

In the pine stand in southern Finland, stand volume increased from 14 m^3ha^{-1} at the time of drainage to 220 m^3ha^{-1} after 50 years (Fig. 3). This corresponded to 4.1 m^3ha^{-1} average annual volume growth after drainage. In northern Finland, the total volume was 122 m^3ha^{-1} at 50 years drainage age, and the average annual volume growth during the 50-year period was 2.2 $m^3ha^{-1}yr^{-1}$. At stand-level, both basal area and volume growth peaked at 20 - 30 years drainage age in both regions. During the last two decades growth was limited by poor drainage. The difference in the volume increase between southern and northern Finland was almost 100 %.
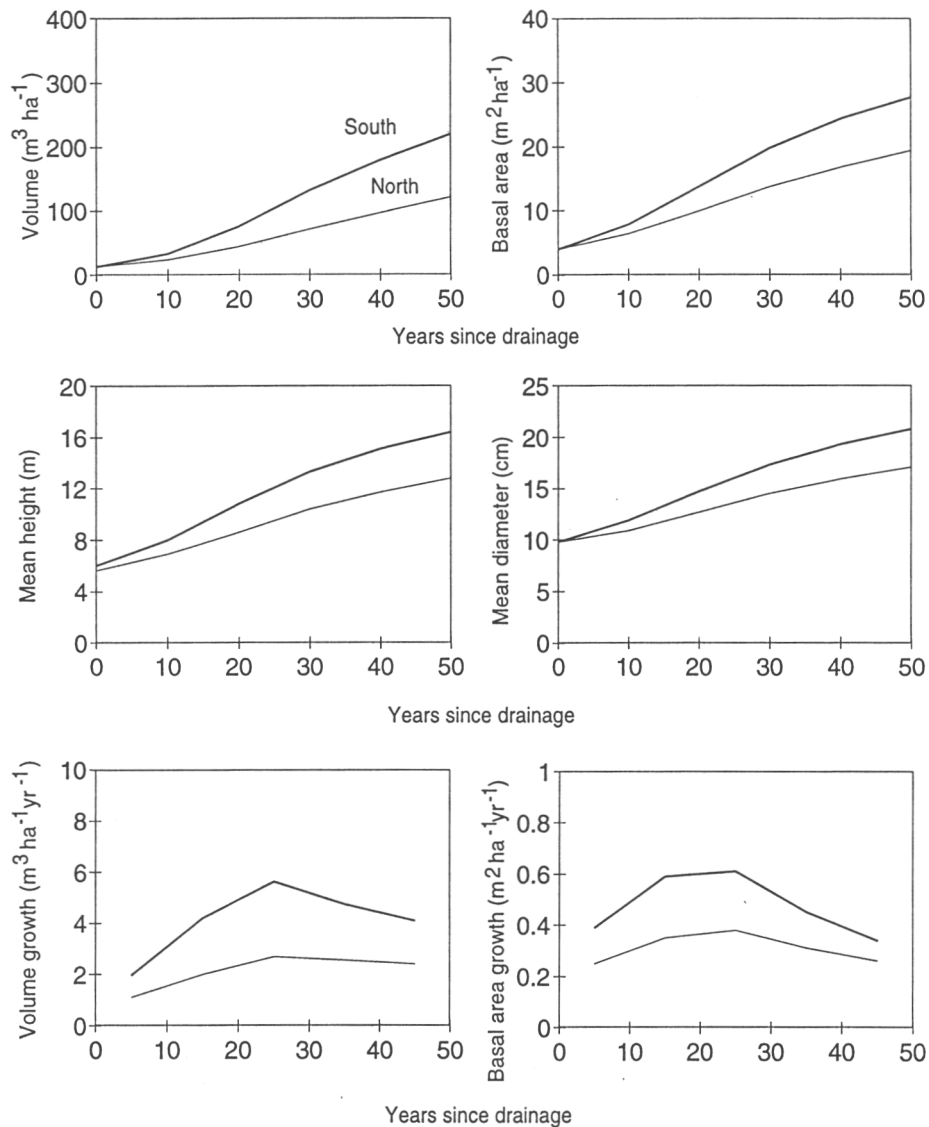
Figure 3. Development of stand volume, basal area, mean height, mean diameter, volume growth, and basal area growth in northern and southern Finland as a function of drainage age in a pine stand.

The volume of the spruce stand in southern Finland increased by 300 m^3ha^{-1} in 50 years (Fig. 4). The average annual volume growth was 6 m^3ha^{-1}. In northern Finland, the total increase in stand volume was 178 m^3ha^{-1}, which corresponded to 3.6 $m^3ha^{-1}yr^{-1}$ on the average. Since the stand was initially well-stocked, self-thinning considerably affected the stand development during the two last decades in southern Finland. Stand volume growth peaked between 20 - 30 years after drainage and basal area growth ten years earlier. In northern Finland, growth peaks occurred ten years later than in southern Finland. The difference in the volume increase between northern and southern Finland was 60 %.

22
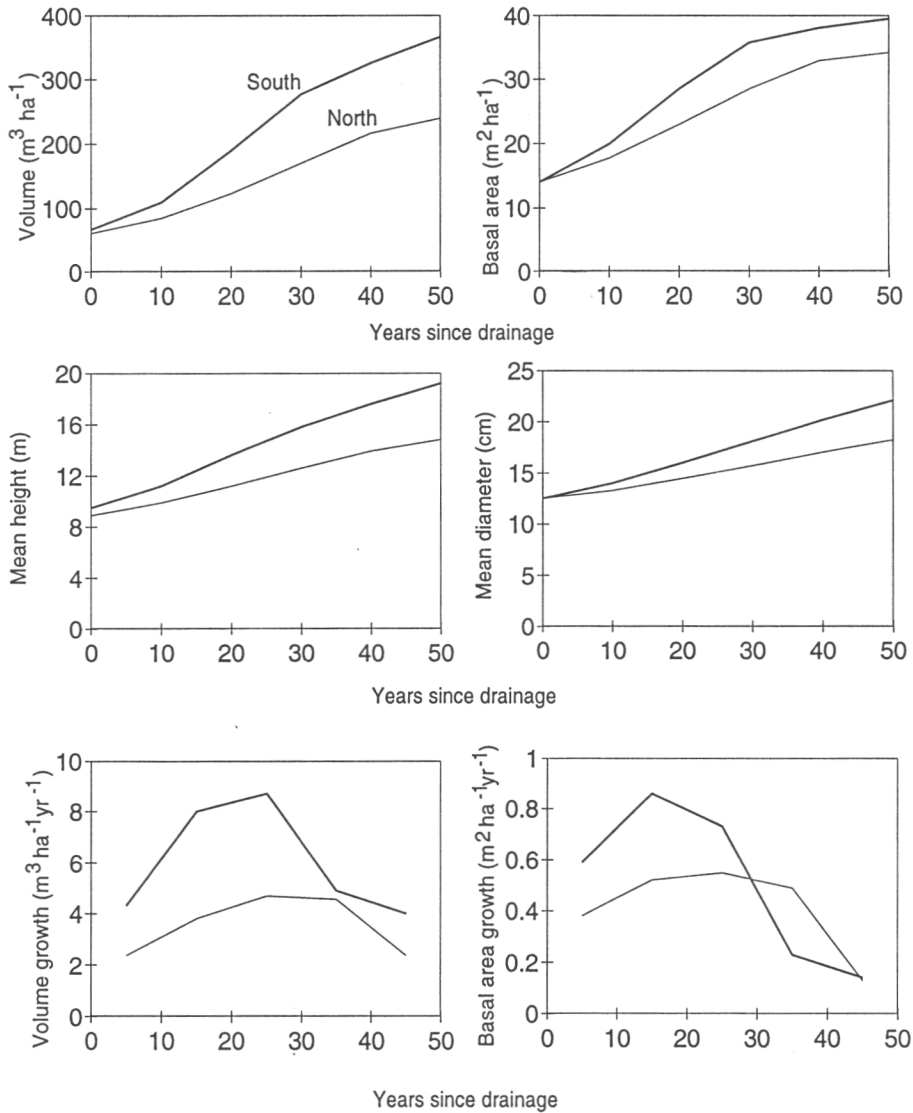
Figure 4. Development of stand volume, basal area, mean height, mean diameter, volume growth, and basal area growth in northern and southern Finland as a function of drainage age in a spruce stand.

In the birch stand in southern Finland, the volume increased by 225 m^3ha^{-1} during the 50-yr period (Fig. 5). The average volume growth was 4.5 $m^3ha^{-1}yr^{-1}$. In northern Finland, the increase in volume was 137 m^3ha^{-1}, corresponding to an average growth of 2.7 $m^3ha^{-1}yr^{-1}$. Stand basal area growth peaked at 25 - 30 years drainage age. In northern Finland, volume growth showed an increasing trend during the whole period, while in southern Finland volume growth peaked about 20 years after drainage. Because the development of birch in southern Finland was heavily affected by self-thinning between the period 30 - 50 years after drainage, only the beginning of the period was comparable with, e.g., pine. Despite the same site type, birch showed faster growth than pine.

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Figure 5. Development of stand volume, basal area, mean height, mean diameter, volume growth and basal area growth in northern and southern Finland as a function of drainage age in a birch stand.
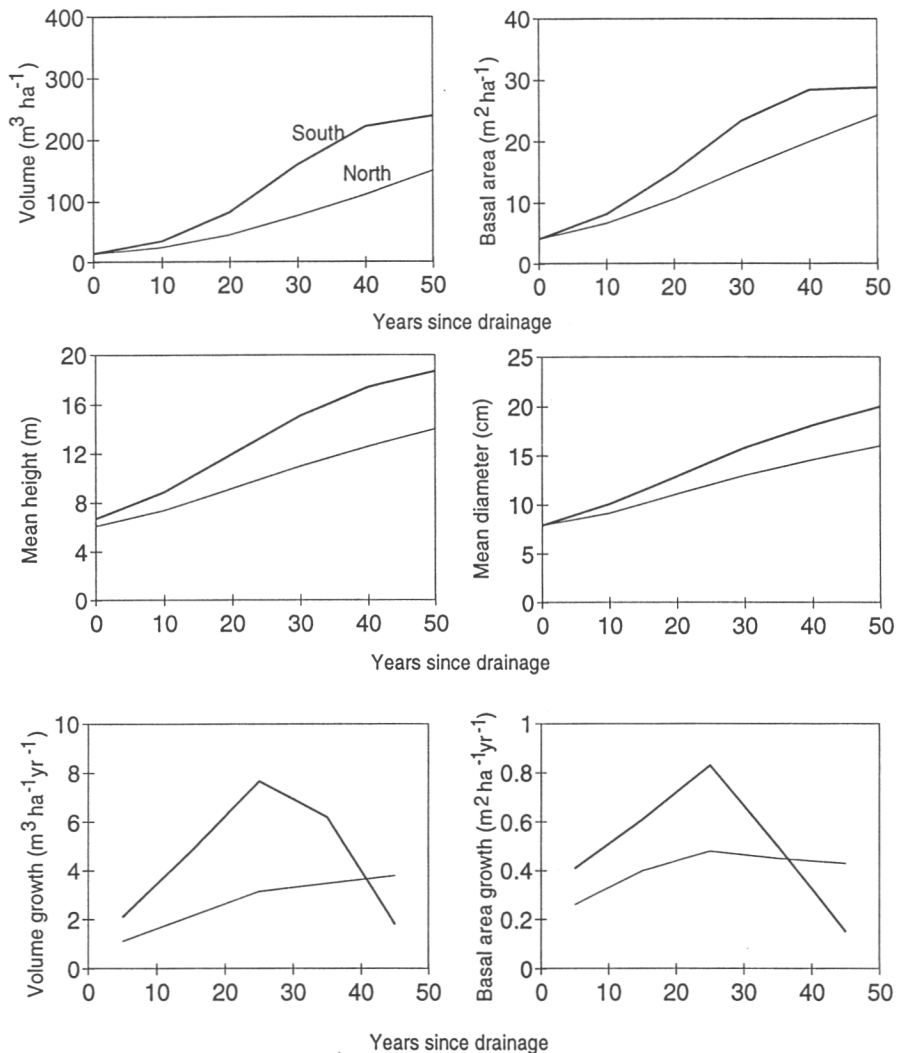
43. Predicting the response of pine to ditch network maintenance

The first simulated stand was considered full-stocked (2300 ha^{-1}, 10.4 m^{2}ha^{-1}) with a typical diameter distribution for drained peatlands (Fig. 2b). After a fifteen-year growth period in southern Finland, the stand volumes were 9.9, 20.8 and 26.0 m^{3}ha^{-1} greater in stands treated with ditch cleaning, complementary ditching and the combination treatment, respectively, than in the non-treated stand (Fig. 6). In northern Finland, the differences were smaller: 6.8, 14.4 and 17.9 m^{3}ha^{-1}. The increase in annual growth varied from 0.7 - 1.7 m^{3}ha^{-1}yr^{-1} in southern Finland and from 0.5 - 1.2 m^{3}ha^{-1}yr^{-1} in northern Finland.
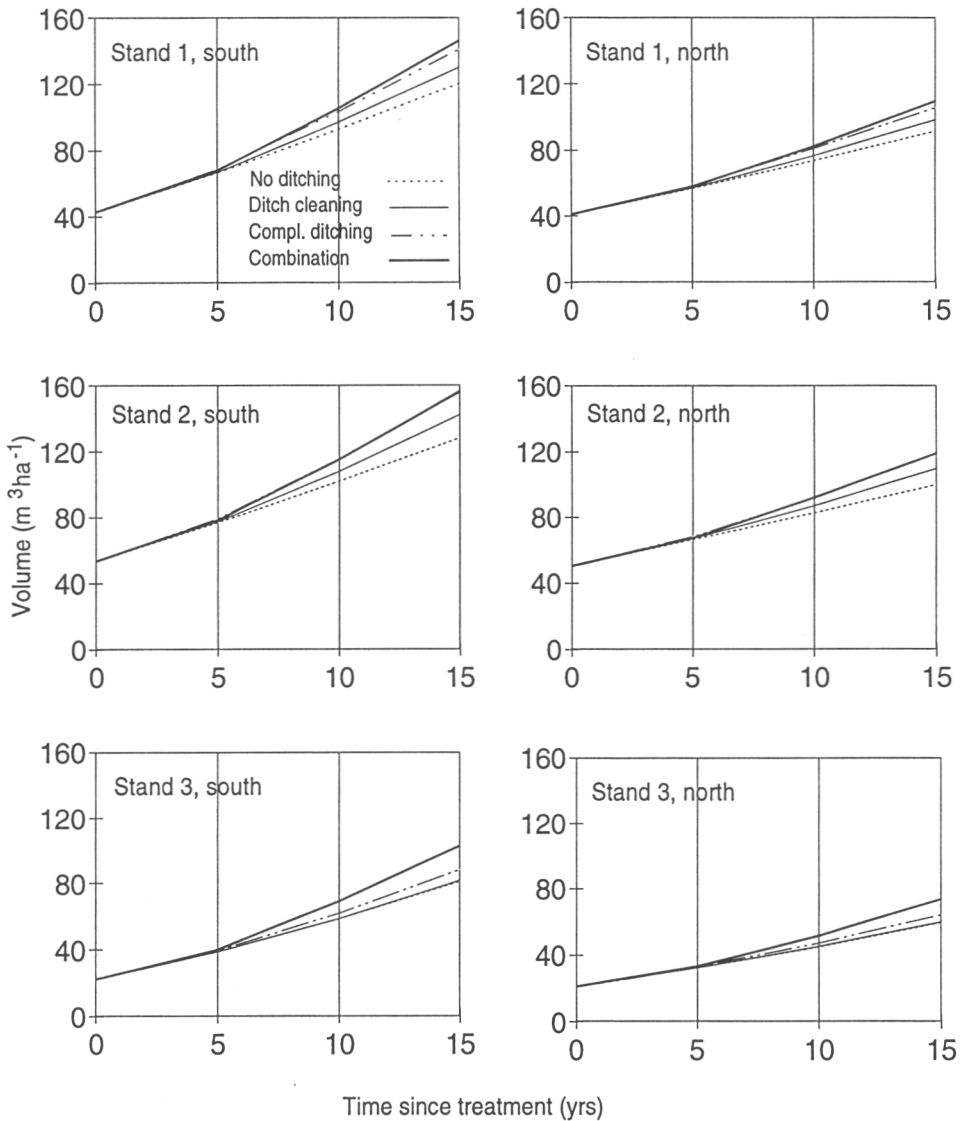
Figure 6. Development of stand volume after different improvement ditching treatments in pine stands 1 - 3 in southern and northern Finland.

In stand 2, the basal area was slightly higher (11.8 m^2ha^{-1}), but the number of stems was much lower (1500 ha^{-1}): i.e., the stand was composed of fewer trees with greater dimensions (Fig. 2b). In this case, ditch cleaning increased volume more (14.4 m^3ha^{-1}) than in stand 1 (Fig. 6). The combination treatment and complementary ditching produced almost equal increases in stand volumes; after a fifteen-year simulation, the total differences, compared to the non-treated stand, were 26 and 27 m^3ha^{-1}. In northern Finland, the corresponding values were 9.8, 18.9, and 19.3 m^3ha^{-1} for ditch cleaning, complementary ditching and the combination treatment, respectively. The annual volume growth increased 1.0 - 1.8 $m^3ha^{-1}yr^{-1}$ in southern Finland and 0.7 - 1.3 $m^3ha^{-1}yr^{-1}$ in northern Finland.

Stand 3 was composed of a low number of small trees (Fig. 2b) and was clearly understocked with respect to both stand basal area and stem number (5.9 m²ha⁻¹, 1200 ha⁻¹). Fifteen years after improvement ditching, only the combination treatment had increased stand volume considerably: 21.7 and 14.5 m³ha⁻¹ in southern and northern Finland, respectively (see Fig. 6). Complementary ditching produced 4.7 and 7.0 m³ha⁻¹ higher volumes than were produced in the non-ditched stand, while the effect of ditch cleaning was insignificant. The increases in the annual growth for complementary ditching and the combination treatment, respectively, were 0.5 and 1.5 m³ha⁻¹yr⁻¹ in southern Finland and 0.3 and 1.0 m³ha⁻¹yr⁻¹ in northern Finland.

In all simulations, the differences in stand volumes did not become apparent until 5 years had passed after ditching. This was due to the nonlinear growth responses. Assuming that similar conditions prevail, the differences in volumes among treatments can be expected to increase in the future in all stands.

5. Discussion

51. The quality of the data

The quality of the data can be judged according to two criteria: 1) how well the data represent the population of trees and stands to which the models should be applied, and 2) how well the essential features and processes in growth dynamics can be described on the basis of measurements made in the field. Because generally applicable models were intended, the growth dynamics had to be described with common and easily measurable variables.

Aiming at valid and unbiased models, an objective random sample representing drained peatland stands all over the country was used as the data in studies I and II. Actually these were the only data covering the whole country. Even though the data sets were large and represented different regions, they were not ideal for modelling purposes. Because of the concentration of practical forest drainage in the 1960s and 1970s, most stands in the sample were composed of small-sized trees on the average: in studies I and II, more than 90 % of the trees were under 20 cm in diameter. Especially in the NFI8 data, the fixed size of the sample plot, irrespective of stand density, produced numerous small trees in recently drained and dense stands, but only a few trees in more advanced stands. Problems were encountered in model construction when the growth or height of large trees was predicted. Because the poorest sites or stands that were in unsatisfactory silvicultural condition were lacking from the SINKA data, overestimates concerning growth may occur in such sites and stands. In general, these sites may be unsuitable for timber production, and their importance may thus be only marginal.

In study III, data from experimental stands were used. The trees in these data were mainly small as well, but more evenly distributed over the diameter range. The problems were related to the short observation period, the experimental design and the distribution of the trees into site types. The trees in the control plots could not be considered as a basis for comparison, because they showed a slight response to the ditching of the other plots.

Because only nine stands located on poor sites were represented, the effect of site quality on the response could not be properly studied.

In study I, the effect of drainage treatment was expressed in a simple way on the basis of the differences in drainage ages among the stands. The method was rather imprecise, and it was not possible to account for all effects of the drainage treatment. In order to obtain a better view of the temporal growth dynamics, the age of drainage should have been determined more accurately (e.g., in 5-year categories) for the whole data. Correspondingly, any thinnings which had been carried out in the previous 15 years should have been dated in order to better cover the growth response period. In study III, the actual time-series permitted more effective modelling of the growth response to improvement ditching with common stand and tree attributes.

In order to avoid overestimates in basal area growth models (I) in non-fertilized stands, the effect of fertilization on growth was estimated in the modelling data and correction multipliers were calculated. Although biased results may have been obtained for single stands, it was considered the only alternative, because fertilization has been widely applied to drained peatlands during the past decades, and it was not possible to omit the fertilized stands from the modelling data.

52. Site factors in basic growth equations

Site fertility causes between-stand variation in growth rate and pattern. In Finland, ground vegetation has generally been used as an indicator of site quality. Drained peatlands are complicated objects to classify on the basis of ground vegetation, because their composition is dependent on both the site moisture condition and the nutrition. In study I, an assumption was made that site quality referred to nutrition, and the differences in growth due to varying site moisture following drainage were expressed as a function of drainage age.

It has been shown that the botanical classification systems of undrained peatland sites (Cajander 1913, Heikurainen 1959) explain tree growth poorly prior to drainage (Heikurainen 1971, Gustavsen and Päivänen 1986), while differences in growth can be found after drainage (Heikurainen 1959, Hånell 1984). However, systems which include numerous site types do not provide a good basis for classifying sites in terms of post-drainage timber productivity. Hånell (1984) distinguished eight site types that showed differences in post-drainage timber yield. Laine (1989) has proposed a scheme of seven drained peatland site types, in which differences in moisture were not considered (c.f. Sarasto 1957).

The yield classes defined in study I on the basis of Huikari's (1952, 1974) site types were different for each tree species. For pine and birch, the better average growth in spruce mires compared to that in pine mires could be explained by the ecological differences between these main site types (Eurola and Huttunen 1990, Eurola et al. 1995). In study I, Laine's (1989) drained peatland site types did not show clear differences in growth, which may be partly due to the inaccurate definition of the types based on the information provided by the data. However, several yield classes formed groups that corresponded closely to Laine's (1989) drained peatland site types. The yield classes appeared to be

most important in explaining the variation in the growth of birch due to varying site quality.

When sites were defined for each tree species, the classification had the advantage of accounting most flexibly for the variation in growth: e.g., a yield class for pine might contain two yield classes for birch, thus allowing a better adjustment of the growth of birch. However, the disadvantage of the method was that the growth of different species could not be compared within the yield classes.

The average temperature sum is commonly used to describe the effect of geographical variation on tree growth because it summarizes the effect of latitude and elevation. However, either of these attributes may have additional effects on tree growth (Hånell 1984). The effect of temperature sum on growth was different for different species in study I. This may be due to the physiological differences between the coniferous and deciduous species and subsequent differences in the determination of growth. Huikari et al. (1967) used the length of the thermic growing season (the number of days when temperature exceeded +5 $^{\circ}$C) to describe the effect of geographical location on growth.

Increasing peat thickness decreased the growth of pine in study III. Shallow peat (<0.5 m) has been shown to increase tree growth (Hånell 1984, see also Payandeh 1973). Huikari et al. (1967) concluded that, in general, stand growth was lower in sites where peat was thick. Hånell (1984) and Payandeh (1973) also used the degree of humification of the surface peat to explain stand growth. Peat properties were not determined in the data sets used in studies I-III.

The growth of pine was lower with wide ditch spacing if improvement ditching was not done (III). In the NFI8 data, ditch spacing was not recorded, and the variable was not used in study I. According to Seppälä (1972), increasing ditch spacing decreases stand growth, and the effect is more evident the poorer the site. He also found regional differences due to variation in large scale topography. However, Heikurainen (1980) concluded that ditch spacing has no effect on stand volumes or growth. The effect of ditch spacing is important in areas where regular ditch spacing has been established. Even in areas where ditches are set up irregularly, the ditch spacing or distance to the ditch may influence growth, but the effect becomes more complicated to determine (Payandeh 1973).

Site moisture, as indicated by the drainage age, was the most important growth regulator in recently drained peatlands (those drained less than 15 yrs earlier). In areas drained decades ago, the site moisture condition influences tree growth too, but the growth is mainly determined by other factors than the drainage age. The effect of stand stocking, site quality, previous management measures, and intensity of the original drainage (ditch spacing and ditch depth) may become more important. The need for improvement ditching was used as a dummy variable in the basal area growth models (I), and it decreased growth in stands where poor drainage condition at present was noticed (see Payandeh 1973). The variable reflected the current properties of the site and was not expressed as a function of time, although it has a temporal aspect. Stand growth rate can be adjusted in simulations if the information collected in the field suggests that site drainage is in poor condition; and later, if improvement ditching is carried out, it is possible to account for its effect. However, when long-term stand simulations are done, the time when improvement ditching should be carried out cannot be predicted with the models.

53. Tree vigor and competition in basic growth equations

Because the post-drainage succession generally initiates from stands growing in pristine peatland sites, the particular properties of the stands influence tree growth after drainage. In pristine peatland stands, uneven-aged stand structure, as indicated by a reversed J-shaped diameter-distribution of the trees, is prevalent (Heikurainen 1971, Gustavsen and Päivänen 1986). It has been suggested that this is due to the high potential of moist peat to regenerate, but the low capability of undrained sites to support further growth of seedlings and saplings. Because grown-up trees are located in the least wet sites, their spatial distribution is uneven, and the stands are thus more or less understocked.

In general, tree growth is dependent on age, and tree size is thus a function of age. Due to this, tree growth is usually expressed as a function of tree diameter in growth models (Vanclay 1994). The correlation between tree age and size is not so good for trees growing in drained peatlands because some of the trees were already growing in the site, for a varying number of years, before the drainage (Seppälä 1969). There was great variation in the relationship between growth and diameter in studies I and III. Both tree age and drainage age have been used to better describe tree vigor in growth models (Hånell 1984, Miina 1994), but these variables have limited use in predictions because the age is generally not determined for all trees in forest inventories. The characteristics of the tree crown could be used to better describe the growing potential of an individual tree in drained peatland sites (Payandeh 1973). It is presumed that, e.g., crown ratio could be predicted for all trees (Hynynen 1995a).

Stand age, as determined from the dominant trees, has been used to explain stand growth after drainage (Payandeh 1973). However, the mean age of the dominant trees may not be a good indicator of the average growth potential of an uneven-sized stand. Huikari et al. (1967) used the so-called 'economic age', which was calculated by correcting the biological age downwards, to explain stand growth. No information on tree ages was available in this study.

When the average growth was expressed as a function of tree diameter, spruce showed lower growth rates, when small, than birch and pine (I). Subsequently, large spruces grew better than birches and pines of similar size. This was in accordance with the differences in the growth dynamics among these species: pine and birch grow fast when small, while spruce may show good growth when large, too (Mielikäinen 1985). To some extent, the lower growth of small spruces was also due to the structure of the data: they were growing in more stocked stands on the average, and their growth was thus limited by competition from larger trees.

The basal area of the trees larger than the target tree (BAL) allowed higher growth for trees that were in a favourable competitive position: i.e., it diversified the size distribution within a stand as a function of competition. The nonlinear relationship suggested that co-dominant and intermediate trees were only slightly affected, while the growth of small trees decreased rapidly as competition increased. This was interpreted as a consequence of the uneven-sized structure and low stocking found in drained peatland stands (Hökkä and Laine 1988). The low inter-tree competition in uneven-sized stands is due to the fact that

the largest trees occur one by one with a low total number per hectare. They do not compose a uniform canopy layer, which could affect the growth of smaller trees considerably. As an increasing number of trees formed a more even canopy layer, BAL increased, and the decreasing effect on growth became more apparent.

Stand basal area has commonly been used as a measure of competition at stand (or plot) level (Hånell 1984, Miina 1994, Penner et al. 1995). The growth of pine was lower in stands where the basal area was high (I and III), while the basal area appeared not to affect the growth of birch and spruce in study I. The growth of spruce was limited by the large diameter of the tree of median basal area (I). These results raise several relevant points. First, it does not seem realistic that the growth of birch would not be limited by the increasing site occupancy. However, the growth of young pubescent birch trees has been shown not to be limited by high density (Niemistö 1991), probably because of their good tolerance of shade (Ferm 1990). In older stands, competition decreased growth, as indicated by the response of birch to the thinning treatment (Niemistö 1991). While the data mostly originated from young stands, competition did not yet show a significant decreasing effect on growth. Another important point is the dependence between site drainage and stand stocking in drained peatlands. As an effective transpirator, birch may compensate for poor drainage conditions with a high transpiration rate in a dense stand. Consequently, growing conditions generally become better the denser the stand is (see Penner et al. 1995). Because the data were a sample of practical forest drainage areas, which, on the average, were not in optimal state with respect to site moisture, the interaction between density and site drainage on growth may have been important. In well-drained areas, the negative effect of competition could be more apparent. A third point is that drained peatland stands are generally understocked, due to the fact that pristine peatland stands are generally initially sparse. Considerable ingrowth takes place after drainage (Hökkä and Laine 1988), suggesting that competition may not limit tree growth. Even in older drainage areas, self-thinning due to excess density may be insignificant (Miina and Pukkala 1995) and the basal area growth of single trees may still increase (Seppälä 1969). Nevertheless, the lack of a stand-level competition factor may lead to overestimates when the growth of dense advanced birch stands is predicted. For large birches, gradually decreasing growth due to increasing tree basal area was the only effect limiting tree growth.

Thinnings carried out during the past 5 years increased the growth of all tree species studied (I). For pine, the response to thinning was not limited to the first 5-yr period after the treatment, because lower competition due to the decreased stand basal area permits higher tree growth for a longer time. For birch, the thinning response was limited to the first 5-yr period. For spruce, the decreasing effect of larger median diameter on tree growth partly compensated for the effect of thinning from below, because in thinnings median diameter increases, which, in turn, decreases tree growth after the treatment. Because thinning decreases interception and transpiration, thus increasing site moisture (Päivänen 1982), the actual growth response may be less than what could be expected on the basis of decreased competition. In these data, the growth response may be overestimated, because stands growing better initially may have been exposed to thinnings more often than other stands. Furthermore, the response may also be partly due to improvement ditching, which is generally carried out simultaneously with thinning. Altogether, the thinning response should also be studied in more detail in thinning experiments (see Hökkä et al. 1996).

The growth of birch and spruce was higher in mixed than in pure stands, suggesting that both species benefit from competition from another species (I). The results may partly reflect the effect of site on growth, because pure birch stands tend be found in sites that are problematic in terms of nutrition. Similarly, in spruce mires, pure spruce stands are common in less fertile sites, while the proportion of birch is greater in better sites (Gustavsen and Päivänen 1986). According to Hånell (1984), the stand basal area growth was higher in stands where the combined proportion of spruce and birch was higher. Huikari et al. (1967) concluded that the higher proportion of birch of the total volume decreased the stand volume growth in spruce mires in northern Finland. In mineral soil stands, Mielikäinen (1985) observed that the growth of pubescent birch decreased as the proportion of spruce increased, while the proportion of birch did not influence the growth of spruce.

54. Site factors in predicting the growth responses

The observed differences in growth among the age categories describing the response to drainage were assumed to be due to the temporal changes in site moisture (I). Digging the ditches causes an immediate lowering of the groundwater table and a rather quick subsidence of the surface peat (Hillman 1997). Soil aeration is improved, which increases microbial activity (Lieffers 1988) and the subsequent growth of tree roots and rooting depths (Paavilainen 1966, Laiho and Finèr 1996). Although most of the change in the water level draw-down and peat subsidence takes place within a few years after drainage, the diameter growth response of trees shows an increasing trend for a much longer time: i.e., 10 - 15 and 15 - 25 years for Scots pine and Norway spruce, respectively (Seppälä 1969), and 13 - 19 years for black spruce (Dang and Lieffers 1989).

In general, the temporal changes in growth obtained in study I were in accordance with the results given by Seppälä (1969). Spruce showed a clearly lower growth rate only for the youngest drainage age class, which corresponded to the slow response of spruce (Seppälä 1969), while the insignificant differences among the other age categories may have been due to insufficient data. For pine, the distribution of the basal area growth response over time was more similar to the radial growth response given by Seppälä (1969, 1976) than it was to Seppälä's basal area growth. For birch, the temporal response has not been described earlier. Seppälä's (1969) data showed continuously increasing basal area growth during the whole 50-year study period for both spruce and pine. This may be explained by the concentration of the data in well-drained sites. In a random sample of drained peatland stands, the deterioration of the drainage network is expected to become visible in tree growth 15 - 20 years after drainage of a pristine peatland (Heikurainen 1980). The temporal differences in stand-level growth in this study were also similar to those obtained by Keltikangas et al. (1986): with a given stand volume and site type, the volume growth was generally lowest in sites drained less than 10 yrs ago and highest in sites drained 10 - 20 yrs ago. In areas drained more than 20 yrs ago, stand volume growth gradually decreased as drainage age increased.

The most distinct changes in growth rate take place during the first 15 yrs after drainage (Seppälä 1969). It is probable that the growth of the first two five-year periods was described reliably, especially in the growth models for pine and birch (I). After the 10th

year, a 15-yr period was used because the NFI8 data did not permit more detailed classification. The growth rate of this period was the highest, which was in accordance with the lag between maximum diameter growth and corresponding basal area growth, but it is probable that there is temporal variation within the period which the models are incapable of describing.

It can be assumed that the mechanism causing the growth response to improvement ditching is similar to that causing the response to first-time drainage, because the site water regime and subsequent soil aeration are affected in both treatments. Trees are probably in better shape to respond to improvement ditching than to the drainage of a pristine peatland. In the data for basal area growth models (I), the effect of ditch network maintenance treatments on tree growth proved to be insignificant. In study III, the growth of pine showed a response to different improvement ditching treatments, and it was possible to express the growth increase as a continuous function of time. There were differences between the treatments in the pattern and magnitude of the response, the most distinct growth impact being connected to the heaviest treatment. The negative effect of wider ditch spacing on the response to ditch cleaning showed that in initially poorly drained sites trees responded less.

Even though it has been suggested that the growth response to forest drainage is dependent on site quality (Seppälä 1969) and geographical location (Heikurainen and Kuusela 1962, Laine and Starr 1979), these effects were not accounted for in study I, because it was not possible to express the temporal response as a continuous function of time for all data. Furthermore, site quality was described with categorical variables. Including interactive effects would have resulted in more complicated models: several new variables referring to each age category would have to be defined and the response would have to be described for each class. In the model for improvement ditching (III), the variables related to site quality and geographical location showed erratic correlations due to the small sample, suggesting that it was not possible to estimate their effect on the response correctly.

55. Tree vigor and competition in predicting growth response

It was not possible to determine the effect of tree vigor or competition on the growth response to the drainage of a pristine peatland due to the insufficient data in study I. In study III, it was shown that the temporal growth response to improvement ditching was dependent on tree diameter and stand basal area. Within a plot, the response effect was concentrated in large trees, which increased their growth most. Large trees are generally located close to the old ditches and have the highest growth potential due to their good competitive status. The combination treatment resulted in the most equal response of trees of all sizes, which can be explained by the spatially even treatment that improved the growth of both large trees and small trees located close to the new ditches.

Plot basal area influenced the growth response to ditch cleaning and complementary ditching treatments positively. This result may be related to the interrelationships among the properties of the peat, site drainage, stand stocking, and growth in drained peatland sites. According to Päivänen (1982), the effect of stand volume on the groundwater table depth is greater the deeper the groundwater table initially is. Greater changes are due to

the higher groundwater coefficient in deeper peat layers (Heikurainen 1964). Because the groundwater table is influenced by the tree stand through interception and transpiration, stands with higher basal areas are expected to have lower groundwater tables (Laine 1986). Thus, it can be assumed that the effect of ditch cleaning or complementary ditching on the groundwater table is greater in areas where the groundwater table has been initially deeper. With improved growth the stands are able to better control the groundwater table (Maki 1971, Duncan and Terry 1983, Laine 1986, Penner et al. 1995). In poorly stocked stands with a higher initial groundwater table, ditch cleaning and complementary ditching do not change the ground water table considerably, and the sparse stand is not capable of contributing to the drainage significantly. Consequently, the effect of ditching may be limited to the proximity of the ditches, and the response may remain lower. In combination treatment areas, sparsely forested stands also responded because the intensive treatment caused a considerable change in site drainage, as indicated by the changes in groundwater table levels (Ahti and Päivänen 1997). In order to better explain the variation in the growth response, data from water table fluctuations before and after treatment should be studied.

Some of the effect could be explained by site quality: in well-stocked stands the site quality may also be better thus permitting a higher response. All in all, the growth model allowed stands with higher initial basal area to respond equally well to both complementary ditching and to the combination treatment.

56. Annual variation in growth of pine

In constructing the basal area growth models (I), the effect of annual climatic variation on growth was assumed to be insignificant, because the 5-year growth periods were distributed over ten years. However, a five-year period is so short that several exceptionally good or poor growth years may have influenced the average growth. Information about the effect of annual climatic variation on growth of pine in drained peatland sites in the years 1979 - 1989 was obtained from the increment core data analyzed in study III. The data were concentrated only in nine locations, but they permitted some interpretations of the results. The estimated index series was compared to two independent indices defined from NFI8 pine sample trees growing in both pristine peatland sites and mineral soil sites in middle parts of Finland (Henttonen, unpublished).

The indices obtained from study III (the growth model in Table 3 in study III) showed growth fluctuations resembling both mineral soil indices and undrained peatland indices (Fig. 7). During the years 1979 - 1983, the pattern of growth of pine in all these sites was rather similar, but the level of growth in drained peatlands was more similar to that observed in mineral soil sites. During the years 1982 - 1989, tree growth in drained mires followed a pattern that was closer to that of pristine peatlands, and in 1988 and 1989 the growth index completely differed from that observed in mineral soil sites. In general, the variation over the years was greatest in pristine peatlands. It can be assumed that the average growth during the 5-year period that covered the years 1979 - 1983 was lower than the long-term average. Because the NFI8 data were measured in 1985 and 1990, the average growth is probably close to a long-term average. This holds true also for part of the SINKA data, but the index series was too short to cover the whole period when the SINKA data were measured (1984-1994).
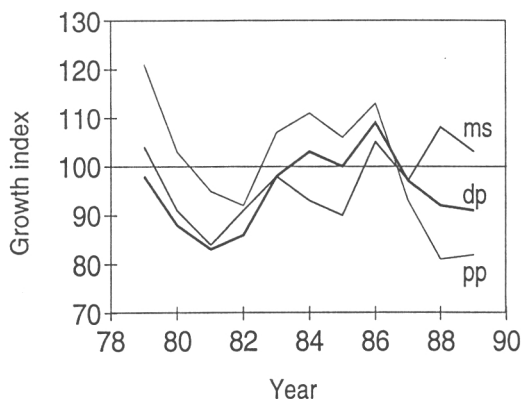
Figure 7. Growth indices obtained in study III for pine growing in drained peatland sites (dp), and two independent indices defined from NFI8 sample pine trees growing in both pristine peatlands (pp) and mineral soil sites (ms) in the middle parts of Finland (Henttonen, unpublished).

A detailed analysis of the climatic parameters affecting the growth index in study III was not carried out, but the lower growth in some exceptionally poor years (e.g., 1985 and 1987) suggested that cold and wet growing seasons limited tree growth on both pristine and drained peatlands. Joensuu (1980) has obtained rather similar growth indices for pine growing in drained peatland sites and those growing in mineral soil sites in middle parts of Finland. Dang and Lieffers (1989) assumed that the same parameters are important in determining growth variations both in drained and undrained peatland sites.

57. Height-diameter models

For all species, the shape of the height-diameter curve was rather linear as determined by low values for the exponent c (II), if compared to other studies (e.g., Lappi 1997). The reason for this was assumed to be that the structure of stands growing on drained peatlands is more uneven than that of stands growing on mineral soil sites (Hökkä and Laine 1988, Hökkä et al. 1991). Clumped spatial distribution of trees permits large variation in tree height. Furthermore, inter-tree competition does not affect height distribution considerably in low-stocked stands. The exponent was highest for birch, which may form denser and more even-aged stands than pine or spruce on drained peatlands during the first rotation (Saramäki 1977).

For all three species, the height-diameter curves became more flat towards the north (see Korhonen 1993) and for birch towards higher elevations. Average tree height increased as the plot median diameter or plot basal area increased. The average size of the trees (D_{gM}) has also been shown to determine the shape of the diameter distribution in drained peatland stands (Hökkä et al. 1991). Thinning increased the intercept, because the shortest trees of equal diameter have the highest probability of being removed in thinning from below. The level of the curve was lower in ombrotrophic and eutrophic sites, probably due to the poorer stem form. The slope of the average height-diameter curve changed as the median diameter or basal area changed: i.e., the height of trees of the same diameter increased as the average size of the trees or stand stocking increased.

Very flat curves were obtained, especially for pine and birch, if both the slope and intercept of the curve were low, as determined by low values of stand attributes. These curves referred to recently drained, sparsely forested mires in which the stand was composed of trees that were growing in the site prior to drainage. At that stage, generally the large trees are not much taller than the small ones due to their stunted height development. In pristine peatlands, it is common that the dominant trees may be more than a hundred years old, but the dominant height is only 10 - 11 m (Gustavsen and Päivänen 1986), suggesting that trees increase their diameter even though the height development has ceased (Heikurainen and Kuusela 1962).

The property of the height-diameter models is that the slope is predicted standwise as a function of the average size of the trees and stand basal area. This makes the models more flexible to fit a variety of stand structures, which is useful in long-term forecasts when changes in stand structure are expected.

58. Accuracy of the equations

In all models, trends between the mean residuals and different explanatory variables were removed during the model construction. The performance of the models was tested in the modelling data by estimating the model bias as the difference between the observed and predicted growth/height at the original scale of the response variable. All basal area growth models (I) appeared to produce slight overestimates of growth on the average, but the main problem was related to the increasing trend in the estimated bias as tree diameter exceeded 15 cm. This was most evident for spruce. The result was similar both in the modelling data and in independent test data. It was assumed that when the models were estimated with data sets that were concentrated in small trees, the models would be biased for the larger ones. The estimated mean biases of the height-diameter models in the modelling data were insignificant on the average, but the models for pine and birch also showed biased predictions as tree diameter exceeded 20 cm.

The biases may cause problems in long-term simulations, when trees eventually become large. Because the predicted values are used as input values to predict future growth, a small systematic bias in predictions may result in a considerable error in, e.g., a 100-year simulation period.

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. This was done in study II, but the effect of this correction was only marginal. In general, the residual variances were fairly large for the basal area growth models, resulting in large correction terms for the exponential transformation (I). The estimated biases in both modelling data and test data suggested that predictions given by the spruce basal area growth model should be corrected by diameter classes to avoid negatively biased (too high) growth predictions for trees greater than 15 cm in diameter.

In order to avoid unreliable predictions in simulations, the models were calibrated with the sample tree data of NFI8 with respect to tree diameter, geographical location, and site quality before applying them to the MELA growth simulator. However, there remains a need to update both the growth models and height-diameter models when future inventories provide more data about larger trees.

The growth model for improvement ditching showed no trend in bias as a function of tree diameter (III). When average bias was estimated in the modelling data at stand level, the model appeared to be unbiased. As the stands were selected for the experimental purposes, the average growth response may be biased for all peatland pine stands where improvement ditchings are carried out.

In describing the growth response to drainage in specific stands, the basal area growth models are inaccurate, because variation in the response between trees (Heikurainen and Kuusela 1962, Seppälä 1969, Hånell 1984) could not be accounted for (I). In addition to drainage age, other stand-level attributes, such as site quality (Seppälä 1969), have been shown to influence the response. Thus, single stands and trees may show deviations from the post-drainage growth pattern predicted by the models. The growth dynamics will be correctly described only for the mean of a greater population of drained peatland stands. In this respect, the growth model for improvement ditching is more accurate.

59. Stand dynamics

591. Post-drainage stand development

In addition to the growth models and height-diameter models, the models for self-thinning used in the MELA growth simulator also influenced the stand-level simulations. Because the simulated pine and birch stands were generally low-stocked, the effect of self-thinning was considerable only when the development of the birch stand in southern Finland was simulated. Due to the higher initial stocking in the spruce stand, self thinning slowed the volume development in southern Finland. In general, the predicted rate of self-thinning was probably too high. Self-thinning models may not act properly in drained peatland stands, because of the wide range in tree diameters and clumped spatial distribution of trees. However, without the self-thinning, the growth model may result in stocking which is too high, especially for birch stands, due to the lack of the stand-level competition factor in the model.

In general, a slow initial development of stand volume for all species was expected after drainage. This could be explained by the lower growth of trees during the first 10 years, as determined by the growth models, and by the low initial stocking (the trees were mainly small and the number of stems was low). Hånell (1984) has given similar results from Sweden. At stand level, the higher relative responses of pine and birch, compared to that of spruce, could be explained by the different growth dynamics of the species (Mielikäinen 1985) and the greater temporal changes in the growth of pine and birch following drainage (I). The volume growth of spruce was initially higher due to the greater stand volume.

The development of the basal area growth obtained in this study in southern Finland can be compared to that presented by Hånell (1984) for the pine-dominated tall-sedge type and the spruce-dominated bilberry-horsetail type in unthinned stands in southern Sweden. For the pine stand, the post-drainage behaviour of growth was similar, while in the spruce stand, the basal area growth curve in this study showed a heavier decrease 30 years after drainage due to the self-thinning. Stand volumes achieved 40 years after drainage were higher for both pine and spruce in this study than those obtained by Hånell (1984).

The development of volume growth of pine and spruce stands as a function of stand volume can also be compared to the relative growth rates given by Keltikangas et al. (1986) for a tall-sedge pine fen and a *Vaccinium myrtillus* spruce swamp in middle parts of Finland. The pine stand showed equal growth rates until the stand volume exceeded 150 m^3ha^{-1}. A lower growth rate was obtained for greater volumes in this study. For the *Vaccinium myrtillus* spruce swamp, the volume growth as a function of volume was similar in both studies up to 200 m^3ha^{-1}, but for greater volumes growth was lower in the present study.

The pine and birch stands showed rather similar development of stand volume following drainage. The faster development of the birch stand can be explained by differences in site quality: the yield class for pine also included oligotrophic sites, which were missing from the yield class of birch. Furthermore, the initial stand was slightly denser for birch. Keltikangas and Seppälä (1977) have suggested that pine and birch grow equally well in mesotrophic and oligo-mesotrophic drained peatland sites in Ostrobothnia, while Saramäki (1977) concluded that the growth of pine was clearly higher than that of birch in equal sites in northern Finland. More simulations should be done to compare the development of these species on the basis of the developed models.

Even though the difference in temperature sums used for southern and northern Finland was not considerable (150 dd°C), the difference in stand volumes at the end of the simulation period was almost two-fold for pine and birch. Hånell (1988) concluded that the difference in the average productivity of a site during the post-drainage rotation was generally more than three-fold within a much wider range (600 - 1600 dd°C) in temperature sum. According to Hånell (1984), the change in site productivity as a function of temperature sum which he presented was somewhat smaller than that presented earlier by Heikurainen (1972). Compared to mineral soil sites, the variation in growth as a function of temperature sum may be greater on drained peatlands because of the higher humidity in the north, which may affect tree growth on peatlands more than the change in temperature sum alone would suggest.

It should be remembered that the results were based on simulations with one sample stand for each species, and different results would have been obtained with different initial stand conditions.

592. Stand-level response to improvement ditching

Because the growth response was higher the greater the tree diameter or initial stand basal area, full-stocked stands composed of large trees responded most to improvement ditching. If the stand was composed of mainly small trees, the stand-level volume development was different, depending on the method applied. In an under-stocked stand, only the combination treatment gave a notable growth response. The average response was clearly highest for the combination treatment, but in stands with a high basal area composed of large trees, complementary ditching occasionally produced even higher stand volumes than the combination treatment, which appeared non-realistic. This was due to the unbalanced data and initial differences in the growth rates of the trees to which the different treatments had been applied. All these effects could not be accounted for in the

model construction and were thus included in the model parameters. Consequently, the model may give too high a response to complementary ditching in extreme circumstances.

The model assumes higher response in stands with high basal area. This may be the case when average low-stocked stands are considered, but in well-stocked stands the groundwater table is kept down as a result of interception and transpiration (Maki 1971, Duncan and Terry 1983, Laine 1986). Thus, a limit could be found where the effect of any ditching treatment on growth remains marginal because these kinds of stands are not actually suffering from excess water. It is also realistic to assume that improvement ditching is not needed in all drained peatland stands before the final cutting and regeneration. However, Laine (1986) has shown that the relationship between the groundwater table and stand growth rate is linear as far down as a depth of 70 cm.

It was possible to determine the effect of different improvement ditching methods on stand growth with the model, but reliable comparisons to the non-treated stands could not be made, because it was not possible to determine the long-term behaviour of growth in the non-treated stands. It is probable that a decreasing temporal trend is needed to describe the effect of continuously impaired site conditions on tree growth, especially in low-stocked stands. Furthermore, mortality may increase in such conditions. The stand level volume development of non-ditched stands may be much poorer than that assumed here.

The results suggested that when improvement ditching is planned, the method applied can be selected on the basis of stand conditions: the additional growth obtained from the combination treatment compared to complementary ditching in stands where basal area exceeds a certain limit (e.g., 10 - 12 m^2ha^{-1}) is only marginal. It would be more economical to carry out complementary ditching or, if the original ditch spacing is narrow, ditch cleaning. Correspondingly, in a poorly stocked stand, only the combination treatment can give a notable response. However, this kind of measure is the most expensive and may not be economical in sites with low initial stand volumes.

Because the experimental stands in the data were low-stocked, no stand treatments were carried out. In practice, improvement ditching is generally connected with commercial thinning, because transpiration and interception decrease abruptly due to the reduced stand basal area which results from thinning, and a subsequent increase in the groundwater table may follow (Päivänen 1982). Furthermore, old ditches may become blocked in timber transportation. To compensate for the negative effects of these conditions on stand development, improvement ditching needs to be carried out. The combined effect of these measures on tree growth may not be the same as the sum of the separate effects.

6. Conclusions and prospects for future research

By constructing growth models, the effect of different growth factors - e.g., site quality, inter-tree competition, tree vigor, and ditching treatment - on individual-tree growth in drained peatland sites in Finland was described. Using the models, it was possible to predict the development of pine, spruce, and birch in drained peatland sites with growth simulators. The models were fairly similar to those derived for the various tree species growing in mineral soil sites. It was concluded that the uneven size distribution of trees (Hånell 1984, Hökkä and Laine 1988), the low stocking of stands on the average, and the temporal variation in growth (Seppälä 1969, Hånell 1984) due to drainage treatments

(both the drainage of pristine peatland stands and improvement ditching carried out in drained peatland stands), were important factors in determining tree growth. These are the main features that distinguish stands growing in drained peatland sites from those growing in mineral soil sites.

Due to the uneven size distribution of trees, the effect of inter-tree competition on individual-tree growth was described with a nonlinear relationship in the basal area growth models (I). In the height-diameter models (II), relatively linear curves were obtained due to the low competition and subsequent great within-stand variation in tree height as a function of tree diameter. In the basal area growth models, the average growth at stand level was expressed as a function of stand drainage age as described by the age classes. The temporal variation in growth was in accordance with the results given by Seppälä (1969). With the height-diameter models, different curves were obtained for recently drained stands composed mainly of small trees and those drained a long time ago and composed of large trees. Improvement ditching influenced the annual diameter growth as a function of the ditching method applied, the time elapsed since treatment, the initial tree size, and the initial stand stocking (III).

The stand-level simulations showed that stand volume increased slowly for all species during the first 10 - 20 years after the drainage of a pristine peatland site, while more rapid volume development occurred between 20 - 40 years after drainage. In the pine stand, the increase in stand volumes during the 50-year period following drainage was almost two times greater in southern (1200 dd°C) than in northern (1050 dd°C) Finland. Pine and birch stands showed a fairly similar pattern of post-drainage development. The relative growth increase of the spruce stand was lower than that of the pine and birch stands. The volume growth peaked between 20-30 years after drainage except in the birch stand in northern Finland.

The stand-level response to improvement ditching was highest in well-stocked stands composed of mainly large trees. In an understocked stand with small trees, only the combination of ditch cleaning and complementary ditching caused an increase in stand volume growth.

Even though the models gave a basis for predicting the development of pine, birch and spruce following drainage and the effect of stand management measures like thinning and improvement ditching on the growth of pine, they did not form a comprehensive system for predicting tree growth in drained peatland sites. Ingrowth and self-thinning influence stand-level growth dynamics, but were not specifically described for drained peatlands. Ingrowth following drainage may be substantial in understocked stands with easily regenerable sites (Hånell 1984, Hökkä and Laine 1988), and, if ignored, underestimated stand-level growth may be obtained. However, the importance of ingrowth in predictions is decreasing, because the drainage of pristine peatlands has practically ceased, and there is no need to predict the growth of newly ditched peatlands. Specific self-thinning models (Hynynen 1993) are applied in growth simulators to prevent non-realistic development of stand stocking (Ojansuu et al. 1991). The self-thinning models derived for even-aged stands growing in mineral soil sites may be incapable of predicting self-thinning in drained peatland stands, which are characterized by uneven size distribution and clumped spatial distribution of trees. Furthermore, it is probable that in drained peatlands self-thinning, or mortality, is to some extent a function of site drainage, which, in turn, is of no

importance in models derived for mineral soil sites. Thus, models predicting self-thinning in drained peatland sites should be capable of accounting for these aspects.

The modelling of management options and their effect on growth could be improved. While thinning has been observed to increase growth for 10 - 15 yrs following the treatment (Hynynen 1995b), there is a need to develop a more complete model to predict the thinning response in drained peatland stands. For the purposes of long-term simulations, a model should be developed to predict when and where improvement ditching is needed. Developing a system to describe site quality with a continuous variable instead of categorical ones would permit more efficient use of site quality in growth modelling (see Ojansuu 1996). The growth response to improvement ditching should be evaluated during a longer observation period and by collecting information from more fertile sites and from birch and spruce. Furthermore, the combined effect of thinning and improvement ditching needs to be described.

When information on tree growth in drained peatland sites is collected, especially for modelling purposes, some additional measurements should be considered. The drainage age is the most important variable in determining the growth of recently drained stands. There are processes in the soil (e.g., nutrition) that show a correlation with the drainage age even in older drainage areas and which may be important for growth, too (Kaunisto and Paavilainen 1988, Laiho 1997). Furthermore, the timing of improvement ditching is most probably a function of drainage age. Consequently, the drainage age should be determined more accurately for all stands (e.g., in 5-yr classes estimated on the basis of increment cores). Ditch spacing is important in areas where regular spacing is established. It partly determines the method that should be chosen if improvement ditching is to be carried out, and it is also correlated with stand growth.

The fact that the data were somewhat unbalanced with respect to regionality and clearly unbalanced with respect to tree size caused problems in studies I and II. In study III well-stocked stands were lacking. Despite the fact that the proportion of stands with large trees was weighted in the SINKA data, large trees were still under-represented in the modelling data. Thus, there is a need to update and validate the models when data from more advanced stands become available. In data collection, more stands and trees - but fewer plots within stands - should be measured, because it has been shown that, in growth studies, the variation between stands is more important than the variation among plots within stands (Penner et al. 1995). And perhaps the most important requirement is that in drained peatlands, where considerable changes in site and stand conditions take place over time, several successive measurements of the same plots and trees are needed in order to obtain a better understanding of growth processes even though it will be more expensive.

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I

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.

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
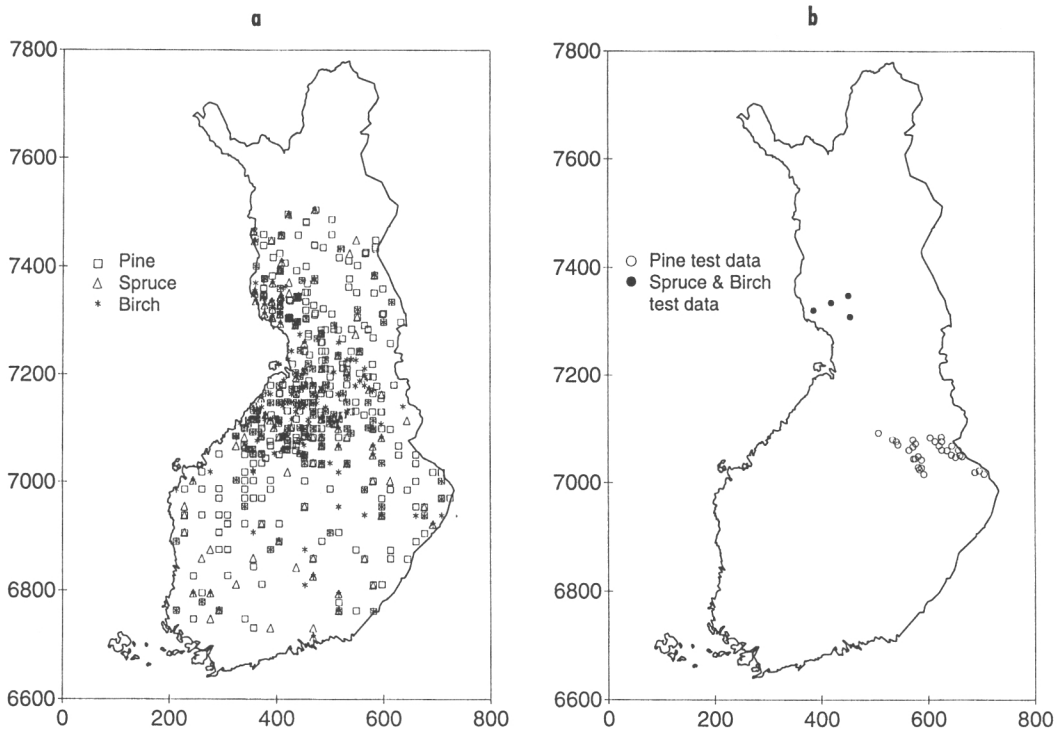

Fig. 1. Location of the modelling data (a) and test data (b) by tree species.

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-drain-age 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
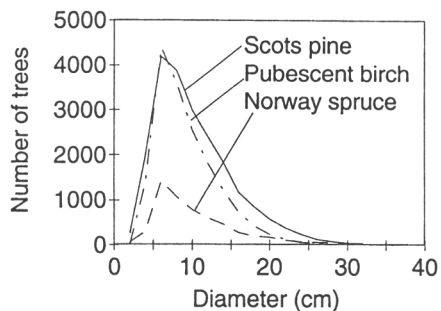[f] average height of 100 thickest trees per hectare

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 $-2 \times$ 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 rela-

tionship 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
(BAL)^2		−0.00152785	0.00014132	0.0000
ln(G)		−0.24680408	0.02625567	0.0000
(Tsum × 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 $\times (d)^{0.5}$		0.31576897	0.07907760	0.0001
s3 $\times (d)^{0.5}$		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.
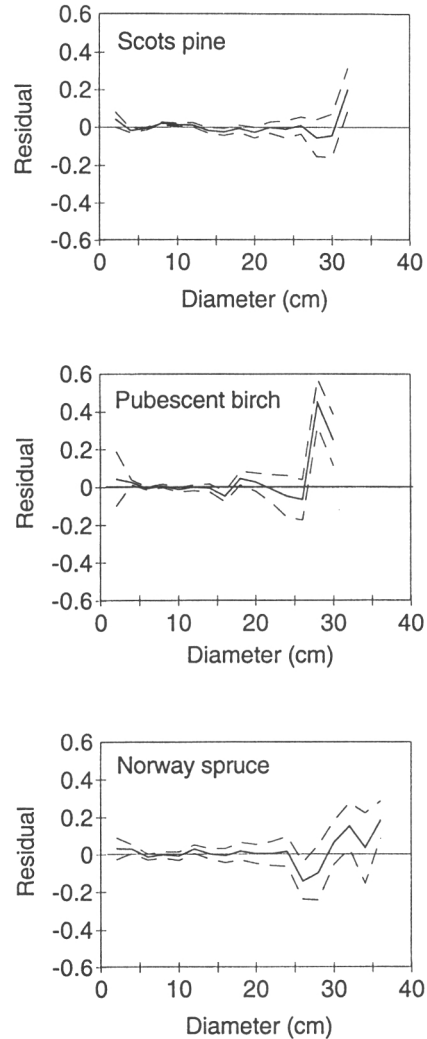
The average bias for the models at the original

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	−1.9933	−1.3053	−2.1686
(cm^2/5yrs)	(0.0938)	(0.0843)	(0.1857)
Relative	−0.0632	−0.0591	−0.0854
	(0.0042)	(0.0207)	(0.0080)

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).

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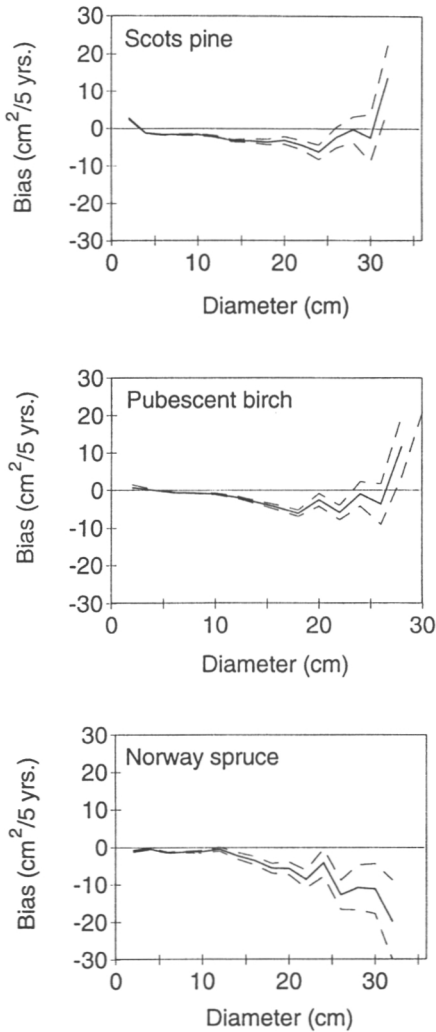. First, the noncorrected predictions were estimated as a function of tree diameter in the modelling data. Then, the estimated bias was corrected to zero with a correction term which was calculated for each 2-cm diameter class for all models as follows:

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

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

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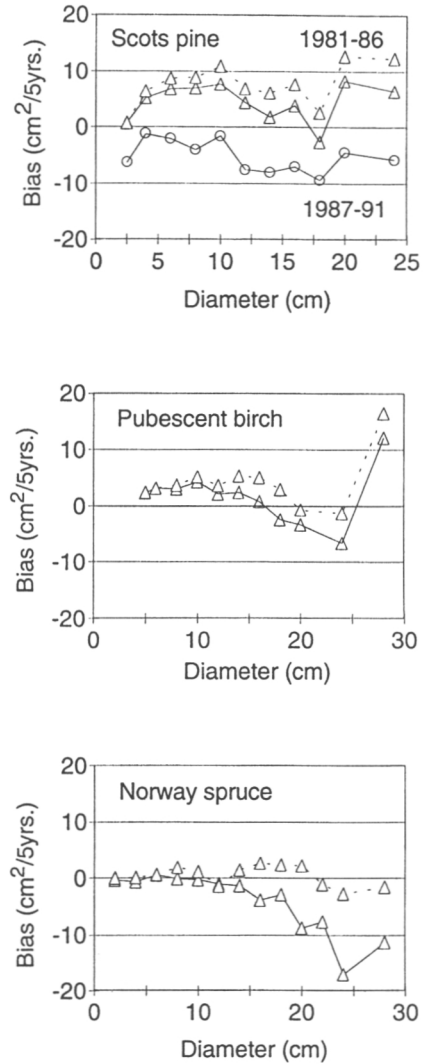
Fig. 5. Estimated mean bias of the models as a function of tree diameter in the independent test data sets using constant variance correction (solid lines) or a correction term for each 2-cm diameter class (see Eq 2, dashed lines). For Scots pine, bias was estimated for two successive 5 yr. periods.

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 cm²/5yrs 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 cm²/5 yrs (s.e. 0.361), and –2.72 cm²/5 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 varia-

bles 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.

Acknowledgments

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II

Height-diameter curves with random intercepts and slopes for trees growing on drained peatlands

Hannu Hökkä

Abstract

Models for predicting tree height were constructed for Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and pubescent birch (*Betula pubescens*). The data consisted of two separate sets of permanent sample plots forming a representative sample of drained peatland stands in the whole country. A logarithmic height-diameter curve with one non-linear parameter specific to each tree species was applied. It was assumed that the intercept and slope of the curve would vary randomly from stand to stand. Stand characteristics were used to predict the mean intercept and slope. A nonhomogeneous variance of the residual error was modelled as a function of tree diameter. A mixed linear model technique was applied to fit the models. The diameter of the tree of the median basal area, stand basal area, geographical location of the stand, and site quality were used as fixed independent variables in explaining the variation in the intercept. The diameter of the tree of the median basal area and the stand basal area were used in explaining the variation in the slope.

Key words: *Betula pubescens*, peatland forest, height-diameter curve, *Norway spruce*, *Pinus sylvestris*, random parameters

Introduction

According to forestry statistics, the area of peatlands and paludified forests drained for forestry in Finland is 5.9 mill. ha (Yearbook of Forest Statistics 1993). In the beginning of the 1980s the proportion of peatlands was about 24 % of the total forest land area and about 22 % of annual growth (Paavilainen and Tiihonen 1987). In northern Finland, the importance of peatland forestry is even greater, because peatlands are concentrated in areas that are topographically and climatically most suitable for paludification.

Tree stands growing on drained peatlands differ from those growing on mineral soils because the age, size, and spatial distributions of trees are generally more uneven (Hökkä and Laine 1988, Hökkä et al. 1991, Miina et al. 1991). The basic reason for this is the initial uneven structure of the virgin peatland stands (Heikurainen 1971, Gustavsen and Päivänen 1986). After drainage, the dependence between tree age and tree size is variable. If not regenerated at the time of drainage, only pubescent birch (*Betula pubescens*) can form stands that become relatively even-aged during the first rotation (Saramäki 1977). The range of variation in tree height is obviously greater than on mineral soils due to the uneven spatial distribution of trees. Consequently, the relationship between diameter and height may also vary more than in stands with even structure.

Except for Scots pine (*Pinus sylvestris*), the same height models have been applied previously to mineral soils and drained peatlands (Veltheim 1987). The data behind the models consisted mainly of mineral soil sites. It can be assumed that these models give biased results when applied to stands on drained peatlands. Constructing separate models for drained peatlands and mineral soil sites can be justified by the differences in stand structure. Furthermore, considerable changes in stand structure take place with increasing time since drainage (Hökkä and Laine 1988). This is due to the differences in the post-drainage growth potential of trees of different size and age (Seppälä 1969). Changes in stand structure influence the form of the height-diameter curve. Thus, one requirement for a model predicting the curve is flexibility.

The aim of this study was to construct height-diameter curves for Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and pubescent birch (*Betula pubescens*) growing on drained peatlands. The models should give accurate predictions of tree height using common tree, stand, and site characteristics measured in forest inventories.

Materials and methods

The data

The data consisted of two separate inventory data sets, covering the whole area where forest drainage has been applied in practical forestry. For southern Finland, the permanent sample plots of the 8th National Forest Inventory (NFI8) were used. For northern Finland, Permanent Forest Inventory Growth plots (SINKA) were used. The former is a systematic subsample of the sample plots of NFI8. The latter is a random stratified subsample of the sample plots of NFI7. All plots in the data sets were classified as peatlands. The data sets overlapped in the southern part of northern Finland. A more detailed description of the data sets is given in Penttilä and Honkanen (1986) and Mielikäinen and Gustavsen (1993).

In the NFI8 data, each stand was represented by only one plot, while in the SINKA data, a cluster of three sample plots was situated in each stand. Because the data sets were finally combined, and because within-stand variation was not the main interest in this study, only one plot out of three was taken from the SINKA data. This was the plot which was located closest to the original NFI7 sample plot.

Only sample tree data were used because tree height was not measured for the other trees. In the NFI8 data, sample trees were collected from a circular subplot, the radius of which was either 2.82 m or 4.89 m, depending on whether the tree diameter was less or greater than 10.5 cm. The minimum measured diameter was generally 4.5 cm. In the SINKA data, the radius of the sample tree subplot varied from stand to stand, giving on average 30-35 sample trees. Minimum measured diameters were 4.5 cm if the stand was past pole age, 2.5 cm otherwise. In the NFI8 data, the number of sample trees in a stand was consistently lower.

Some trees or stands were removed from the data for various reasons. Stands with only one tree were deleted because at least two sample trees per stand were needed to fit the

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height-diameter curve standwise. Some sample trees of exceptionally poor stem form were removed. Some stands were removed if the sample tree diameters were small compared to the stand's mean diameter, making it obvious that all sample trees were suppressed trees belonging to a younger tree generation.

Based on the average stand characteristics, most stands could be characterized as being in the phase of shifting to commercial size (Table 1). Stand ages were not determined because their connection to the developmental stage of the stand is vague. The average tree size was greatest in the spruce data and smallest in the pine data. The number of trees was smallest in the spruce data because spruce-dominated stands were concentrated in southern Lapland in the SINKA data. Outside this area, the spruces mainly came from mixed stands. Furthermore, in southern Finland, spruce mires are much less common than pine mires. For all tree species, the data were concentrated in Ostrobothnia, where the proportion of drained peatlands compared to the total forest land area is at its maximum (Fig. 1). Site quality classification was based on Huikari's (1952, 1974) system of six site classes, which has been used in NFI. The distribution of trees into different site quality classes was uneven and differed by species (Table 2).
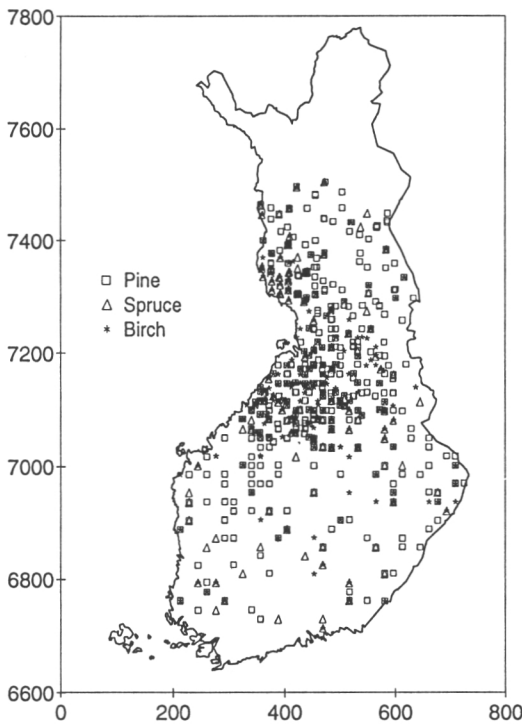
Figure 1. Location of the sample plots by tree species.

Table 1. Minimum, mean, maximum, and standard deviation of tree, stand and site characteristics by tree species.

| | Tree species | | | | | | | | | | | |
| | Norway spruce | | | | Pubescent birch | | | | Scots pine | | | |
Variable	min.	mean	max.	s.d.	min.	mean	max.	s.d.	min.	mean	max.	s.d.
h (m)	1.7	8.7	24.0	4.9	2.6	9.3	23.0	3.4	1.5	7.4	23.3	3.7
d (cm)	1.2	11.8	34.2	6.4	2.0	9.4	31.5	4.6	1.0	10.2	33.5	5.7
G^a (m²ha⁻¹)	2.0	17.1	45.1	8.54	1.4	15.4	45.1	7.92	0.36	10.8	36.5	7.16
D_{gM}^b (cm)	5.5	14.9	30.9	4.89	3.7	12.2	26.4	4.33	2.7	11.9	27.5	4.30
Pine, % of G	0.0	21.1	97.1	25.3	0.0	25.5	94.6	27.1	4.1	78.8	100.0	24.5
Spruce, "	2.5	46.9	100.0	26.9	0.0	14.0	86.3	20.9	0.0	5.4	77.9	12.0
Birch, "	0.0	31.2	96.5	24.4	2.0	59.5	100.0	28.6	0.0	15.7	89.6	21.0
N coord (km)	67149	71562	75040	2046	67149	71561	75040	1457	67301	71429	75040	1702
E coord (km)	2290	4343	6930	928	2130	4449	7090	838	2130	4611	7250	967
dd^c (°C)	717	1015	1341	122	717	1017	1295	86	712	1004	1295	110
Elevation (m)	10	106	260	58	2	102	280	56	20	130	300	55
Stands	131				279				458			
Trees	769				2133				3450			

a stand basal area
b diameter of the tree of median basal area
c average temperature sum in degree days (threshold value +5 °C)

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Table 2. Distribution of trees into site quality classes (Huikari 1952, 1974) by tree species.

Site quality class	Tree species		
	Spruce	Birch	Pine
S1 Eutrophic mires	160	164	219
S2 Herb-rich mires	173	837	479
S3 *Vaccinium myrtillus* and tall-sedge mires	355	847	888
S4 *V. vitis-idaea* and small-sedge mires	81	262	1499
S5 Cottongrass and dwarf shrub mires	-	23	362
S6 *Sphagnum fuscum* mires	-	-	3

Methods

The height formula used here was the exponential model, used also by Flewelling and de Jong (1994) and Lappi (1997):

$$h = 1.3 + A\exp(-bd^{-c})$$ (1)

where h is the total height of a tree and d is tree diameter at breast height (dbh). After transferring 1.3 to the left side and taking logarithms, the model is linear except for parameter c:

$$ln(h-1.3) = a - bd^{-c}$$ (2)

where $a = lnA$. When the parameters of the height model can vary from stand to stand, the height of tree i in stand j can be described with model:

$$ln(h_{ij} - 1.3) = a_j - b_j d_{ij}^{-c} + e_{ij}$$ (3)

where e_{ij} is an error term. With respect to parameters a_j, b_j and tree diameter, the model was parametrized according to Lappi (1997):

$$ln(h_{ij}-1.3) = A_j - B_j x_{ij} + e_{ij}$$ (4)

where $x_{ij} = ((d_{ij}^{-c})-(30^{-c}))/((10^{-c})-(30^{-c}))$ (5)

Using this expression, A_j can be interpreted as the expected value of $\ln(h\text{-}1.3)$ for trees with a diameter of 30 cm and B_j as the expected difference of $\ln(h\text{-}1.3)$ between trees with diameters of 30 cm and 10 cm (Lappi 1997). The appropriate value for parameter c was determined by tree species. Alternative models (Eq. 4) with exponents varying from 0.2 - 1.5 were fit for each stand by the ordinary least squares (OLS) method. The minimum sum of squares of the residuals was used as an indicator of the best exponent. The values chosen were 0.3, 0.4 and 0.7 for Norway spruce, Scots pine and pubescent birch, respectively.

Due to the two-level data structure - trees within stands - the mixed linear model technique as implemented in ML3 software (Prosser et al. 1991) was applied. The model principle can be described by a simple example generated by any two-level data set. The dependence of the response variable Y on the first-level explanatory variable X and the second-level explanatory variable Z is expressed using a simple first-level regression equation for Y and X (see Prosser et al. 1991),

$$Y_{ij} = b_{0j} + b_{1j}X_{ij} + e_{ij} \qquad (6)$$

and equation that describe the variation of the random coefficients (b_{0j} and b_{1j}, which are the intercept and the slope, respectively) as a function of the second-level variable Z:

$$b_{0j} = \gamma_{00} + \gamma_{01}Z_j + u_{0j} \qquad (7)$$

$$b_{1j} = \gamma_{10} + \gamma_{11}Z_j + u_{1j} \qquad (8)$$

By combining Eq. (6) - (8) the following equation is obtained:

$$Y_{ij} = \gamma_{00} + \gamma_{10}X_{ij} + \gamma_{01}Z_j + \gamma_{11}Z_jX_{ij} + (u_{0j} + u_{1j}X_{ij} + e_{ij}) \qquad (9)$$

Variables in the fixed part are: the intercept, first-level explanatory variable X_{ij}, second-level explanatory variable Z_j and cross-product Z_jX_{1ij}. The random part (in parentheses) consists of three random effects that are the intercept (u_{0j}), the slope (u_{1j}) and the residual error (e_{ij}) (Prosser et al. 1991).

Tree height was assumed to depend on tree diameter according to Eq. (3), the exponent c being specific to each species. Another basic assumption was that height-diameter curves vary randomly from stand to stand with respect to both intercept (A) and slope (B) (Lappi 1996). This variation was modelled by assuming these parameters to be composed of a fixed mean function and random stand effects with mean zero and constant variance. The mean was expressed as a function of stand and site characteristics. When estimating the mean function for parameters B, and using a stand-level variable Z_j in explaining B_j, a variable Z_jx_{ij} must be included in the fixed part of the model. In the following, the variances of the random intercept and slope are termed σ^2_{u0} and σ^2_{u1} (and the corresponding standard deviations are termed σ_{u0} and σ_{u1}). The covariance between the random intercept and slope is termed σ_{u0u1}.

The models were estimated using the restricted iterative least square (RIGLS) method recommended for small samples (Prosser et al. 1991). It is an iterative method producing restricted maximum likelihood estimates for the parameters. The model evaluation was

done according to several criteria. Comparing the parameters and their standard errors indicated whether the parameters were significant. Model improvement resulted in decreased values of the variances of the random parameters as well as lower value for the -2×log-likelihood. Transformations were made to linearize the relationship between the response and explanatory variables.

Results

Norway spruce

For spruce, the covariance between slope and intercept (σ_{u0u1}) was not significant, and the correlation was relatively low (-0.24). However, the variances of random stand effects (σ^2_{u0} and σ^2_{u1}) indicating between-stand variation in parameters A and B, which refer to the intercept and slope in Eq. (4), were significant (Table 3). The number of independent variables explaining the variation in intercept was small, probably due to the low number of stands and trees. The logarithm of the diameter of the tree of median basal area (D_{gM}), logarithm of stand basal area, and north coordinate (divided by1000) explained the variation in intercept. D_{gM} and tree diameter explained the slope of the curve.

Table 3. Model for the height-diameter curve for Norway spruce. In the random part, estimated variances of the random effects are given. Standard errors are in parentheses. For notations, see Table 1.

Parameter	Fixed part	Random part	
A	6.154($\pm$0.4065)	Stand level	
	0.1058 ($\pm$0.05155) $\ln D_{gM}$		
	0.1683 ($\pm$0.02182) $\ln G$	σ^2_{u0}	0.003633($\pm$0.001507)
	-0.02518($\pm$0.004846) Ncoord	σ_{u0}	0.060274
B	0.6648($\pm$0.09735)	σ^2_{u1}	0.002213($\pm$0.001056)
	0.1045 ($\pm$0.03671) $\ln D_{gM} \cdot x^1$	σ_{u1}	0.047043
		Tree level	
		σ^2_{e}	0.02431($\pm$0.001375)

^{1} tree diameter as expressed in Eq. (5)

Pubescent birch

For birch, the covariance of the stand-level random effects was significant (Table 4), and correlation was considerably higher than for spruce (0.579). Fixed stand-level variables explaining intercept A were the logarithm of D_{gM}, north coordinate (divided by1000), elevation above sea level, the logarithm of the total basal area of birch, and a dummy variable which had value 1 if the stand had been thinned during the past five

years, or 0 otherwise. The slope of the curve (B) was explained by tree diameter, D_{gM}, and stand basal area.

Despite logarithmic transformation, the variance of the OLS residuals was not constant at the tree level. When plotted against tree diameter, the squared residuals indicated that the variance of e_{ij} tended to decrease as tree size increased (Fig. 2). It is possible to express the variance of the residual error as a function of some independent variable if constant variance cannot be assumed. The following variance function was used to describe tree-level variance:

$$\text{var}(e_{ij}) = (Max(d_{ij}, p)^q)\sigma_{e1}^2 + \sigma_{e0}^2 \tag{10}$$

The search for the appropriate values for the parameters p and q was done with trial-and-error method based on two criteria: the value of the -2×log-likelihood, and the graphic fit with the group means of squared residuals in diameter classes (Fig. 2) and the alternative models produced by different parameter combinations. Values were determined to be 9 and -2 for p and q, respectively. The variance function was included in the model following the way it is implemented in the ML3 software (see Woodhouse 1993), and the linear parameters (σ_{e0}^2 and σ_{e1}^2) were estimated simultaneously with the whole model.

Table 4. Model for the height-diameter curve for pubescent birch. σ_{u0u1} denotes covariance and ρ correlation between the random stand effects. For other notations, see Tables 1 and 3. Nonhomogeneus variance at the tree level is accounted for.

Parameter	Fixed part	Random part	
A	6.465 ($\pm$0.417)	Stand level	
	0.4743($\pm$0.03084) lnD_{gM}		
	0.1339($\pm$0.01302) ln$((G_b/100)+1)$		
	-0.04331($\pm$0.005426) N coord		
	-0.0004369($\pm$0.0001349) Elevation	σ_{u0}^2	0.01772($\pm$0.002417)
	0.06447($\pm$0.01824) Thin (0/1)	σ_{u0}	0.133116
B	-0.05942($\pm$0.04247)		
	0.2123($\pm$0.01955) ln$D_{gM}\cdot$x	σ_{u1}^2	0.004265($\pm$0.0008604)
	-0.004922($\pm$0.0008383) G$\cdot$x	σ_{u1}	0.065307
		σ_{u0u1}	0.005031($\pm$0.001283)
		ρ_{u0u1}	0.5788
		Tree level	
		σ_{e0}^2	0.003595($\pm$0.0007539)
		σ_{e1}^2	0.852($\pm$0.09086)

When compared to the model with constant tree-level variance, modelling the variance as a function of tree diameter produced a considerably lower value for the -2×log-likelihood and also decreased the variance of the slope σ^2_{u1}. Furthermore, the correlations between the random terms at stand level were lower. However, incorporating the variance function into the model changed the estimates of the fixed part only slightly; therefore, only the model with variance function is presented here.
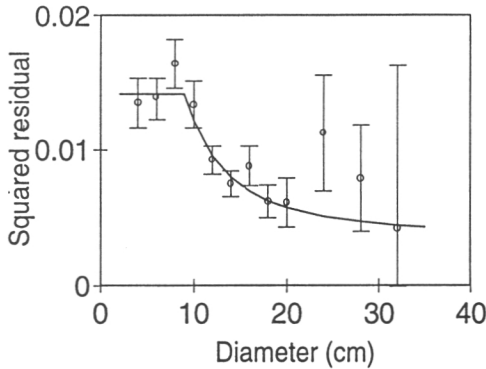
Figure 2. Mean squared residuals and respective standard errors of model (4) for birch by tree diameter classes, and the estimated variance function (10).
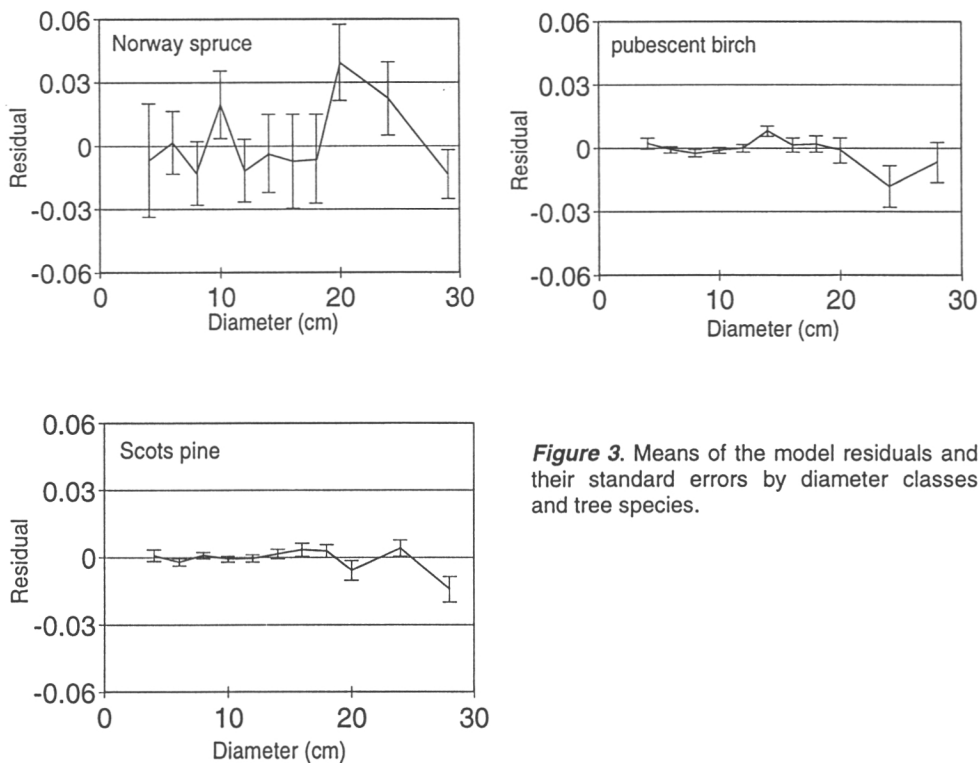
Scots pine

The positive correlation between the random stand effects was the highest for pine (0.655, Table 5). The intercept was explained by the logarithm of D_{gM}, the north coordinate, the logarithm of the stand basal area, and the dummy variable for thinning. In contrast to the other models, a dummy variable indicating site quality according to the classification system of Huikari (1952), was significant. The curve was higher for sites S2 - S4. For pine, tree diameter, the logarithm of D_{gM}, and the logarithm of the stand basal area explained the variation in the slope of the curve.

Also for pine, a variance function for the residual term similar to that for birch (Eq. 10) was used. The same values for parameters p (9) and q (-2) resulted in good fit with pine as well. A significantly better model in terms of the -2×log-likelihood resulted, but the fixed parameter estimates remained almost the same.

Model validation

During the model construction, residual plots were used to examine any trends between response and explanatory variables after fitting a model. Tree diameters were classified, and plots were produced to check any trend in the average values of the residuals in these classes (Fig. 3). The figures were produced from the tree-level residuals, and the effect of stand-level variables cannot be seen. No systematic trend in residuals was detected for any species.

Figure 3. Means of the model residuals and their standard errors by diameter classes and tree species.

Table 5. Model for the height-diameter curve for Scots pine. Site is a dummy variable including sites S2-S4 in Table 2. For other notations, see Tables 1, 3 and 4. Nonhomogeneus variance at the tree level is accounted for.

Parameter	Fixed part	Random part	
A	5.369($\pm$0.3139)	Stand level	
	0.3566($\pm$0.03451) $\ln D_{gM}$		
	0.1177($\pm$0.01672) $\ln G$		
	-0.02638($\pm$0.004088) N coord		
	0.05115($\pm$0.01649) Thin (0/1)	σ^2_{u0}	0.02407($\pm$0.002547)
	0.0984($\pm$0.01719) Site (0/1)	σ_{u0}	0.155145
B	0.3742($\pm$0.03857)		
	0.141($\pm$0.01831) $\ln D_{gM} \cdot x$	σ^2_{u1}	0.005395($\pm$0.0009467)
	-0.01263($\pm$0.001274) $G \cdot x$	σ_{u1}	0.07345
		σ_{u0u1}	0.007469($\pm$0.001438)
		ρ_{u0u1}	0.6554
		Tree level	
		σ^2_{e0}	0.005175($\pm$0.0008566)
		σ^2_{e1}	1.93(+0.1243)

10

The models were tested in the modeling data by calculating the model bias as the difference between the observed heights and those predicted by the fixed part of the model at the original scale of height. Before applying the exponential transformation, half of the model variance was added to the logarithmic predictions in order to correct bias in the transformation (Flewelling and Pienaar 1981). In these models, the correction was proportional to tree size according to the following formula:

$$0.5\sigma_f^2 = 0.5((\sigma_{u0}^2 + 2\sigma_{u0u1}x_{ij} + \sigma_{u1}^2 x_{ij}^2) + (\sigma_{e0}^2 + \sigma_{e1}^2((Max(d_{ij},9)^{-1})^2))) \qquad (11)$$

where x_{ij} is tree diameter as expressed in Eq. (5). The average bias of all models was low, especially when the correction term was applied (Table 6). With spruce, the bias did not depend on diameter (Fig. 4). The model for birch slightly underestimated the height of trees 10 - 20 cm in diameter, and overestimated the height of the largest trees. The model for pine was virtually unbiased up to 20 cm dbh. The height of trees larger than 20 cm in diameter was systematically underestimated (Fig. 4). The most probable reason for the bias in large trees was the high proportion of small trees in the data: e.g., 93% of pines and 97% of birches were less than 20 cm in diameter.
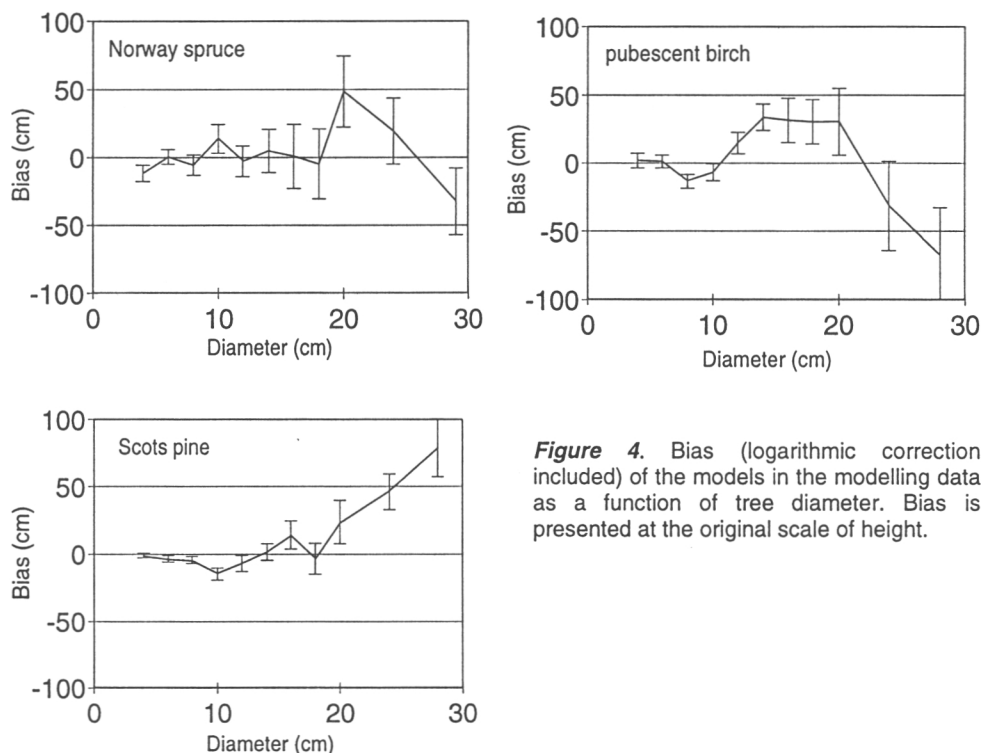

Figure 4. Bias (logarithmic correction included) of the models in the modelling data as a function of tree diameter. Bias is presented at the original scale of height.

Table 6. Average bias (standard errors given in parentheses are biased downwards due to the correlated observations) of the models in the modelling data and the effect of the correction term.

	Spruce	Birch	Pine
Bias, not corrected (cm)	12.79 (4.36)	14.46 (2.68)	12.43 (2.05)
Bias, corrected (cm)	1.94 (4.36)	4.75 (2.68)	1.40 cm (2.04)

Figure 5 gives an example of the height curves predicted by the models. The model for spruce seems to produce curves of rather linear shape, while the models for birch and pine produce more nonlinear curves. Consequently, the range in predicted heights for small trees is narrower for spruce than for the other species. With respect to the accuracy of height measurements, the effect of the logarithmic correction term appears to be trivial.
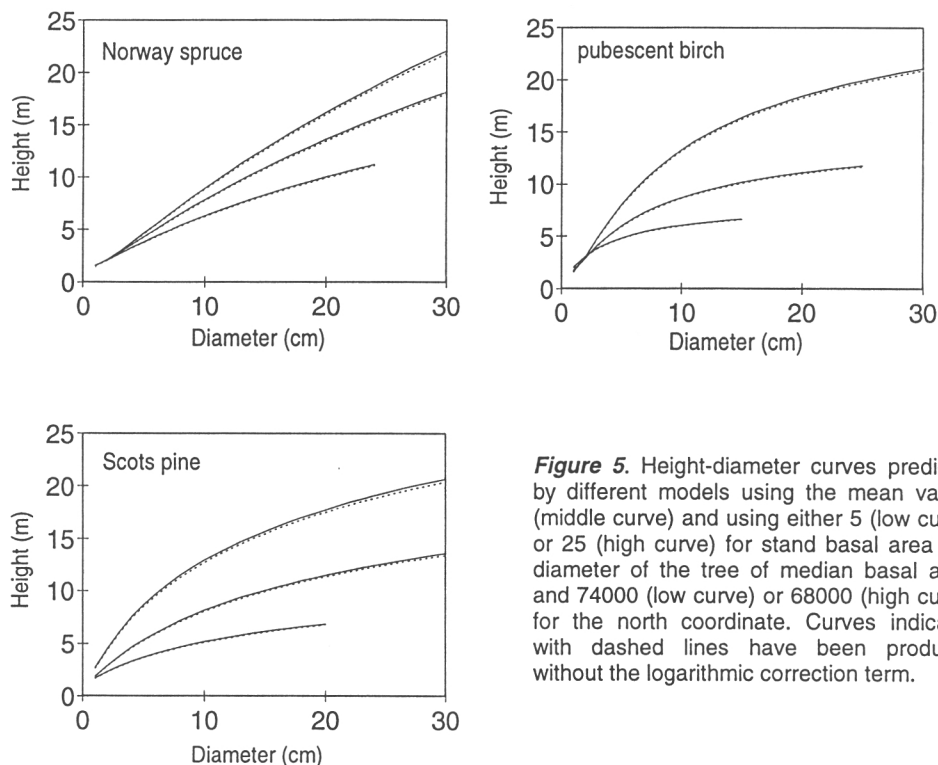
Figure 5. Height-diameter curves predicted by different models using the mean values (middle curve) and using either 5 (low curve) or 25 (high curve) for stand basal area and diameter of the tree of median basal area, and 74000 (low curve) or 68000 (high curve) for the north coordinate. Curves indicated with dashed lines have been produced without the logarithmic correction term.

Discussion

The basic, present use of the models developed will be as part of a growth simulator used in forecasting the development of large-scale forest resources (MELA system, Siitonen 1983). This fact presupposes that the modelling data are regionally representative.

Another important requirement for models of this kind of use is that they should give reliable predictions when applied to various data sets. For these reasons, an objective random sample from all kinds of drained peatland stands all over the country was used as the data in the modelling work. Undrained peatlands were excluded from these data. Actually these were the only data covering the whole country. Although representative, the data were not ideal for modelling purposes, because the stands were mainly young and the trees were small. As suggested by Figure 4, the predictions given by the models may be biased for large trees, which may cause problems in long-term simulations. In order to avoid unreliable predictions, there remains a need to validate and update the models when future inventories provide more data from older stands.

After the logarithmic transformation, the form of the height - diameter relationship is determined by the exponent c. The values obtained here (0.3, 0.4, 0.7) can be considered low compared to other studies. For example, the values for Jack pine (*Pinus banksiana*) stands at different ages varied between 0.6 and 1.6 (Lappi 1997). Flewelling and de Jong (1994) defined the lower limit of c to be 0.5 for western hemlock (*Tsuga heterophylla* (Raf.) Sarg.). The reason for the low values in this study may be that the structure of stands growing on drained peatlands is more uneven than that of stands growing on mineral soils. The diameter distribution at the time of drainage (Heikurainen 1971, Gustavsen and Päivänen 1986) and during several decades following drainage (Hökkä and Laine 1988, Hökkä et al. 1991) is usually reversed J-shaped or extremely right-skewed. Clumped spatial distribution of trees permits great variation in tree height. Inter-tree competition affects height distribution to a lesser extent than in more homogenous stands. The exponent was highest for birch, which may form denser and more even-aged stands than pine or spruce on drained peatlands during the first rotation.

In the models, the fixed stand variables explaining the intercept are logical. The north coordinate takes into account the change in stem form which occurs as a function of latitude (Korhonen 1993). For all three species, the height-diameter curves become more flat towards the north. Elevation above sea level has a similar effect. Average tree height increases as the stand median diameter or stand basal area increases. Thinning increases the intercept, because the shortest trees of equal diameter have the highest probability of being removed in low thinnings. In the same way, the level of the curve is the highest for the most productive sites.

The interaction between tree diameter, stand median diameter and stand basal area indicated how the slope of the average height-diameter curve changed as the median diameter or basal area changed. The same kind of relationship has been presented previously by Lappi (1997) for Jack pine. Thus, the height of a tree of the same diameter varied as a function of the average size of the trees or stand stocking. The average size of the trees (D_{gM}) has also been shown to determine the shape of the dbh-distribution in drained peatland stands (Hökkä et al. 1991).

Stand-level random parameters indicated that both the intercept and slope of the curves varied randomly from stand to stand. The correlation of the stand-level random effects described how intercepts and slopes are related to each other. The positive correlations in these data mean that in stands where the intercepts are high the slopes are steeper than in stands where the intercepts are lower (see Woodhouse 1993); i.e., the slopes are steep in more advanced stands. Accordingly, if both slope and intercept are low, as determined by

low values of stand attributes, the resulting curves seem very flat, especially for pine and birch (Fig. 5). These curves refer to recently drained sparsely forested mires, in which the stand is composed of trees that were growing in the site before drainage. At that stage, the largest trees are not much taller than the small ones due to their stunted height development, but they may recover their growth after drainage depending on their vigor (i.e., age and size) (Seppälä 1969).

The models have the standard advantages of random parameter models. By explicitly taking into account the nested structure of the data, unbiased tests for the parameter estimates were produced. The models can be calibrated with only a few measurements of the response variable, and more accurate predictions can be obtained for specific stands (Lappi and Bailey 1988). In inventory data, logical height curves can be obtained with fewer height measurements. The property of these models is that the slope is predicted standwise as a function of the average size of the trees and stand basal area. This makes the models more flexible to fit a variety of stand structures, which is useful in long-term forecasts when changes in stand structure are expected. These models form one element of a growth simulator, which can be used as a tool for managing drained peatland stands. Together with diameter growth models and models for ingrowth and self-thinning, predictions on stand development can be made as a basis for management decisions.

Acknowledgments

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III

Predicting the initial growth response of Scots pine to ditch network maintenance with an individual-tree diameter growth model

Hannu Hökkä

Abstract

Models were developed for Scots pine (*Pinus sylvestris* L.) growing on drained peatlands to predict the growth response of individual trees to different improvement ditching methods. Increment cores corresponding to the first 5 to 8 years of growth after treatment and a five-year period prior to treatment were collected from experimental stands where ditch cleaning, complementary ditching, a combination of the two, and a control were included. Site characteristics and tree and stand attributes at two occasions (5 yrs prior to and at the time of treatment) were used to explain the annual diameter growth of a tree in a mixed linear model. To describe the growth response to the three ditching treatments, the time since treatment was included first through dummy variables, and then growth responses were expressed as a nonlinear function of time. Annual growth variation - i.e., the growth index for the study period - was accounted for by fixed year effects. Variation around the mean response to each treatment was further explained by tree and stand attributes.

Introduction

Peatlands have a remarkable role in Finnish forestry because they constitute over 30% of the total land area. Peatlands have been drained for forestry on a practical scale since the 1930s, but the most intensive drainage period was during the late 1960s, i.e., 25-30 yrs ago. At present, improvement ditching - ditch cleaning, complementary ditching, and a combination of the two - has been substituted for the drainage of pristine peatlands. On the basis of field inventories where the condition of the ditch networks has been evaluated (Keltikangas et al. 1986), the annual need for improvement ditching was estimated at 120, 000 ha during the years 1986-2005 in order to maintain good conditions for tree growth on drained peatlands (Metsä 2000... 1985; see also Keltikangas et al. 1986, Paavilainen and Tiihonen 1987).

Drained peatlands are labile ecosystems which tend to return to peatland succession if the lowered water table rises again (Heikurainen 1980). Previous studies have shown that drainage ditches become considerably shallower in the 20 yrs following drainage (Heikurainen 1957). Decreased tree growth observed in 15-20 yr old drainage areas has been assumed to be due to the deteriorated ditch networks (Heikurainen 1980). In growth

models, the poor condition of ditches has been used to explain the lower growth of trees (Hånell 1984, Hökkä et al. 1997).

The condition of ditches and the site does not entirely determine the growth rate of trees, because fast growth and great volume may prevent the water table from rising due to high transpiration and interception (Heikurainen and Päivänen 1970, Duncan and Terry 1983, Ahti and Päivänen 1997). Based on a study of competition and growth, Penner et al. (1995) suggested that there is an interrelationship between stand stocking, tree growth and site drainage conditions in drained peatland sites. Therefore, increasing competition may influence individual tree growth positively (see also Laine 1986). Due to this effect and the various factors that affect the rate of deterioration of ditch networks (Paavilainen and Päivänen 1995), great variation (both temporal and spatial) in growing conditions in drained peatland sites can be expected.

Different improvement ditching methods are applied in practical forestry in order to repair the ditch networks (Paavilainen and Päivänen 1995). The decision making is based on rough information on site quality, the age of the original drainage, original ditch spacing, and average stocking (e.g., Kangas et al. 1996). For the purposes of forest management planning, and in order to estimate the economic benefits of the measures, it is important to quantify the growth response of trees to improvement ditching.

While the growth impact following the drainage of a pristine peatland stand has been demonstrated in several studies (e.g., Seppälä 1969, Payandeh 1973, Hånell 1988, Dang and Lieffers 1989), the effect of improvement ditching on tree growth is not well known. Päivänen and Ahti (1988) and Ahti and Päivänen (1997) have shown that changes in the groundwater table take place due to treatment, but the effect of ditching on tree-level growth has remained unclear (Ahti 1995, Ahti and Päivänen 1997). Differences in, e.g., tree vigor, stand and site conditions, and annual climate, which were not considered in these analyses, may have caused significant variation in growth, making it difficult to observe the effect of the treatments. Stewart (1958) concluded that the effect of ditch cleaning on the growth of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) was insignificant.

The aim of this study is to assess the effect of different ditch network maintenance methods on the diameter growth of Scots pine (*Pinus sylvestris* L.), which is the most common tree species in drained peatland sites in Finland. The approach is based on the simultaneous analysis of different factors influencing individual tree growth. The data were collected from permanent experimental stands located in different parts of Finland.

Materials

The data consisted of nine field experiments that were established in pine mires drained for forestry purposes 17-56 yrs earlier. The experimental design included the following treatments: ditch cleaning, complementary ditching, a combination of ditch cleaning and complementary ditching, and untreated control. In ditch cleaning, the old ditches were dug to their original depths; and in complementary ditching, new ditches were dug at a point midway between the old ones. The data were clearly unbalanced because the number of

replicates varied from one to five in different experiments, and all treatments were not included in all experiments (Table 1). Within each experiment, sample plots representing different treatments were delimited from ditch to ditch, and all trees were calipered and mapped. Tree height, height growth and upper diameter measurements were taken from sample trees. Stand characteristics were then calculated plotwise (Ahti and Päivänen 1997).

Table 1. Number of plots, sample trees, and growth years for each experiment.

	Experiment									
	1	2	3	4	5	6	7	8	9	All
plots	9	10	6	16	6	4	22	14	8	95
trees	180	197	120	320	120	107	405	413	133	1995
growth yrs (13 yrs)	2160	2364	1320	3519	1200	1391	4050	5369	1330	22703

In each plot, 20-25 trees belonging mostly to the dominant canopy layer were cored and calipered in 1989 or 1990 in order to determine the annual growth rates. At the time of core sampling, the age of the ditching treatment varied between 5 and 8 yrs. The increment cores were used to calculate plotwise growth during the 5-yr period prior to treatment, and stand characteristics corresponding to that time were produced. The annual diameter growths of the sample trees within the whole 13-yr period were then used as the basis of the growth response analysis.

When the experiments were set up, the stands were understocked and characterized by a small average size of trees (Table 2). Site type and the average peat thickness were determined for each plot. According to Huikari's (1952, 1974) site quality classification, low-sedge pine mires, dwarf shrub pine mires, and cottongrass pine mires were most commonly represented; i.e., most sites were considered oligotrophic or poor oligotrophic. Due to the concentration of the data on poor pine mires, the widest original ditch spacing used in practice (70-100 m) was poorly represented or missing.

The date of establishment varied within four years (1982-1985) for the experiments. This helped to separate the growth response from the annual climatic variation in growth. Plotting the average annual growth by time and treatments suggested that complementary ditching, and ditch cleaning and complementary ditching combined, resulted in higher growth than ditch cleaning or untreated control (Fig. 1). There appeared to be a strong decreasing trend in growth during the last three years in the data as a whole.

Table 2. Mean, minimun and maximum values of tree, stand, and site attributes in the data at the time of set up.

| Attribute	Minimum	Mean	Maximum
d (cm)	2.70	10.83	25.50
id (mm yr^{-1})	0.12	2.15	10.64
D_{gM} (cm)	6.97	11.24	17.44
G (m^2 ha^{-1})	3.43	8.89	18.32
Ncoord. (km)	68647	70658	72767
Ecoord. (km)	2758	4571	5707
tsum^a (dd^{o}C)	867	1043	1178
peat thickness (m)	0.35	89.59	1.00
time since drainage (yrs)	17	35.15	56
original ditch spacing (m)	24	47.01	73

d = tree diameter (over bark)
id = diameter growth during the whole period (13 yrs)
D_{gM} = diameter of the tree of median basal area (over bark)
G = stand basal area (over bark)
^{a} temperature sum in degree days (threshold value +5)
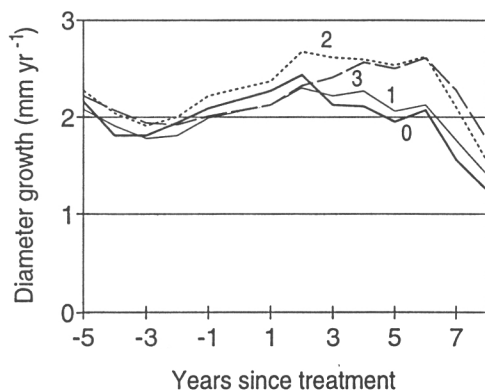
Figure 1. Average annual diameter growth of the sample trees by treatments (0 = control, 1 = ditch cleaning, 2 = complementary ditching, 3 = combined ditch cleaning and complementary ditching) and time since treatment.

The differences in groundwater table depths observed during the pre-treatment calibration period and those calculated as an average from observations of a three-year period following the treatment were 4.2, 5.6, and 10.0 cm for ditch cleaning, complementary ditching and the combination treatment, respectively (Päivänen and Ahti 1988). Even though the ditches bordering the control plots remained untreated, it is possible that the trees in the control plots also responded. This may be due to the fact that the water table was slightly influenced by treatments carried out on the lower parts of the ditch system.

4

Methods

Approach

Trends in annual tree growth due to the drainage of a peatland stand have been analyzed by determining the change in tree ring index (Dang and Lieffers 1989), and by studying the deviation of the observed residual series from that predicted by a climatic model (Zarnovican and Laberge 1994). In neither of these studies were the effects of tree vigor and stand and site conditions on growth explicitly quantified.

Henttonen (1990) described the effect of tree size, age, and competition on the diameter growth of Norway spruce (*Picea abies* L. Karst.) in mineral soil sites with a growth model. The residual variation was decomposed among plot-, tree-, and year effects. The trend in the predicted annual growth indices was then studied. Because the aim of the present study was to develop a model for prediction purposes, the growth model approach was chosen.

A random coefficient model was used as the method. It was assumed that within a plot the following model described the observed data for the trees:

$$\mathbf{y}_i = \mathbf{X}_i \mathbf{b}_i + \mathbf{e}_i, \tag{1}$$

where $\mathbf{X}_i$ is the n_i x r matrix of regressor variables for tree i, $\mathbf{b}_i$ is p x 1 parameter vector for tree i, and $\mathbf{e}_i$ is the n_i x 1 vector of random errors (see Prosser et al. 1991, Lappi and Malinen 1994). It was further assumed that $\mathbf{b}_i$ was a random vector with unknown mean β. Thus the model can be written as follows:

$$\mathbf{y}i = \mathbf{X}_i\beta + \mathbf{X}_i\mathbf{u}_i + \mathbf{e}_i, \tag{2}$$

where $\beta + \mathbf{u}_i = \mathbf{b}_i$. Here, $\mathbf{u}_i$ is a random vector with zero mean and variance covariance matrix Σ. The term $\mathbf{X}_i\beta$ is the fixed part of the model and $\mathbf{X}_i\mathbf{u}_i + \mathbf{e}_i$ the random part, i.e., the error term.

Model

In order to distinguish the growth response to the ditching treatment from other effects influencing individual-tree growth, the effects of all growth factors - the tree's vigor, inter-tree competition, treatments, varying site and weather conditions - were analyzed simultaneously in a growth model. The logarithm of the annual diameter growth of a tree was used as the response variable, and at plot level, growth was expressed as a function of tree diameter (Vanclay 1994) as follows:

$$\ln(id_{jklt} + \alpha) = a_{jkl} + b_{jk}d_{jkl} + e_{jklt,} \tag{3}$$

where id_{jklt} = the diameter growth of tree l in year t on plot k in stand j

α = a small constant added to every growth observation to correct the skewed distribution of the response variable

a_{jkl} = the intercept for tree l in plot k in stand j

b_{jk} = the slope for plot k in stand j

d_{jkl} = the diameter of tree l on plot k in stand j

e_{jklt} = the random error

Thus, the relationship between tree growth and diameter was assumed to vary randomly from plot to plot with respect to the intercept (a) and slope (b) (Lappi 1997). At plot level, parameter b_{jk} in Eq. [3] can be re-expressed:

$$b_{jk} = b + b_{jk} \qquad [4]$$

where b is the unknown mean slope, and parameter b_{jk} denotes the random plot effect (see Eq. 2). Random variation around the mean intercept was assumed at stand (experiment), plot, and tree levels. Furthermore, annual variation in growth among stands may be different (Henttonen 1990): therefore, a random cross-classified effect (see Rasbash and Woodhouse 1995) of year and experiment, a_{jt}, was also needed. Thus, the parameter a_{jkl} was re-expressed as follows:

$$a_{jkl} = a + a_j + a_{jt} + a_{jk} + a_{jkl} \qquad [5]$$

where a is the unknown mean intercept, and parameters a_j, a_{jt}, a_{jk}, and a_{jkl} are random effects at stand, plot, and tree levels.

The model implied that tree growths within a plot were correlated, thus accounting for the nested effects that resulted from the arrangement of the data into four hierarchical levels: experimental stands, plots within stands, trees within plots, and the successive annual growths of individual trees. The crossed effects in the data were connected to time, which reached across the hierarchical levels. It was further implied that a constant correlation between the growths in successive years of the same tree arose from the hierarchical structure of the data: i.e., no special autocorrelation structure was assumed (see Prosser et al. 1991). However, the values of the error term e_{kjlt} were assumed to be uncorrelated.

Variables related to growth factors from different levels of hierarchy were elaborated to explain mean parameters a and b. Because tree size and stand stocking increased with time, values determined for the tree and plot attributes (stand attributes were calculated for each plot) both at the beginning of the study period and at the time of treatment were used. In the model for the whole study period (13 yrs altogether), the mean intercept and mean slope were estimated for both periods: a and b for the pre-treatment period, and a_{tr} and b_{tr} for the post-treatment period. Expressing the slope as a function of plot-level variables made it necessary to include the product of tree diameter and the variable of interest in the fixed part (Prosser et al. 1991). Accordingly, random slopes were assumed for both periods at plot level.

In conclusion, the following combined equation for the whole study period, arranged into fixed and random parts, was obtained:

$$\ln(\text{id}_{jklt}) = (a + a_{tr} + bd_{jkl} + b_{tr}d_{tr,jkl})$$
$$+ (a_j + a_{jt} + a_{jk} + a_{jkl} + b_{jk}d_{jkl} + b_{tr,jk}d_{tr,jkl} + e_{jklt}), \qquad [6]$$

where subscript tr refers to the post-treatment period. In the random part, variances and covariances of the random effects, $\text{var}(a_j)$, $\text{var}(a_{jt})$, $\text{var}(a_{jk})$, $\text{var}(b_{jk})$, $\text{var}(b_{tr,jk})$, $\text{cov}(a_{jk}, b_{jk})$, $\text{cov}(a_{jk}, b_{tr,jk})$, $\text{var}(a_{jkl})$, and $\text{var}(e_{jklt})$ were unknown constants (variance components). All random parameters were assumed to follow independent multivariate normal distributions with zero mean and constant variances and covariances at each level.

In the fixed part, variables referring to tree and plot attributes and having values that corresponded to the date 5 yrs before the treatment explained the pre-treatment growth. When the post-treatment annual growths were explained, the values of these variables corresponded to the time of treatment. To analyze the change in the relationship between growth and the explanatory variables due to the ditching treatment, the same tree and plot variables were included in the model a second time. These variables explained only the post-treatment growths: i.e., their values were set to zero for the pre-treatment period. The variables measured at two occasions and their estimated coefficients indicated the models for the mean intercept (a) and mean slope (b) for the pre-treatment period. The models for the post-treatment period were obtained by adding the estimated coefficients of the variables which explained both a and a_{tr} or both b and b_{tr} together. Attributes that had constant values over time - like site quality - explained both a and a_{tr}.

The fixed time effect consisted of two components: the annual variation in growth, and the time since treatment. These will be termed hereafter the year effects, referring to the fixed calendar years, and the time-treatment effects, referring to the number of years since the treatment. The time-treatment effects explained only the post-treatment growths.

Because of the different hierarchical levels in the data, MLn software (Woodhouse 1995) was used in the analysis. The estimates of the fixed parameters and the variance components related to the random effects were estimated simultaneously with the restricted iterative generalized least square (RIGLS) method, which produces restricted maximum likelihood (REML) estimates for the parameters (Goldstein 1989).

Determining the basic growth model

For the pre-treatment period, separate models were constructed for each treatment to study whether the treatments differed from each other initially in terms of growth dynamics. Parameters for the tree and plot variables related to tree vigor and stand stocking (the logarithm of tree diameter and the second power of the logarithm of tree diameter, the plot basal area, and the product of the plot basal area and the logarithmic tree diameter) were estimated simultaneously for each treatment. Dummy variables were used to estimate the year effects. Site variables (temperature sum, site dummies for the *a priori* sites) were common for all treatments within each stand. The random part consisted of a random intercept at all levels and the year-experiment cross-classification term at stand level. The treatment-specific parameters were fairly similar, producing similar models.

For the post-treatment period, treatment-specific models were constructed correspondingly. Additional dummy variables were used to account for the time-treatment

effects. When the models were compared, the control treatment differed from the others due to its higher growth rate, as indicated by the smaller coefficient of the second power of lnd (lnd^2). Since there was no reason to assume higher basic growth for the control treatment only, the difference was assumed to be attributable to the missing treatment effect for the control. This was supported by the initial plottings, which suggested that the trees in the control plots had also responded in several experiments. Attempts to model this slight response were unsuccessful due to the problem of overparameterization.

In conclusion, the whole model, with responses to the improvement ditching treatments, was estimated by assuming no time-dependent response for the control treatment and the same basic growth function with equal parameter values for all ditching treatments. This basic function was considered as the reference growth to which the other treatments should be compared when the growth response was evaluated. For the control treatment, the parameter for lnd^2 was allowed to be different in the basic growth function in order to account for the obvious increase in growth due to the unintentional 'treatment'.

Results

Model with discrete time

The growth responses were first accounted for by dummy variables. Site, plot, and tree variables in the fixed part were grouped according to their contribution to the intercept (a, a_{tr}) or slope (b, b_{tr}) in Eq. [6] (Table 3). The temperature sum was the only variable indicating the geographical variation in the data and explaining the intercept at stand level. Huikari's (1952, 1974) site quality classes were used in re-grouping the sites into two classes. The combined poor oligotrophic and ombrotrophic sites showed lower average growth than the combined mesotrophic and oligo-mesotrophic sites.

At plot level, the intercept for both periods (a, a_{tr}) was explained by plot basal area, which had a decreasing effect on individual tree growth (Table 3). After the treatment, high basal area limited growth more than before the treatment. Neither of the tree-level measures for inter-tree competition (lnd/D_{gM} or $lnd-lnD_{gM}$) affected growth significantly.

The relationship between tree diameter and growth was different in different periods. Tree growth was lower the greater the tree diameter was during the pre-treatment period. After treatment, the slope between growth and diameter became almost zero, as indicated by the sum of the coefficients of lnd and lnd_{tr}. The second power of the logarithm of tree diameter was insignificant in the pre-treatment period, but the same variable decreased individual tree growth after the treatment when its value corresponded to the time of treatment. Different values were estimated for the non-treated control and the ditching treatments. The slope between growth and tree diameter after the treatment (b_{tr}) was explained by the plot basal area at the time of treatment (Table 3). The positive coefficient increased the slope as plot basal area increased.

In the random part, all variance components defined in Eq. [6], except the covariance between the intercept and the slope during the pre-treatment period, were significant (Table 3). The greatest variance component was found at tree level.

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Table 3. Model for predicting the growth of Scots pine before and after improvement ditching. The response variable is ln(id+1). Variables with subscript tr refer to tree and plot attributes observed at the time of treatment. Temporal treatment response is included with dummy variables. For notations, see Table 1.

				Fixed part		
				Intercept (a, a_{tr})		
	Variable	parameter	s.e.	Variable	parameter	s.e.
a	G	-0.0244	0.0039	*Time-treatment effects*		
a_{tr}	G_{tr}	-0.0247	0.0069	1.clean	0.0354	0.0313
				2.clean	0.0537	0.0313
a, a_{tr}	constant	-0.2995	0.7456	3.clean	0.094	0.03131
	tsum	0.00180	0.0070	4.clean	0.0985	0.03133
	peat	-0.00168	0.0006	5.clean	0.1061	0.03134
	site [a]	-0.0997	0.0315	6.clean	0.145	0.03299
				7.clean	0.1667	0.03468
	Year effects			8.clean	0.119	0.03634
	1979	-0.0202	0.0566	1.compl	0.0614	0.03151
	80	-0.1237	0.0542	2.compl	0.109	0.03152
	81	-0.1719	0.0535	3.compl	0.1432	0.03155
	82	-0.1392	0.0535	4.compl	0.1468	0.03157
	83	-0.0169	0.0582	5.compl	0.1863	0.03157
	84	0.0328	0.0617	6.compl	0.2007	0.03359
	85	0.0005	0.0660	7.compl	0.2404	0.03597
	86	0.0943	0.0683	8.compl	0.1899	0.03791
	87	-0.0346	0.0684	1.comb	0.0261	0.03225
	88	-0.0834	0.0687	2.comb	0.0604	0.03226
	89	-0.0869	0.0689	3.comb	0.1381	0.03228
	90	-0.2587	0.0807	4.comb	0.1792	0.0323
				5.comb	0.2356	0.0323
				6.comb	0.2733	0.0344
				7.comb	0.3142	0.0368
				8.comb	0.2208	0.0413

			Slope (b, b_{tr})	
	Variable	parameter	s.e.	
b	lnd^{b}	-0.1914	0.0247	
b_{tr}	lnd_{tr}	0.1715	0.0439	
	$(lnd/contr_{tr})^{2}$	-0.0553	0.01272	
	$(lnd/ditched_{tr})^{2}$	-0.0677	0.01272	
	$lnd^{b}_{tr} \times G_{tr}$	0.007567	0.003026	

		Random part		
	Variable	parameter	s.e.	
Intercept (a)	experiment	0.04101	0.02002	
	experiment×year	0.007299	0.001125	
	plot	0.002932	0.001059	
	tree	0.06064	0.002098	
	time	0.03631	0.000359	
Slope (b) at plot level				
	lnd	0.02373	0.006818	
	lnd_{tr}	0.001674	0.000277	
Covariance between intercept and slope				
	plot/lnd_{tr}	-0.001599	0.000428	

[a] Site dummy referring to Huikari's (1952, 1974) site quality classes 4 and 5.

[b] 2.2 has been subtracted from all ln(d) to center the variable.

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The growth response showed an increasing trend up to year 7 and a clear drop in the 8th year (Fig. 2). The model produced a slightly higher level of growth response to complementary ditching, probably because the average diameter growth prior to the treatment was the highest for that treatment. If it is assumed that growth responses in the first year after treatment are about the same for all treatments, the treatments follow the expected ranking from lightest to heaviest as follows: ditch cleaning, complementary ditching, and the combination treatment (Fig. 2). Adding the effect of ditch cleaning and complementary ditching together resulted in approximately the same effect as the combination treatment. Assuming that variation in growth caused by varying stand and tree attributes was controlled by the model, the fixed year effects can be interpreted as growth indices for the study period (Table 3).
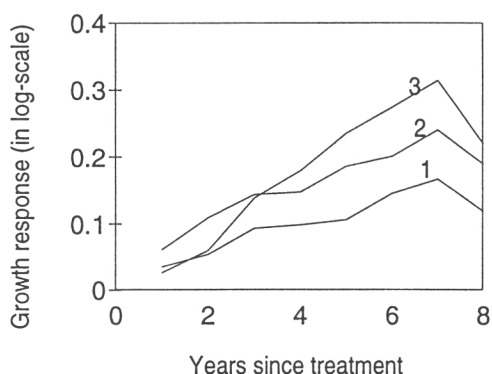
Figure 2. Growth response to different treatments (see Fig. 1 for notations). Time-treatment effects are predicted by dummy variables (Model in Table 3).

Determining trend functions

In the second phase, the dummy variables referring to the time-treatment effects were replaced by continuous functions of time for the three ditching treatments. The following sigmoidal model was chosen as the growth response curve (Ratkowsky 1990):

$$f(t) = p_1 \cdot (1 - \exp(-(t \cdot p_2)^{p_3}))$$ [7]

where parameters p_2 and p_3 were determined by treatments (Table 4). The graphic fit and the minimum value of the -2×log-likelihood of the whole model, when different parameter values were tried, were used as the criteria. The parameter p_1 indicated the asymptote of the growth curve of each treatment and was estimated simultaneously with other model parameters. Because the basic growth model was otherwise similar to that given in Table 3, only the growth curve parameters are presented in Table 4.

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Table 4. Growth curve parameters for each treatment.

Treatment	p_1	(s.e.)	p_2	p_3
Ditch cleaning	0.134	(0.018)	0.17	2.5
Complementary ditching	0.174	(0.018)	0.23	1.7
Combination	0.294	(0.018)	0.2	2.5

Prediction model for improvement ditching

The third model was intended as a tool for making predictions concerning the expected growth response to different improvement ditching methods using site, plot, and tree attributes measured at the time of treatment. Thus the pre-treatment data were removed. Bark functions (Heinonen 1994) were used to remove bark from the overbark tree diameters, producing the corresponding underbark diameters and plot basal areas.

The intercept was explained by plot basal area, temperature sum, and two site dummies referring to Huikari's (1952, 1974) site quality classes 4 and 5 (Table 5). The slope was explained by tree diameter and plot basal area. The random part was simplified by estimating only the random intercepts at each level, and the random cross-classification between plot and year at plot level. Changing this term from stand level to plot level was justified by the treatment that most probably increases annual within-stand variation of growth after ditching. This was also supported by the clearly lower value for the $-2\times$log-likelihood. In Table 5, the fixed year effects were included. In order to determine a value for the constant for the prediction model, the year effects need to be removed from the fixed part and estimated as a random effect at stand level. Because the other model parameters remained the same, this model version was not presented here.

The time trends were estimated for the three treatments using the values presented in Table 4 for parameters p_2 and p_3, and allowing parameter p_1 to be estimated with the model run. The variation in parameter p_1 was then explained by tree diameter, plot basal area, and ditch spacing (Table 5). For all treatments, the largest trees responded most. Tree size influenced the response most in complementary ditching, while the effect was of equal magnitude for ditch cleaning and the combination treatment. Increasing plot basal area increased the response to ditch cleaning and complementary ditching, while an insignificant negative effect was obtained for the combination treatment. For well-stocked stands, the model produced almost equal response to complementary ditching and the combination treatment (Fig. 3). Wider ditch spacing had a significant negative influence on the response to ditch cleaning and a negative influence on the mean intercept at plot level for the control treatment.

Table 5. Model for predicting the response of Scots pine to improvement ditching with current stand, site, and tree characteristics. The response variable is ln(id+0.7); d and G correspond to values excluding bark at the time of treatment. Temporal treatment response is expressed as a continuous function of time (f(t), see Eq. 7 and Table 4). For notations, see Tables 1 and 3.

Fixed part

Intercept a

Variable	parameter	s.e.	Variable	parameter	s.e.
			Time-treatment effects p_l		
constant	0.3889	0.8875	f(t) clean	-0.4431	0.1446
tsum	0.002057	0.0008	f(t) compl	-0.5818	0.1303
site4[a]	-0.1355	0.0389	f(t) comb	-0.0305	0.1285
site5[a]	-0.2587	0.0587	f(t) ×lnd clean	0.1604	0.0334
G	-0.05485	0.0059	f(t) ×lnd comp	0.2113	0.0345
dspc[c] contr	-0.00391	0.0015	f(t) ×lnd comb	0.152	0.0363
Year effects			f(t) ×lnG clean	0.2179	0.0604
1984	0.0193	0.0190	f(t) ×lnG comp	0.1772	0.0627
85	-0.01647	0.0190	f(t) ×lnG comb	-0.0267	0.0568
86	0.1048	0.0206	f(t) ×dspc[c] clean	-0.00448	0.0018
87	-0.0378	0.0230			
88	-0.1106	0.0260			
89	-0.1149	0.0260			
90	-0.3016	0.0333			

Slope b

Variable	parameter	s.e.
lnd[b]	0.4361	0.1926
(lnd/control)^2	-0.1469	0.0473
(lnd/ditched)^2	-0.1827	0.0469
lnd[b]×G	0.03712	0.010

Random part

	Variable	Variance	s.e.
a	experiment	0.05612	0.02703
	plot	0.002156	0.001287
	plot×year	0.006282	0.000498
	tree	0.1035	0.003529
	time	0.03238	0.000453

[a] Site dummies referring to Huikari's (1952, 1974) respective site quality classes.

[b] 2.18 has been subtracted from all ln(d) to center the variable.

[c] Ditch spacing.
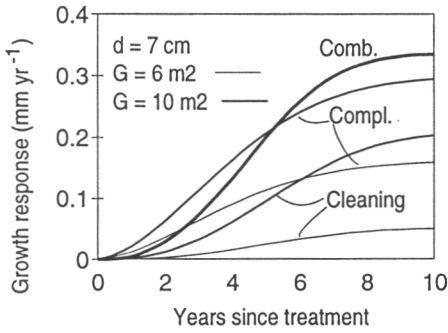
Figure 3. Some examples of growth responses of a tree with diameter 7 cm (under bark) to different treatments as a function of plot basal area (G, under bark), and time since treatment as predicted by the model in Table 5. For the combination treatment, plot basal area did not influence the response.

Model validation

No trends were detected in the residuals of the different models when plotted against various explanatory variables. Only the residuals of the prediction model (Table 5) are presented here (Fig. 4). For this model, residuals at the original scale of growth were produced and plotted against tree diameter. Generally, a logarithmic correction term is added to predictions (Flewelling and Pienaar 1981) before transforming growth to the original scale. Here, the correction was as follows:

$$0.5 \cdot \sigma^2 = 0.5 \cdot \left(\sigma^2_{stand} + \sigma^2_{plot,year} + \sigma^2_{plot} + \sigma^2_{tree} + \sigma^2_e \right) \qquad [8]$$

It turned out that the mean residuals deviated from zero (-0.223 mm/yr, Fig. 4) when averaged at observation level. Only the growth of the smallest trees (diameter under bark < 5cm) became slightly underestimated when the average residuals were compared to those of the bigger trees, which showed no trend as a function of tree diameter. It was possible to obtain zero mean residuals by excluding the stand-level variance component from the model, but this also changed the coefficients of lnd and plot basal area considerably. Additional stand-level variables also reduced the bias, but only the temperature sum was kept in the model because nine observations did not support a complex model at stand level. The non-zero mean residuals were connected to the small sample of experimental stands and, moreover, to the fact that large experiments were established in poor sites. There was a negative correlation between the number of trees in a stand and the average growth of the stand. When the mean residuals were calculated at stand level as an average of the stand-wise averages, the model appeared unbiased (-0.079, with s.e. of 0.228).
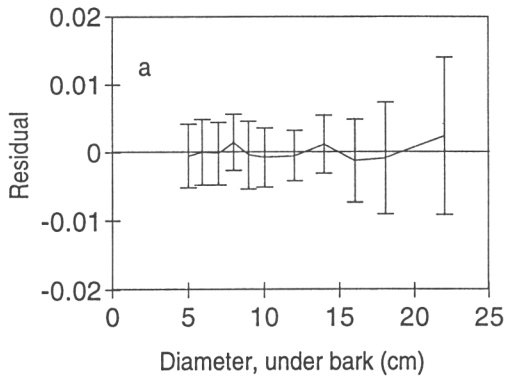
Figure 4.(a-c) Mean residuals and corresponding standard error of mean of the model in Table 5 in a logarithmic scale as a function of tree diameter (a) and plot basal area (b), and the mean residuals in the original scale of growth (logarithmic correction term included) in the modelling data as a function of tree diameter (c).
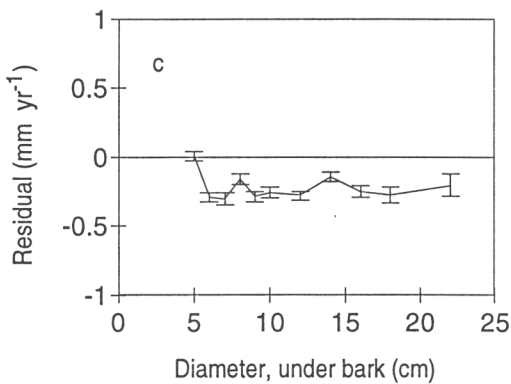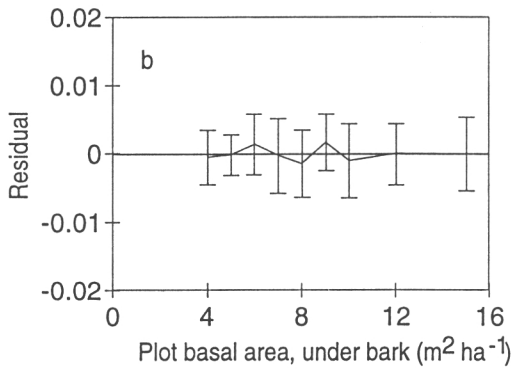
The reliability of the models was evaluated by comparing the estimates of the fixed year effects produced by the models to the growth indices obtained from an independent growth index series. For undrained peatland sites in the middle parts of Finland (Ostrobothnia), growth indices have been derived from the sample trees of the 8th National Forest Inventory (NFI8) permanent sample plots (Henttonen, unpublished). In general, the minima and maxima occur in the same years (Fig. 5). The indices obtained from the models of this study deviated from the independent index due to the lower average growth prior to the treatment and the higher growth after the treatment.
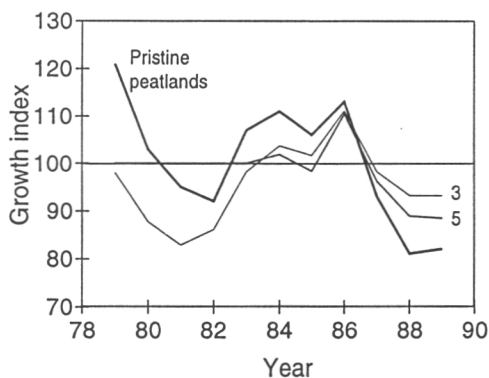
Figure 5. Growth index based on the 8th National Forest Inventory (NFI8) sample trees growing on undrained peatlands in middle parts of Finland (Henttonen, unpublished; mean of the period 1979-1989 = 100) and the indices produced by the models given in Tables 3 and 5.

Discussion

The growth model approach was used to study the effect of ditch network maintenance on the individual tree growth of Scots pine on peatland on the basis of tree ring data. The analysis was concentrated at plot level because improvement ditching is a stand-wise treatment which was here carried out on the plots. It should be emphasized that the results presented are tentative because the data covered only 5 - 8 yrs of growth after the improvement ditching.

Within the data, larger experiments were established in the poorest sites, as indicated by the negative trend between the number of observations and the average growth of the stand. To some extent this is the case *in situ*, where better sites cover smaller areas than sites of medium or poor productivity, but one cannot draw this conclusion on the basis of only nine stands. It can be assumed that the model will give unbiased predictions when applied to predict growth in a random sample of drained peatland stands.

The analysis was carried out with the mixed linear models technique, which is commonly applied to hierarchical and complex data sets (Lappi 1986). Nested, crossed and cross-classified effects were accounted for. The method has the advantage of providing valid tests for the model parameters. In growth forecasts with measurements from the response variable available, the random effects can be predicted and models calibrated in specific stands or trees to obtain more accurate predictions. Random variation around the mean intercept at different levels and around the mean slope at plot level was explained by the site, stand (plot) and tree attributes in the fixed part of the model (Lappi 1997).

The approach was similar to that used by Henttonen (1990) when studying the trend in growth indices of Norway spruce in southern Finland. In the present study, by explicitly describing the effect of tree size, competition, and site quality in the growth model, it was possible to distinguish the temporal variation in growth and decompose it between the annual variation and the trend. Even though it was possible to detect the effect of different factors influencing tree growth, the estimated parameters were clearly correlated. Because of the problem of overparametrization, not all components could be accurately estimated, and error in single effects may be included. However, the method has an advantage in evaluating the effect of drainage on tree growth: the basic growth and the growth response can be predicted in varying conditions in absolute terms (cf. Dang and Lieffers 1989, Zarnovican and Laberge 1994). The same method can be applied, e.g., to fertilization studies to estimate the growth response of trees.

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The effects of tree size, competition, and site quality on growth were accounted for by common tree, stand (plot), and site characteristics. When increment cores were sampled, all trees were not calipered, so it was not possible to produce accurate plot basal areas for each year. Subsequently, tree diameters and plot basal areas at two occasions were used to predict the annual growths. Tree diameter was the only indicator of the growth potential of the target tree. In drained peatland stands, inter-tree competition influences growth in a complex manner, and both negative and positive effects may be found, as discussed by Penner et al. (1995). In these data, tree-level measures of competition were insignificant, but individual tree growth was lower in plots where basal area was great. The lack of tree-level competition may be due to the very low average stocking in these stands or the incapability of the variable used to describe competition between trees (cf. Hökkä et al. 1997). The relationship between a tree's growth and its diameter varied according to stand stocking. Generally, the higher growth of the larger trees resulted in stands with a higher basal area. Thus, this effect served partly as a tree-level measure of competition.

Because most of the sites were medium- or low-productive, only two or three classes formed from the *a priori* sites showed different growth rates. Due to the narrow range in temperature sum and the small sample at stand level, there was great variation in the dependence between growth and temperature sum. In the model given in Table 3, there was a negative trend with respect to peat thickness and tree growth, which reflects the impairment of average site quality as peat depth increases (see Hånell 1984).

The fixed year effects were used to describe the annual variation in growth. As in all time series, the beginning and end of the period were most uncertain (Henttonen 1990). The year effect and time-treatment effect may have been confounded in the last year because only a few experiments were involved and the variables were correlated. Consequently, the growth decline in year 8 was probably overestimated in Figure 2, because the three experiments represented were all located in the north. The year effects showed the same kind of behavior as the independent growth index series from undrained peatlands in the middle parts of Finland (Henttonen, unpublished). Since indices from drained peatlands were not available, all differences between indices could not be explained.

Sigmoidal growth curves were fitted to describe the temporal growth response (Laird and Ware 1982, Goldstein 1986). The growth rate after the 8th year was not available in the data, but the sigmoidal curves made it possible to attain the maximum growth on the basis of the observed initial response. The growth response of Scots pine to site management - e.g., drainage and fertilization of peatlands - varies. If the forest drainage of pristine peatland sites is considered, the response is shown to peak between 10-15 years following drainage (Seppälä 1969, Miina 1994), depending on site quality; decreased growth may be expected after that. The growth response to the fertilization of peatlands may last for 20 yrs (Moilanen 1993). In this study, the sigmoidal growth curves assume that the achieved growth level will be maintained, which may be too optimistic. As a consequence of the *a priori* assumption of poor drainage of these sites, a decreasing growth trend of unknown magnitude for the control treatment could be expected. The detection of a time trend in the post-treatment data was disturbed by the effect of unintended 'treatment'. On the other hand, the pre-treatment period was so short (5 yrs) that attempts to detect any trends were unsuccessful.

It was shown that the temporal growth response varied among trees and plots, and it was possible to express this variation as a function of treatment, tree diameter, plot basal area and ditch spacing. The diameter growth response was concentrated in the largest trees, which are generally located close to the old ditches and have the highest growth potential due to their good competitive status. The largest trees on the control plots also responded because it was the lower negative coefficient of lnd^2 which caused the difference between the control treatment and the other treatments. The combination treatment resulted in the most equal response in trees of all sizes, which can be explained by the spatially even treatment that improves the growth of both large trees (close to old ditches) and smaller trees (far from the old ditches but close to the new ones).

Plot basal area had a positive effect on the response to ditch cleaning and complementary ditching treatment, while the effect on the response to the combination treatment was insignificant. This result may be due to the interrelationships among the properties of the peat, site drainage, stand stocking, and growth in drained peatland sites. According to Päivänen (1982), the effect of stand volume on groundwater table depth is greater the deeper the groundwater table initially is. The groundwater table is influenced by the tree stand through interception and transpiration: stands with higher basal areas are expected to have lower groundwater tables (Laine 1986). Greater changes in deeper peat layers are due to the higher groundwater coefficient (Heikurainen 1964). Thus, it can be assumed that the growth response is also greater in areas where the groundwater table has initially been deeper. With improved growth, these stands are able to better control the groundwater table (Duncan and Terry 1983, Laine 1986, Penner et al. 1995). In the combination-treatment areas, the response was evident even in sparsely forested stands because the intensive treatment caused a considerable change in site drainage, as indicated by the average groundwater table levels after the treatment (Päivänen and Ahti 1988). Some of the effect may be explained by differences in site quality: in stands where the basal area was high, the site quality may also have been better. In order to better explain the variation in the growth response, data from groundwater table fluctuations before and after the treatment should be included in the analysis.

When tree diameter and plot basal area explained the response, wider original ditch spacing had a negative effect on the response to ditch cleaning and on the average growth rate of trees in the control treatment. Seppälä (1972) has shown that the negative relationship between tree growth and ditch spacing is most evident in the poorest sites.

The random cross-classification between the year and the experiment indicated that annual growth variation was different in different locations (Table 3). After the treatment, variation between year and plot became more important because trees which have been subjected to different ditching treatments respond to annual climatic variation differently even if they occur in the same location (Table 5). Of all variance components, tree-level variance was the greatest, probably because only tree diameter explained growth within plots. Distance to the nearest ditch and tree age (Payandeh 1973, Hånell 1984, Miina 1994), as well as competition indices (Miina 1994), have been used to explain individual tree growth on drained peatlands. In the present study, the distance to the new ditch in complementary ditching and combination treatments would most probably have reduced the tree-level variation (Ahti 1995).

On the average, ditch cleaning had only a moderate influence on individual tree growth (see Stewart 1958). Complementary ditching caused about a two-fold growth increase.

This was in accordance with observed responses in mean groundwater levels and the assumed effects of these measures on site drainage (Päivänen and Ahti 1988, Ahti and Päivänen 1997). Ditch cleaning causes a slight decrease in groundwater table levels by increasing base flow, and its influence is greatest close to the old ditches. In complementary ditching the original ditch spacing is halved, with consequent increases both in surface flow and interflow, even though the average decrease in groundwater table level is not clearly greater than that in ditch cleaning (Päivänen and Ahti 1988). If the treatments are combined, site drainage is heavily changed, and a clear response (additive, on the average) may be expected both in groundwater table levels and tree growth.

The average growth response in the data can be considered moderate. This was partly due to the short observation period, and also partly due to the fact that the experiments were conducted in low-productive sites. To obtain a more comprehensive view of the growth response of Scots pine to different improvement ditching methods, data covering a longer post-treatment time period and a wider range in site quality should be collected. However, the net growth increase following improvement ditching may be remarkable if no treatment at all would have led to a continuously decreasing growth rate. For the purposes of valid comparison, it is important to model the long-term development of the control plots. Here the trees growing on the control plots also showed a response to the treatment: it is probable that in field experiments the water level draw-down cannot be limited to the area of treated plots, but the control plots may be affected as well.

Acknowledgments

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