METSÄNTUTKIMUSLAITOKSEN TIEDONANTOJA 835, 2002
FINNISH FOREST RESEARCH INSTITUTE, RESEARCH PAPERS 835, 2002

Models for predicting stand development in MELA System

Jari Hynynen, Risto Ojansuu,
Hannu Hökkä, Jouni Siipilehto,
Hannu Salminen and Pekka Haapala

VANTAA RESEARCH CENTER

METLA

METSÄNTUTKIMUSLAITOKSEN TIEDONANTOJA 835, 2002
THE FINNISH FOREST RESEARCH INSTITUTE. RESEARCH PAPERS 835, 2002

Models for predicting stand development in MELA System

Jari Hynynen, Risto Ojansuu,
Hannu Hökkä, Jouni Siipilehto,
Hannu Salminen and Pekka Haapala

VANTAA RESEARCH CENTER

Hynynen, J., Ojansuu, R., Hökkä, H., Siipilehto, J., Salminen, H. & Haapala, P. 2002. Models for predicting stand development in MELA System. Metsäntutkimuslaitoksen tiedonantoja. The Finnish Forest Research Institute. Research Papers 835. 116 s. ISBN 951-40-1815-X. ISSN 0358-4283.

This document addresses the models that are developed to be applicable in the simulation of stand development for forest management planning purposes. A detailed description is provided of the models predicting regeneration, growth and mortality, together with auxiliary models required for the simulation of stand development.

Models were developed to be applicable for the all tree species and on all the forest site types throughout the Finland. The model input were restricted to those variables that are measurable in large-scale forest inventories. Extensive data from repeatedly measured inventory growth plots and permanent sample plots were used in the model development. Most of the models in the simulation system can be categorized as individual-tree, distance independent models.

After model building they were evaluated and calibrated using the temporary sample plot data from the 8th National Forest Inventory. The purpose was to calibrate the predicted growth to the average level obtained from the growth measurements of national forest inventory, and obtain the growth predictions also for those tree species, and site types that were poorly represented in the modelling data.

Keywords	model calibration, mortality models, regeneration models, stand simulation, site index.
Publisher	Finnish Forest Research Institute, Vantaa Research Center, Finland. Accepted by research director Kari Mielikäinen 4.2.2002.
Printed in	Hakapaino, 2002.
Distribution	Finnish Forest Research Institute, Vantaa Research Center, Library. P.O. BOX 18, FIN-01301 Vantaa, Finland. Tel. +358-9-857 051, Fax +358-9-8570 5582, E-mail: kirjasto@metla.fi.

Author's addresses	Finnish Forest Research Institute, Vantaa Research Center. P.O. BOX 18, FIN-01301 Vantaa, Finland. Tel. +358-9-857 051: *Hynynen, J.* (jari.hynynen@metla.fi), *Ojansuu, R.* (risto.ojansuu@metla.fi), *Siipilehto, J.* (jouni.siipilehto@metla.fi). Finnish Forest Research Institute, Rovaniemi Research Station. P.O. BOX 16, FIN-96301 Rovaniemi, Finland. Tel +358-16-336 411, Fax +358-16-336 4640: *Hökkä, H.* (hannu.hokka@metla.fi), *Salminen, H.* (hannu.salminen@metla.fi). The Social Insurance Institution. Nordenskiöldinkatu 12, FIN-00250 Helsinki, Finland. Tel +358-9-43411: *Haapala, P.* (pekka.haapala@kela.memonet.fi).

Update information	For updated documentation referring to the simulation models, see WWW-site: http://www.metla.fi/ohjelma/mot/index-en.htm.

Preface

The purpose of this report is to provide the detailed documentation of the models applied to describe the biological processes in MELA System. Thus, this report serves as a complementary documentation of MELA System (cf. Siitonen et al. 1996).

Models describing stand dynamics are described. They include models for natural regeneration, growth, and mortality supplemented with necessary auxiliary models, such as models for site productivity and some tree dimensions. However, all the man made forest management operations, such as rules for regeneration or thinnings, are outside the scope of this report.

The most of the symbols and definitions of the variables describing stand and tree characteristics are restricted to those that are commonly applied in forestry literature in Finland. However, few exceptions have been made. The definition of stand dominant height is different from that applied in practical forestry in Finland. Instead of average height of 100 thickest trees per hectare, in this document, stand dominant height refers to mean height of trees with diameter larger than stand mean diameter weighted with stand basal area. Accordingly, stand dominant diameter and stand dominant crown ratio are defined as mean diameter and crown ratio of trees with diameter larger than mean diameter, respectively. The applied definitions were considered to be suitable for use with data obtained from angle gauge sampling. Furthermore, relative measures for stand density instead of absolute ones are applied to describe the within-stand competition in most of the presented models. The relative measures were regarded as more independent from stage of stand development, and to better reflect the specific effects of different tree species on within-stand competition.

The models collected in this report are the result of long-lasting and intensive co-operation of the growth and yield researchers in the Finnish Forest Research Institute. In addition to the co-authors of this report, I gratefully acknowledge all the colleague researchers for providing many valuable comments throughout the modelling project. The authors also acknowledge MELA Team for the fruitful co-operation. We are indebted to those who initiated and accomplished the field measurements, and thus provided the extensive empirical data sets for model development. Finally, the authors wish to thank Marja-Liisa Herno for the layout of this report.

Vantaa, January 2002
Jari Hynynen

Contents

Symbols

Tree

age	Tree age, year
a0	Initial, theoretical age for a new tree, year
d	Tree diameter at breast height, cm
d_s	Tree diameter at stump height, cm
dh13	Initial diameter of a tree that has reached the breast height, cm
dhref	Initial reference diameter of a tree that has reached the breast height (TVKK and NFI7 data), cm
ba	Tree basal area, cm^2
i_{ba5}	Tree basal area growth under the next 5-year period, cm^2
BAL	Basal area of trees larger than the object tree, m^2 ha^{-1}
RDFL	Relative density factor of trees larger than the object tree
cr	Tree crown ratio (length of the live crown/ tree height)
h	Tree height, m
i_h	Annual height growth, m
i_{h5}	Tree height growth under the next 5-year period, m
i_{hr}	Relative portion of the annual height growth
n_i	Stem number represented by a sample tree
th	The time that it takes for a tree to reach the breast height, year
thref	The reference time that it takes for a tree to reach the breast height (TVVK and NFI7 data), year
p_{comp5}	Probability of a tree to die during the coming 5-year period
p_{old} (age)	Probability of a tree to die due to aging at the given age
p_{old5}	Probability of a tree to die due to aging during the coming 5-year period
Δba_r	Relative basal area growth response to fertilization, %
Δba_r(ref)	Relative basal area growth response to fertilization with temperature sum equal to 1 250, %.
sp_x	Categorical variables referring to tree species. Definition of x: Sp = Scots pine (*Pinus sylvestris*), Np = Norway spruce (*Picea abies*), sb = silver birch (*Betula pendula*), pb = pubescent birch (*Betula pubescens*), as = aspen (*Populus tremula*), ga = grey alder (*Alnus incana*), ca = common alder (*Alnus glutinosa*), ds = other deciduous tree species, cs = other coniferous tree species.

Stand – Growing stock

Age	Stand age, year
A	Stand age at breast height, year
A_{max}	The maximum age of a tree species
D_g	Mean diameter weighted by tree basal area, cm
D_{gs}	Mean diameter at stump height weighted by tree basal area, cm
DgM	Median basal area diameter, cm
D_{dom}	Dominant diameter, defined as the mean diameter of trees thicker than Dg, cm
BA	Basal area (over bark), m^2 ha^{-1}
$BA\%_{Ns}$	Proportion of Norway spruce of stand basal area, %
$BA\%_b$	Proportion of birch of stand basal area, %
CR_{dom}	Dominant crown ratio, defined as the mean crown ratio of trees thicker than Dg
H_{dom}	Dominant height, defined as the mean height of trees thicker than Dg, m
IH_{dom5}	Dominant height increment during the next 5-year time period, m
N	Number of trees per hectare
N_{max}	Maximum allowable stem number of the stand
iN	Number of new trees under the next 5-year period
N_{ref}	Average number of trees per hectare in NFI7 sub-strata
RDF	Relative density factor (definition in Chapter 4.2)
RDF_x	Relative density factor by tree species denoted with x. Sp = Scots pine, Ns = Norway spruce, sb = silver birch (*Betula pendula*), pb =

	pubescent birch (*Betula pubescens*), and ds = other deciduous tree species
PUB	Categorical variable for the presence of *Betula pubescens* in a stand
SY_{1400}	Seed year interval with temperature sum 1400 dd.

Stand – Site

LAT	Latitude, km
LONG	Longitude, km
ALT	Altitude, m
TS	Total annual temperature sum with threshold +5 °C
TSc	Accumulated temperature sum during a calendar year
LAKE	Lake index; referring to the proportional coverage of lakes within a distance of 20 km radius
SEA	Sea index; referring to the proportional coverage of lakes within a distance of 20 km radius
SC_x	Fertility class according Kuusela and Salminen (1969) (categorical variable), where x = 1, 2 … 8. Definition of x-values: 1 = very rich, 2 = rich, 3 = damp, 4 = dryish, 5 = dry, 6 = barren, 7 = rocky lands, sands and alluvial land, 8 = hilltops and fjelds
SI	Site index; dominant height at 50 years age at breast height, m
SI_x	Site index for tree species denoted with x. Definition of x: Sp = Scots pine, Ns = Norway spruce, sb = silver birch (*Betula pendula*), pb = pubescent birch (*Betula pubescens*), and ds = other deciduous tree species.

Categorical variable referring to the site characteristics decreasing the yield capacity of site (categorical variables):

STONY	Stoniness
PALU	Paludification
HUMUS	Very thick raw humus
FUSC	Occurence of *Spaghnum fuscum* hummocks or pools or both of them in the site (Huikari 1952, 1974)
UNDRAINED	Undrained peatland.

Categorical variable referring the land use classes:

SCRUB	Low productive land with annual average yield between 0.1 $m^3 ha^{-1}$ and 1.0 $m^3 ha^{-1}$
WASTE	Low productive land with annual average yield less than 0.1 $m^3 ha^{-1}$
SP	Categorical variable referring to accomplished soil preparation during the preceding 10 years.

Others

JD	Julian day
CULT	Categorical variable referring to artificial regeneration (cultivated stand)
PLANT	Categorical variable referring to planting
$THIN_{x-y}$	Categorical variable referring to thinning within the last x-y years
DR_{x-y}	Categorical variable referring to time since original ditching
PDR	Categorical variable referring to need for complementary ditching or ditch cleaning
k	Stand index
i, j	Tree indexes
t	Time index
u	Random stand effect
w	Random tree effect
e	Random effect.

1 Introduction

The models presented in this report have been developed to be applied in the simulation of stand development for forest management planning purposes. Initiative in model development was brought out by the need for more reliable models to describe the biological processes in MELA System. MELA is a forestry model and an operational decision support tool for integrated forest production and management planning designed for the Finnish conditions (Siitonen et al. 1996).

The main tasks for models applied as tools for decision making in forestry, classified by Burkhart (1992), are as follows:

- inventory updating
- evaluation of silvicultural alternatives
- management planning
- harvest scheduling.

It is unrealistic to assume that there exists a single model that would be able to fulfil in an optimal way all the requirements for the different management purposes mentioned above. Neither there exist a single data set, that would serve well as modelling data for such a model.

MELA System is widely applied in forest management at various planning levels with varying time span of planning, and in different parts of Finland. MELA System includes only one set of simulation models, which is employed in order to provide information for several purposes across the above mentioned tasks. The development of models for this kind of system is highly demanding task, which cannot be performed without compromises in model building.

One of the primary requirements for growth and yield models applied in forest management planning, is capability to produce unbiased prediction of the development of the forest resources. Data from forest inventories provide the most representative and reliable information about the existing forest resources. Therefore, data from forest inventories are often used as both modelling data and as the starting point of the simulation for future forecasts. In MELA applications on national and regional levels, the National Forest Inventory data are used in analyses about the development of forest resources.

Being so, the models have to be compatible with forest inventory data. Input variables of the models need to be restricted to those available in forest inventory data. The input of the models should be compatible with the modelling data, as well as with the inventory data the models are applied to. Because of that, many stand and tree characteristics that would provide valuable information for growth prediction, cannot be used. Therefore, considerable simplifications are necessary in model development. As the result, growth equations developed from the inventory data are relatively simple and straightforward including only on few stand and tree variables.

For forest management planning and for decision making in forest policy, long term forecasts about the development of forest resources are needed. In order to be reliable and behave in a logical way when applied in long term simulations, models should to be well designed. The relationships between variables of the models should be described with sound biological and ecological basis and expressed with the functions that are suitable for describing biological processes. Well-designed model structure ensures the logical behavior even when applied in the neighbourhood the limits of the modelling data. Often, compromises must be made to achieve model structure with logical behaviour at the expense of the best possible statistical fit within the modelling data.

In Finland, intensive forest management of commercial forests has been practised for many decades. Thus, evaluation of the alternative management schedules is an essential part of forest management planning. The growth and yield models should be capable to reliably predict the responses to various silvicultural treatments on the development of managed stands. For long-term planning, growth models are required to be able to predict the effects of silvicultural practices that are currently applied in practical forestry, and also the effects of the more extreme levels of these practices that may not be applied in forestry at present.

The first generation of models for predicting the biological processes in MELA System was developed in the late 1970's. An overview of these models is provided by Ojansuu et al. (1991). These models were applied in MELA until 1997. The development of the new generation of the models for description of biological processes in MELA System was started in 1995. The main objectives of this project was to

- increase the flexibility of the models to predict stand dynamics under alternative silvicultural practices with the special emphasis on response to thinnings
- improve the description of site factors affecting stand development
- improve models for drained peatlands
- improve models for birch and other deciduous tree species on mineral soils.

The purpose of this report is to provide a detailed description of the system for simulating the development of biological processes in MELA System. The document covers 1) the description of modelling data, 2) definition of the variables applied in stand description, 3) description of the models, 4) the evaluation and calibration of the models with the help of temporary National Forest Inventory-data.

2 Overview of the simulation of biological processes in MELA System

2.1 Required stand and tree information

In order to apply the models in the simulation, some basic information about the stand and trees have to be available in the initial data base.

Site description applied in the models is compatible to that of the Finnish National Forest Inventory supplemented with some geographical variables which can be predicted as a function of site coordinates. The required variables referring to site factors are presented in Chapter 4.1.1.

The stand is described with the help of sample trees. Each sample tree represents a certain stem number per hectare and tree variables common for all trees in the cohort. Values for sample tree variables has to be given in initial data base. The tree variables required for the models include tree species, tree diameter at breast height, tree height, tree crown ratio, and age of a tree (at breast height). If tree age is unknown, stand age is given for each tree and unknown tree crown ratio can be predicted with a crown ratio model included in the system.

If the models are applied to the data including only plot- or stand-level (compartmentwise) information together with average tree measures, required sample tree information can be derived from size-distribution models. Those models are not discussed in this document not either other methods to complete databases for the initial situation of stand simulation.

2.2 Simulation procedure

Overview of the simulation of biological processes in MELA System is illustrated in Figure 1 with references to corresponding chapters in this document.

Before predicting the stand dynamics, some specific stand and tree measures not available in forest inventory data are calculated. Site is described with models applying the information on both permanent site factors and on measurements of the growing stock. Site variables are predicted in the beginning of the simulation. Models and variables applied in site description are presented in Chapter 4.1.

Within-stand competition is described with the help of relative competition variables described in Chapter 4.2.

In growth models for trees growing on mineral soils, tree crown ratio is applied as one of the driving variables. Currently, the lower limit of live crown is a among the measured sample tree characteristics in the Finnish national forest inventory data. However, in many inventories the crown height or crown ratio is still not available. For those cases, tree crown ratio is predicted with models presented in Chapter 4.6.1. Further, during the simulation, models are used for updating tree crown ratios.

Growth prediction of the sample trees is based on individual-tree models. Simulation step is five years. Regeneration and ingrowth during the coming five-year simulation step, as well as the juvenile development of trees until they reach the height of 1.3 m are predicted with regeneration models (4.3). The growth of trees over 1.3 m is predicted with distance-independent models for tree basal-area growth (4.4.1.1, 4.4.2.2) and height growth (4.4.1.2, 4.4.2.3). Height growth on mineral soils of individual-tree is driven by the height development of dominant trees (4.1.2.1).

Mortality of trees is predicted with individual tree survival model (4.5.1), and stand-level model for self-thinning (4.5.2). The self-thinning line controls stand development in situations, where accelerated mortality is expected due to suppression and competition, for example unthinned stands.

In the end of simulation period, stand data base is updated. Static models are employed to predict stem volume (4.6.2*)* and to asses technical quality of the stems (4.6.2). Stand-level information is then calculated by summing up the treewise information from each cohort.

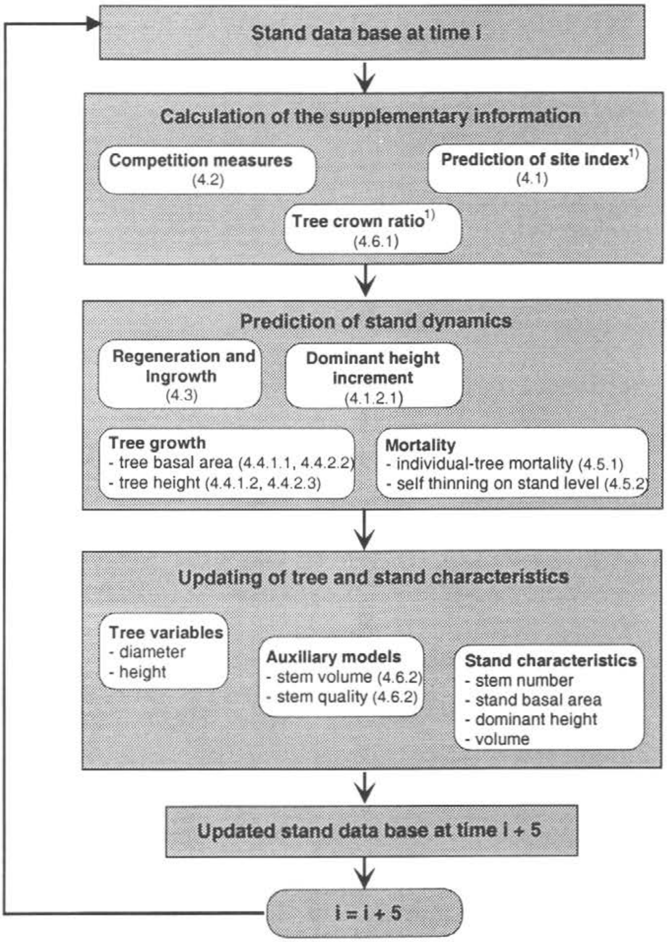


Figure 1. Flow chart of the simulation of biological processes in MELA System. ([1] On mineral soils.)

3 Modelling data

3.1 Regeneration and ingrowth

The models for the average number of naturally regenerated trees per hectare, and for distributions of tree species are based on statistics of 7th National Forest Inventory (NFI7). NFI7 was a systematic sample of tracts with temporary sample plots. The L-shaped tracts were located in 8 km grid including 21 angle-count sample plots with basal area factor 2 $m^2 ha^{-1}$. The statistics are calculated from NFI7-plots which fulfill the following stand conditions:

- dominant height over 1.3 m
- mean diameter at breast height weighted by basal area under 8 cm
- total age under 50 years in Southern Finland, and under 120 years in Northern Finland
- stand is not classified as under-productive according to other reasons except for unsuitable tree species for the site.

Models for height increment of small trees, ie. model for time that it takes for a tree to reach the breast height, are based on data from temporary sample plots (TTVK-data) collected by Y. Vuokila and J. Laasasenaho during 1968–1971 (Varmola 1993). TTVK-data consisted of 122 subjectively chosen, artificially regenerated young stands, in which stand dominant height was 5 m on the average (Ojansuu et al. 1991). Stands were chosen in order to represent wide variety of stand densities and site types. In each stand, one sample plot was established subjectively on fully stocked location. From every sample plot, 20 sample trees were chosen. Sample trees were measured for diameter at breast height, height, bark thickness, age, and annual growth for diameter and height during the preceding 15 years.

3.2 Growth

3.2.1 Mineral soils

Models for individual-tree basal area growth and height growth, as well as models for height development of dominant trees, are based on data collected from permanent sample plot data sets INKA (Inventory growth plots) and TINKA (Young forest inventory growth plots) (Gustavsen et al. 1988). These data form a sub-sample of the stands containing the sample plots of the 7th National Forest Inventory (NFI7) in Southern Finland and of the 6th National Forest Inventory in northern (NFI6). The INKA plots were established during 1976–1982, and they were re-measured twice with five-year interval during 1981–1987 and 1986–1992. TINKA plots were established in 1984–1986, and were once re-measured, five years after establishment, during 1989–1991.

The INKA and TINKA plots were chosen among the stands measured in NFI6 and NFI7 that were located in very rich (grove), rich (growlike), damp (fresh), sub-dry (dryish) or dry (dry) sites (Kuusela and Salminen 1969, the names used by Tonteri et al. 1990 are given in parentheses). For Norway spruce and birch, only the three most fertile site classes were sampled. Only single-storied and healthy stands, with the proportion of major tree species at least 50 % of the total volume of growing stock were accepted. Stands dominated by Scots pine, Norway spruce or birch species with the stand dominant height over five meters, were included in INKA data. TINKA plots were established in young stands dominated by coniferous tree species. TINKA data included both naturally and artificially regenerated stands, with dominant height under five meters at the time of the first measurement.

A plot cluster of three permanent sample plots was established in each sampled stand. Circular sample plots were located systematically 40 meters apart from each other. Plot size varied according to stand density so that minimum number of trees per plot was 35 in Northern Finland, and 40 in Southern Finland. Thus, the minimum number of trees in a stand was 100 and 120, respectively. All the trees of the sample plot (tally trees) were measured for diameter at breast height. Further, health and technical quality of the trees were recorded according to categorical variables.

In each sample plot, a concentric smaller circular plot was delineated with an area equal to 1/3 of that of the sample plot. The trees within the smaller plot were sample trees, which were measured for height and crown height in addition to tally tree measurements. Only the sample trees were included in the modelling data.

The proportion of birch in INKA data was limited. There were only 26 birch stands, of which 14 stands was dominated by silver birch, while in 12 stands dominant tree species was pubescent birch. In addition to pure stands, birch trees were growing as mixed species in 181 pine stands and in 95 spruce stands. The proportion of birch in mixed stands was generally under 20 % of the volume of the growing stock.

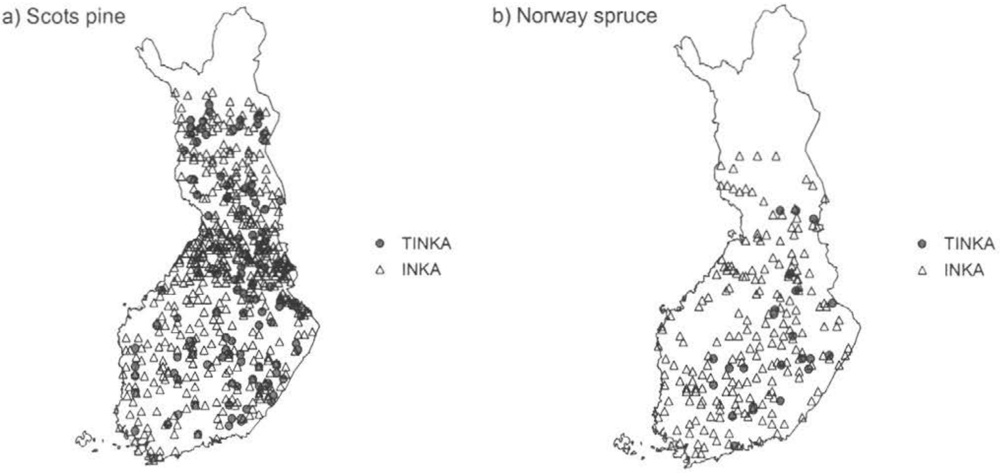
In order to obtain more representative birch material for modelling purposes, additional data were collected from repeatedly measured thinning experiments for birch established by the Finnish Forest Research Institute (e.g. Niemistö 1997). Data from permanent sample plots included 13 birch stands, of which 11 were artificially regenerated and two naturally regenerated. One stand was dominated by pubescent birch, and twelve stands were dominated by silver birch. Six of the stands were established on abandoned fields, the rest being located in forest sites. Rectangular sample plots with average size of 1 000 m^2 were established in experimental stands. From the sample plots, 40 sample trees, on the average, were selected. The probability of a tree to be selected to sample tree was proportional to diameter. Trees were measured for same characteristics as in INKA plots. The number of successive five-year growth periods varied from one to five.

In order to balance the birch data between INKA and experimental stands, only 15 % of sample trees measured from the sample plots of thinning experiments, were randomly selected to the final modelling data.

Altogether, data from 3 060 sample plots on mineral soils were applied in the model development including 25 379 trees. The proportion of Scots pine trees were 67 %, Norway spruce 24 %, and birch 9 %. The total number of observations used in the modelling varied according to model (Table 1, Fig. 2).

Table 1. Number of sample plots, trees and observations by tree species used in models for mineral soils.

Model		Tree species		
		Scots pine	Norway spruce	Birch sp.
Height development of dominant trees	Sample plots	493	520	67
	Trees	1758	1601	321
	Observations	3913	3610	718
Basal area growth	Sample plots	1641	835	402
	Trees	13574	5528	2348
	Observations	22811	9285	3757
Height growth	Sample plots	1786	872	402
	Trees	14377	5755	1540
	Observations	23992	9577	2572
Crown ratio	Sample plots	1784	910	402
	Trees	17018	6013	1540
	Observations	31764	10708	5235


a) Scots pine

b) Norway spruce

c) Birch

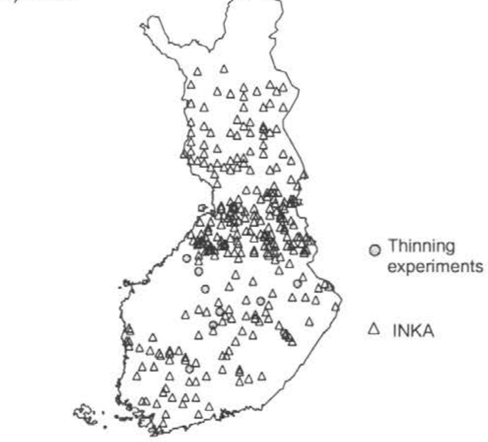


Figure 2. Location of stands included in the modelling data.

Statistics on the stand and tree data on mineral soils used in height development model for dominant trees are given in Table 2, and the data used in tree basal area growth model are presented in Tables 3, 4 and 5 by dominant tree species.

In models for tree basal area growth and tree height growth, predicted variable is growth during the coming five years. In INKA and TINKA data, time interval between successive measurements was not always exactly five years, because some of the stands were measured during the growing season. In those cases, integer numbers are not exact measures of the stand ages and the periods between the successive measurements. The stand ages were corrected to correspond to the growth occurred up to the measurement date. The relative amount of the annual growth during the measurement year up to the measurement date was added to the number of full growing seasons. The corrected ages were also used in the data for the models of height development of dominant trees.

The age correction in the stands that were measured during the growing season was approximated with the help of cumulative height growth of the growing season. The approximated relative proportion of height growth cumulated up to measurement date of the total annual growth was based on the graphically expressed curve, in which relative height growth (ihr) was expressed as a function of cumulative temperature sum of the growing season (Raulo and Leikola 1974). In this study, the relative proportion of annual height growth was expressed as a function of accumulated temperature sum (TSc):

$$\mathrm{ihr} = 1/(1 + \exp(2.80 - 0.0137 * \mathrm{TSc})) . \qquad (1)$$

TSc was estimated as a function of total annual temperature sum (TS) and the julian day (JD) as follows:

$$\mathrm{TSc} = \mathrm{TS}/(1 + \exp(34.9 - 0.410 * \mathrm{JD} + 0.00170 * \mathrm{JD}^2 - 0.00000275 * \mathrm{JD}^3)) . \qquad (2)$$

Equation 2 was calculated based on daily mean temperature data in Helsinki, Vaasa, Jyväskylä, Joensuu, and Ivalo in the 1972–1974 (Meteorological yearbooks of Finland 1972–1974). Age was corrected for stands measured between the beginning of May and the end of August.

Time-dependent growth variation, such as climatic growth variation, was not taken into account in model development. However, growth indices were applied in the context of model calibration (Chapter 5) in order to take into account the time-dependent growth variation.

Before measured tree and stand data were applied in growth modelling, site index by dominant tree species was predicted with models presented in Chapter 4.1. Further, relative measures for stand density and the status of a tree in within-stand competition were calculated using the methods presented in Chapter 4.2.

Table 2. Information about tree and stand characteristics in the modelling data for height development of dominant trees.

	Scots pine			Norway spruce			Birch		
	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
Tree									
h	2.0	12.2	31.2	2.38	17.5	32.8	6.1	16.7	30.8
d/D_{dom}	0.73	0.98	1.22	0.80	0.99	1.24	0.83	0.99	1.25
Stand – growing stock									
Age	5	48.2	161	6	59.1	156	9	38.9	88
RDF	0.005	0.447	1.370	0.002	0.44	1.251	0.008	0.278	2.664
Stand – site									
TS	659	1017	1344	732	1136	1348	940	1112	1288
ALT	5	148	320	10	115	360	17	118	200
LAKE	0.00	0.09	0.53	0.00	0.12	0.52	0.00	0.17	0.64
SEA	0.00	0.01	0.57	0.00	0.01	0.40	0.00	0.00	0.07
SC1				0	0.03	1	0	0.09	1
SC2	0	0.01	1	0	0.36	1	0	0.41	1
SC3	0	0.22	1	0	0.60	1	0	0.50	1
SC4	0	0.61	1	0	0.01	1			
SC5	0	0.15	1						
STONY	0	0.17	1	0	0.11	1	0	0.04	1
PALU	0	0.06	1	0	0.10	1	0	0.02	1
HUMUS	0	0.03	1	0	0.04	1	0	0.01	1

Table 3. Information about tree and stand characteristics in the modelling data for Scots pine.

Characteristic	Mean	Std. deviation	Min.	Max.
Tree				
d	11.9	7.0	0.3	43.5
h	9.58	5.32	1.15	30.90
cr	0.64	0.16	0.04	0.99
Stand – growing stock				
H_{dom}	11.15	5.09	1.40	28.43
Age	61.5	31.5	5	188
BA	13.29	8.22	0.01	49.28
RDF	0.389	0.205	0.002	1.714
D_g	13.6	6.2	5.4	38.8
Stand – site				
SI_{Sp}	12.83	3.06	6.49	26.56
TS	998.5	159.4	659	1344
LAT	7128	221	6652	7568
ALT	151.5	68.6	5	320

Table 4. Information about tree and stand characteristics in the modelling data for Norway spruce.

Characteristic	Mean	Std. deviation	Min.	Max.
Tree				
d	15.6	7.9	0.3	46.2
h	13.03	6.00	1.30	31.50
cr	0.78	0.12	0.29	0.99
Stand – growing stock				
H_{dom}	15.62	5.87	2.33	30.80
Age	73.9	33.7	9	188
BA	19.56	9.89	0.11	61.68
RDF	0.487	0.213	0.025	1.575
D_g	18.4	6.9	1.8	38.8
Stand – site				
SI_{Ns}	16.31	4.22	6.88	27.97
TS	1099	131	679	1348
LAT	6989	186	6676	7560
ALT	123.5	60.3	10	360

Table 5. Information about tree and stand characteristics in the modelling data for birch.

Characteristic	Mean	Std. deviation	Min.	Max.
Tree				
d	12.2	6.8	1.0	41.4
h	11.9	5.58	1.7	31.4
cr	0.57	0.13	0.08	0.98
Stand – growing stock				
H_{dom}	14.83	6.05	2.60	31.2
Age	74.9	38.2	12	193
BA	16.18	8.67	0.10	58.89
RDF	0.474	0.230	0.027	1.567
D_g	16.3	6.54	1.2	38.5
Stand – site				
SI_{sb}	17.55	3.95	6.62	27.0
TS	1016	166	659	1350
LAT	7108	226	6658	7568
ALT	144.4	73.0	2	360

3.2.2 Peatlands

The modelling data consisted of two separate inventory data sets covering the whole area where forest drainage has been applied in practical forestry (Fig. 3a). 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 (Penttilä and Honkanen 1986, Mielikäinen and Gustavsen 1992).

The permanent NFI8 plots were established in 1985 to produce data concerning changes in the Finnish forests. The re-measurement was carried out in 1990. The plot establishment was based on systematic sample tracts. Each tract contained a cluster of 3 to 4 plots, and the distance between tracts was 16 km.

The NFI8 sample plot was composed of two circular plots: a greater plot with a radius of 9.77 m and a smaller one 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 diameter at breast height was less than 4.5 cm, only a limited number of selected trees were measured.

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 data were sampled by stratified systematic sampling from stands containing sample plots of the 7th National Forest Inventory 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 which means mean annual increment over 1 $m^2 ha^{-1}a^{-1}$ (Valtakunnan metsien...1977)) and homogeneous with respect to site and stand developmental stage. Birch-dominated stands were sampled only in the southern parts of Northern Finland and spruce-dominated stands in Lapland.

The SINKA cluster was composed of three circular sample plots located 40 m apart. The size of the sample plots was adjusted according to the stand density. The whole SINKA cluster contained approximately 100 tally trees. The minimum diameter was 4.5 cm if the stand was past pole stage, and 2.5 cm otherwise.

All accepted plots were classified as productive forest land and were located on drained peatland. For the basal area growth modelling data, plots where any cutting or drainage treatments had taken place during the period of five growing seasons were omitted. Only one SINKA sample plot out of three in a cluster was included to the height-diameter modelling data because the number of sample trees in each plot was much lower in the NFI8 data than in the SINKA data. For both modelling data sets, plots including parts of more than one stand, and plots with severe or complete damages 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.

For pine, spruce and birch, separate data sets 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. For height-diameter models, the minimum number of trees in the stand was two.

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 6). Pine stands and birch stands were most common in Ostrobothnia, while spruce stands were more evenly distributed throughout the country (Fig. 3). For all tree species, the data were concentrated in Ostrobothnia, where the proportion of drained peatlands of the total forest land area is at its maximum.

Plotwise stand variables at the first measurement occasion were calculated on the basis of tree tally. Means of the stand variables indicated that the data sets consisted of stands with low stocking (Table 7). Diameter distributions for different species showed that most of the trees were less than 10 cm in diameter.

Table 6. Number of stands and trees in different peatland data sets by species.

Model		Tree species		
		Scots pine	Norway spruce	Birch sp.
Basal area growth	Stands	555	382	503
	Trees	20644	5645	16593
Tree height	Stands	458	131	279
	Trees	3450	769	2133

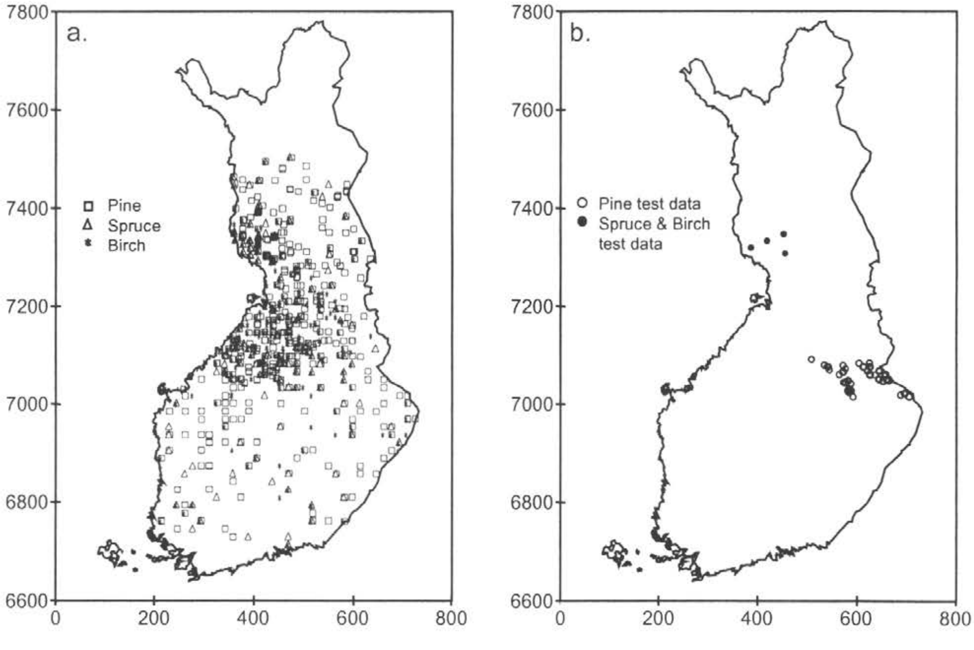


Figure 3. Location of the peatland modelling data (a) and test data (b) by tree species.

Table 7. Mean tree, stand and site characteristics in different peatland data sets by tree species.

Model	Species	Stand characteristics			
		d	BA	Dg	TS
Basal area growth	Scots pine	9,4	10,2	12,0	1074
	Norway spruce	9,7	15,4	13,9	964
	Birch sp.	8,4	15,3	11,9	1000
Tree height	Scots pine	11,2	11,8	11,9	1004
	Norway spruce	11,8	17,1	14,9	1015
	Birch sp.	10,4	15,4	12,2	1017

3.3 Mortality

3.3.1 Self-thinning

Models for self-thinning are based on data collected from untreated control plots of repeatedly measured experimental stands. Detailed description of data is given by Hynynen (1993). Since 1993, when models were published, the data were completed with recent re-measurements from experimental stands. Further, additional data were collected both from silver birch stands and from stands of pubescent birch for the development of separate self-thinning models for birch species.

Stands to be included in modelling data had to be even-aged and single species stands growing on mineral soils. The proportion of dominant tree species had to be at least 75 % of the total volume of the growing stock. Only untreated sample plots were accepted in which no thinnings have been done and no extensive damages have been documented.

To ensure that the stand included in the modelling data was undergoing the phase of self-thinning, an observation from a stand was accepted only, if the stem number of the plot had decreased during the preceding measurement period.

Modelling data included 238 observations from 42 stands (Table 8).

Table 8. Number of stands, sample plots and observations by tree species in modelling data for self-thinning models.

	Scots pine	Norway spruce	Silver birch	Pubescent birch	Total
Number of stands	18	9	10	5	42
Number of sample plots	19	11	17	12	59
Number of observations	95	56	59	28	238

Before model development, diameters at stump height (d_s) were calculated using the model of Laasasenaho (1975), which is as follows:

$$d_s = 2.0 + 1.25\ d\ . \qquad (3)$$

For each stand, site indices were calculated applying the models presented in Chapter 4.1. Information about the modelling data by tree species are presented in Tables 9–12.

Table 9. Information about the data for self-thinning models of Scots pine.

Variable	Mean	Std. deviation	Min.	Max.
Location				
LAT	6854	58.41	6736	7003
LONG	398	161	262	1138
ALT	134	26	50	160
TS	1172	34	1104	1290
Site				
SCx	4		2	6
SI	16.9	3.8	11.5	22.6
Growing stock				
Age	76	29	21	141
$Age_{1.3}$	61	27	13	129
H_{dom}	17.7	5.1	8.0	30.0
N	2567	1998	516	12990
D_g	16.6	6.3	6.9	36.1
BA	29.0	6.7	15.9	50.2

Table10. Information about the data for self-thinning models of Norway spruce.

Variable	Mean	Std. deviation	Min.	Max.
Location				
LAT	6798	21.88	6782	6859
LONG	555	82.64	366	622
ALT	87	18	75	120
TS	1262	18	1233	1275
Site				
SCx	2		1	3
SI	20.7	3.1	14.8	24.7
Growing stock				
Age	56	11.53	34	98
$Age_{1.3}$	42	9	24	85
H_{dom}	16.5	10.6	9.5	29.4
N	2062	609	1090	3880
D_g	19.1	3.7	11.5	27.3
BA	43.8	6.7	26.7	53.9

Table 11. Information about the data for self-thinning models of Silver birch.

Variable	Mean	Std. deviation	Min.	Max.
Location				
LAT	6898	166.23	6696	7219
LONG	462	84.96	389	641
ALT	108	35	35	140
TS	1176	90	1006	1312
Site				
SCx	2		1	3
SI	27.0	5.1	13.9	31.6
Growing stock				
Age	61	28	15	109
$Age_{1.3}$	56	28	11	104
H_{dom}	20.7	4.8	9.9	29
N	1988	1240	572	6484
D_g	16.4	4.8	7.4	25.5
BA	23.8	3.2	14.9	29.1

Table 12. Information about the data for self-thinning models of pubescent birch.

Variable	Mean	Std. deviation	Min.	Max.
Location				
LAT	7185	61.14	7072	7219
LONG	456	19	427	471
ALT	93	43	10	160
TS	1020.36	20.07	1006	1060
Site				
SCx	3	2	4	
SI	11.6	2.0	8.5	15.7
Growing stock				
Age	46	8	30	68
$Age_{1.3}$	39	8	24	62
H_{dom}	15.3	1.9	12.0	18.1
N	2662	1354	1506	5600
D_g	13.0	2.3	8.5	16.7
BA	22.6	2.6	18.2	28.1

3.3.2 Individual-tree mortality

Models for predicting the survival probability of Scots pine and Norway spruce are based on the data from 7th National Forest Inventory (NFI7). NFI7 data were restricted so that the stands included into the final modelling data met the following criteria:

- pine and spruce dominated stand on mineral soils
- proportion of dominant tree species was over 70 % of the stand volume
- stands were not thinned during the preceding six years.

The data included 62 557 trees, of which 560 trees (0.897 %) had been died due to natural mortality during the past five years (Table 13).

The more detailed description of the data is documented by Haapala (1983).

Model for predicting the survival probability of a birch species is based on five experiments, established as permanent plots on either planted or naturally regenerated stands, consisting both silver and pubescent birch. Study sites were fertile mineral soils. Thinning experiments included untreated control plots. Only one 5-year period from each stand was included in modelling data to avoid autocorrelation. The data consisted of 7 427 birch trees, of which 476 trees (6.4 %) had died during past five years. The mean age, dominant height and stem number of the plots varied from 17 years to 50 years, from 12.3 m to 22.4 m and from 370 stems to 3 051 stems ha^{-1}, respectively.

3.4 Auxiliary models

Models for tree crown ratio are based on same data as individual-tree growth models for tree basal area and height on mineral soils (Tables 1, 3–5).

Tree volume functions are developed by Laasasenaho (1982). The data was collected based on National Forest Inventory sampling layout and was representative for whole country. Data description is provided by Laasasenaho (1982).

The empirical model for log volume reduction assessing the amount of falling-off in the technical quality of stems due to defects is based on sample tree measurements of 7th National Forest Inventory (NFI7).

Table 13. Modelling data for individual-tree mortality models (Haapala 1983).

	Scots pine	Norway spruce	Total
Observations	29212	33345	62557
Dead trees	284	276	560
Mortality, %	0.972	0.828	0.895

4 Simulation models

4.1 Description of site

4.1.1 Site variables

The site description is primarily based on site factors. In most MELA-models, influence of the site factors is described with the help of site index. Primarily, site index is predicted as a function of site factors, but it can be calibrated for a given stand with age and height measurements. In some models, site factors are used directly as independent variables.

Site factors are denoted with variables describing geographical location of stands and variation between stands on local scale. Geographical variation is mainly caused by climatic differences and local variation caused by differences in soil characteristics. For geographical variation, temperature sum with threshold value of +5 °C (TS) has been used together with altitude (ALT), lake index (LAKE) and sea index (SEA). The temperature sum for each location is predicted with the method of Ojansuu and Henttonen (1983) to correspond the average of years 1951–1980. Lake and sea indexes describe lake or sea cover proportions in the neighbourhood of the sample plot (Ojansuu and Henttonen 1983). The maximum distance of the neighbourhood is 20 km.

Local differences in site productivity on forest land (average yield over 1.0 $\mathrm{m^3\,ha^{-1}a^{-1}}$) are described by fertility classes (Kuusela and Salminen 1969) which are based on the forest site types of Cajander (1909). Fertility classes from the most fertile to least fertile sites are as follows (the names used by Tonteri et al. 1990 and the *Finnish names* are given in parentheses): very rich (grove, *lehto*) (SC1), rich (grovelike, *lehtomainen*) (SC2), damp (fresh, *tuore*) (SC3), sub-dry (dryish, *kuivahko*) (SC4), dry (dry, *kuiva*) (SC5), and barren (barren, *karukko*) (SC6). Further, two special classes are specified: rocky land, sands and alluvial land (*kalliomaat, hietikot ja vesijättömaat*) (SC7) or hill-tops and fjelds (*lakimaat ja tunturit*) (SC8). The forest sites are supplemented with some specifications reflecting lower yield capacity, and denoted by three extra categorical (dummy) variables: stony (STONY), paludified (PALU), and very thick raw humus layer (HUMUS). Land used for forestry with average yield less than 1.0 $\mathrm{m^3\,ha^{-1}a^{-1}}$ is divided in two groups: scrub land (*kitumaa*) (SCRUB) with average yield between 1.0 and 0.1 $\mathrm{m^3\,ha^{-1}a^{-1}}$, and waste land (*joutomaa*) (WASTE) with average yield less than 0.1 $\mathrm{m^3\,ha^{-1}a^{-1}}$.

4.1.2 Site index

4.1.2.1 Model for height development of dominant trees

Site index is defined as an average height of dominant trees at 50 years of age at breast height. All trees thicker than the mean diameter weighted by tree basal area are dominant trees. Site index is predicted with height development model. The model is based on simultaneous modelling of dominant tree development as a function of age and site variables.

Basic model for stand dominant height (H_{dom}) is

$$H_{dom} = a \cdot e^{b_1 \cdot A^c}, \tag{4}$$

where a, b_1 and c are parameters, and A is stand age at breast height. Parameter a determines the asymptotic maximum height and parameters b_1 and c the model form as function of stand age.

To describe the potential change of growth pattern during the stand development, a term describing the growth anomaly from the average height/age relationship is included in the model. The anomaly term ($A–A_0$) measures the temporal difference from the first age measurement of the time series (A_0) in a linearized scale. The basic model including the growth anomaly term is

$$H_{dom} = a \cdot e^{b_1 \cdot A^c + b_2 \cdot (A^c - A_0^c)}, \tag{5}$$

where b_2 is the coefficient of the current growth anomaly. Equation 5 is linearized by logarithmization:

$$\ln(H_{dom}) = b_0 + b_1 \cdot A^c + b_2 \cdot (A^c - A_0^c) \tag{6}$$

where $b_0 = \ln(a)$.

The final model is based on tree-level analyses of height development. The dependent variable of the logarithmic model is $\ln(h_{kit}-1.3–((D_{dom\,k0} / d_{ki0})-1))$, where h_{kit} is height of dominant tree i in a stand k at time t, and $D_{dom\,k0}$ is mean diameter of the dominant trees in stand k at the last measurement, and d_{ki0} diameter of tree i at same time. The term $((D_{dom\,k0} /d_{ki0})-1)$ describes the heuristic height distribution when stand age at breast height is zero.

In the formulation of the fixed part of the model, it was assumed that the parameter b_0 for asymptotic maximum height is a function of site variables and shape of the height development (parameters b_1 b_2 and c) is independent of site. The hierarchical structure of the data is taken into account by random stand, tree and observation effects (Lappi and Bailey 1988).

The sub-model for the parameter b_0 as follows:

$$b_{0\,kit} = \beta_{0\,kit} + u_{0\,k} + w_{0\,ki} + e_{0\,kit}, \tag{7}$$

where β_0 is a fixed parameter, $u_{0\,k}$ is the random effect of stand k, $w_{0\,ki}$ is the random effect of tree i in stand k and $e_{0\,kit}$ is the random measurement effect at time t for tree i in stand k. The fixed parameter β_0 is a linear function of site variables, competitive status of the site trees and regeneration method:

$$\begin{aligned}\beta_{0\,kit} = {} & \alpha_{0,0} + \alpha_{0,1} \cdot TS_k + \alpha_{0,2} \cdot ALT_k + \alpha_{0,3} \cdot LAKE_k + \alpha_{0,4} \cdot SEA_k \\ & + \alpha_{0,5} \cdot SC1_k + \alpha_{0,6} \cdot SC2_k + \alpha_{0,7} \cdot SC3_k + \alpha_{0,8} \cdot SC4_k + \alpha_{0,9} \cdot SC5_k \\ & + \alpha_{0,10} \cdot STONE_k + \alpha_{0,11} \cdot PALU_k + \alpha_{0,12} \cdot HUMUS_k \\ & + \alpha_{0,13} \cdot RDF_{kt}^{\ 0.5} + \alpha_{0,14} \cdot \ln(d_{kit} / D_{dom\,kt}) + \alpha_{0,15} \cdot \ln(d_{kit} / D_{dom\,kt}) \cdot RDF_{kt} \\ & + \alpha_{0,16} \cdot PLANT \qquad , \end{aligned} \tag{8}$$

where fixed parameters $\alpha_{0,0} - \alpha_{0,12}$ are related to site variables, parameters $a_{13} - a_{15}$ are related with the competitive status of a tree and parameter $\alpha_{0,16}$ is related with the regeneration method.

Parameter b_1 is a fixed constant

$$b_1 = \beta_1 = \alpha_{1,0} \ , \tag{9}$$

where $\alpha_{1,0}$ is fixed parameter. Parameter b_2 include fixed and random parts:

$$b_{2\,kt} = \beta_{2\,kt} + u_{2\,k} \ , \tag{10}$$

where $\beta_{2\,kt}$ is fixed parameter and $u_{2\,k}$ stand level random parameter. The fixed parameter is:

$$\beta_{2\,kt} = \alpha_{2,0} + \alpha_{2,1} \cdot TS_k / 1000 + \alpha_{2,2} \cdot RDF_k \ , \tag{11}$$

where $\alpha_{2,0} - \alpha_{2,2}$ are fixed parameters.

The total model is:

$$\begin{aligned} & \ln(h_{kit} - 1.3 - ((D_{dom\,k0} / d_{ki0}) - 1)) = \\ & \qquad \beta_{0\,kit} + \beta_1 \cdot A_{kt}^{\ c} + \beta_{2\,kt} \cdot (A_{k0}^{\ c} - A_{kt}^{\ c}) + \\ & \qquad u_{0k} + u_{2k} \cdot (A_{k0}^{\ c} - A_{kt}^{\ c}) + w_{0\,ki} + e_{0\,kit} \end{aligned} \ , \tag{12}$$

The parameter values were estimated using the iterative least square (RIGLS) method (Prosser et al. 1991), except for the power parameter c. It was estimated by the grid method. The parameter estimates for Scots pine, Norway spruce, and birch are given in Table 14.

Table 14. Height development model for dominant trees on mineral soils. The independent variable is $\ln(h-1.3-((D_{dom}/d)-1))$. Estimates of the values (value) of the fixed parameters and standard deviations (std), as well as correlations (cor) of the random parameters are presented. Also standard errors of the fixed parameters (std. err.) and the approximated t-values (t-value) for the variances or covariances of the random parameters are presented. The approximated t-values were calculated by dividing the variance by its estimation variance. Fixed parameters printed in italics are not used when the model is used for prediction.

	Para-	Scots pine		Norway spruce		Birch	
Variable	meter	Value	Std. err.	Value	Std. err.	Value	Std. err.
Cons	$\alpha_{0,0}$	3.578	0.1254	3.418	0.0948	3.155	0.2158
TS/1000	$\alpha_{0,1}$	1.453	0.09699	1.48	0.07851	0.6528	0.1905
ALT/100	$\alpha_{0,2}$	0.0875	0.0222				
LAKE	$\alpha_{0,3}$	0.1647	0.09895	0.08331	0.08053	-0.05292	0.09083
SEA	$\alpha_{0,4}$	-0.4558	0.1411	-0.7855	0.1693		
SC_1	$\alpha_{0,5}$			0.2112	0.04797	0.03088	0.05345
SC_2	$\alpha_{0,6}$	0.1385	0.1385	0.1874	0.01846	0.01246	0.02557
SC_3	$\alpha_{0,7}$	0.0782	0.0205				
SC_4				-0.2005	0.0749		
SC_5	$\alpha_{0,8}$	-0.1363	0.0242				
STONY	$\alpha_{0,10}$	-0.1013	-0.1013	-0.0434	0.02683		
PALU	$\alpha_{0,11}$	-0.0365	-0.0365	-0.0892	0.03044	0.1871	0.06254
HUMUS	$\alpha_{0,12}$	-0.1718	-0.1718	-0.1631	0.04528	-0.445	0.08925
$RDF^{0.5}$	$\alpha_{0,13}$	0.1308	0.02158				
ln(d/Ds)	$\alpha_{0,14}$	0.9913	0.01389	0.7811	0.05146	0.7313	0.1254
ln(d/Ds)$RDF^{0.5}$	$\alpha_{0,15}$	-1.041	0.05041	-0.6057	0.1052	-0.6335	0.2456
PLANT	$\alpha_{0,16}$					0.3229	0.0323
PUB						-0.1750	0.0313
	c	-0.20		-0.25		-0.50	
A^c	$\alpha_{1,0}$	-6.054	0.1184	-6.337	0.1363	-6.569	0.2079
$(A^c_0 - A^c)$	$\alpha_{2,0}$	*9.718*	*1.087*	*14.68*	*1.86*	*-3.379*	*1.829*
$(A^c_0 - A^c)TS/1000$	$\alpha_{2,1}$	*-6.436*	*1.037*	*-10.56*	*1.608*		
$(A^c_0 - A^c)RDF$	$\alpha_{2,2}$					*-0.1668*	*0.04598*
Parameter		Std/cor	t-value	Std/cor	t-value	Std/cor	t-value
std(u_0)		0.178	3.8	0.176	3.9	0.0745	2.2
cor(u_0,u_2)		-0.363	2.5	-0.367	2.4		
std(u_2)		2.907	3.4	2.604	3.2		
std(w_0)		0.0940	4.9	0.0738	4.6	0.0519	2.8
std(e_0)		0.0323	5.6	0.0323	5.5	0.0439	3.8
				Observations			
Plots		493		520		67	
Trees		1758		1601		321	
Measurements		3913		3610		718	

4.1.2.2 Prediction of site index

Site index (SI) is defined as a mean height of dominant trees at age of 50 years at breast height. The basic value for SI is always predicted for all tree species as a function of site variables. The growth anomaly part of the model is not used. The following fixed values were given for the competition variables: RDF = 0.75 and ($D_{\mathrm{dom\,k0}}$ / d_{ki0}) = 1. The predicted SI for stand k in logarithmic scale is:

$$\ln(\hat{SI}_k - 1.3) = \beta_{0k} + \beta_1 \cdot 50^c , \tag{13}$$

and in arithmetic scale it is

$$\hat{SI} = \exp(\ln(\hat{SI} - 1.3) + \frac{\mathrm{std}(u_0)^2}{2}) + 1.3 . \tag{14}$$

The model can be calibrated to a given single-storey, even-aged stand k, if stand age at breast height, diameter distribution and height of one or more dominant trees are known. The calibrated logarithmic prediction is a sum of the fixed prediction and the random stand effect ($\dot{u}_0$):

$$\ln(\hat{SI}_k - 1.3) = \beta_0 + \beta_1 \cdot 50^c + \dot{u}_0 . \tag{15}$$

When dominant trees are measured in one time point, the random stand effect is predicted with the following formula:

$$\hat{u}_{0k} = \frac{\mathrm{std}(u_0)^2}{\mathrm{std}(u_0)^2 + (\mathrm{std}(w_0)^2 + \mathrm{std}(e_0)^2)/m_k} \cdot \bar{r}_k , \tag{16}$$

where

$\bar{r}_k$ = mean of the residuals in stand k

m_k = number of height observations in stand k.

To estimate random stand effect ($\hat{u}_{0k}$), the logarithmic residuals for the fixed part of the model (r_{kit}) are first calculated for each sample tree i:

$$r_{kit} = \ln(h_{kit} - 1.3 - ((D_{\mathrm{dom\,0k}} / d_{\mathrm{ki0}}) - 1)) - (\beta_{0\,kit} + \beta_1 \cdot 50^c) . \tag{17}$$

Calibration is restricted in the cases of large residuals because these can be consequences of disturbed earlier stand development or measurement errors. The restriction of calibration is a function of stand age and the absolute value of stand effect in logarithmic scale. Conifer stands under 10 years at breast height, and deciduous stands under 5 year at breast height are not calibrated. If the absolute value of random stand effects is high, a heuristic limiting equation is used. For random stand effects with absolute value smaller than 0.2, the calibration is made as whole. If the absolute value for $\hat{u}_0$ is higher than 0.6, the stand is not calibrated. When the absolute value is between 0.2 and 0.6, the calibration is done only partly. The applied calibration value for stand effect ($\dot{u}_0$) is:

$$\dot{u}_0 = \begin{cases} 0 & \text{if}(\hat{u}_0 < -0.6) \\ -0.6 - \hat{u}_0 & \text{if}(-0.6 \le \hat{u}_0 < -0.4) \\ 0.2 + 3 \cdot \hat{u}_0 + 5 \cdot \hat{u}_0^{\;2} & \text{if}(-0.4 \le \hat{u}_0 < -0.2) \\ \hat{u}_0 & \text{if}(-0.2 \le \hat{u}_0 < 0.2) \\ -0.2 + 3 \cdot \hat{u}_0 - 5 \cdot \hat{u}_0^{\;2} & \text{if}(0.2 \le \hat{u}_0 < 0.4) \\ 0.6 - \hat{u}_0 & \text{if}(0.4 \le \hat{u}_0 < 0.6) \\ 0 & \text{if}(\hat{u}_0 \ge 0.6) \end{cases}, \tag{18}$$

In a calibrated stand, the logarithmic height should be converted to arithmetic scale with the equation 14 by replacing $\text{std}(u_{0k})$ with the estimate of prediction error of u_{0k}:

$$\text{std}(u_{0k} - \hat{u}_{0k}) = \text{std}(u_{0k})^2 - \frac{\text{std}(u_0)^2}{\text{std}(u_0)^2 + (\text{std}(w_0)^2 + \text{std}(e_0)^2)/m_k}. \tag{19}$$

Only sample trees of the dominant tree species are used to estimate the random stand effect. For other tree species, estimated random stand effect of the dominant tree species is used. The calibration is made only once in the beginning of stand simulation.

4.2 Description of stand density and within-stand competition

Competition among trees within a stand is described with two kinds of variables:

- stand density (relative density factor (RDF)
- density of the trees larger than the subject tree (RDFL).

Relative density factor (RDF) attributes the ratio between the actual stand density and the density of a stand undergoing self-thinning. RDF is defined with the help of growing space available for trees in a stand.

For each tree in a stand, a minimum of the growing space required by a tree is calculated with the help of a modified Reineke's (1933) formula:

$$N = \beta_0 \cdot D_{kg}^{\;\beta_1}, \tag{20}$$

where N is number of stems per hectare, D_{kg} is stand mean diameter at stump height weighted with stand basal area, and β_0 and β_1 are parameters, specific separately for each tree species. The values of the parameters β_0 and β_1 in Equation (20) are presented in a logarithmic scale in Table 34.

The definition of the minimum growing space of a tree is based on two assumptions:

1) all available growing space is occupied completely in a stand undergoing self-thinning
2) minimum growing space of a tree depends on the tree diameter in the same way as the average growing space of trees in a stand undergoing self-thinning depends on the mean stand diameter.

Thus, the minimum growing space (ga_i) of tree i is

$$ga_i = \beta_0^{-1} \cdot d_{ki}^{-\beta_1} \tag{21}$$

where d_{ki} is predicted stump height diameter of a tree i. The stump height diameter is predicted as a function of diameter at breast height with the model (3).

Relative stand density is sum of the minimum growing spaces all trees in the stand

$$RDF = \sum_{i=1}^{n} ga_i\ , \tag{22}$$

where n is number of trees in a stand. In mixed stands, RDF is calculated separately for each tree species.

Relative density of the trees larger than the subject tree i is calculated with formula.

$$RDFL_i = \sum_{j=1}^{n_i} ga_j\ , \tag{23}$$

where n_i is number of trees larger than the subject tree i. In calculation of RDFL, all tree species are included.

In MELA System, stand is described with tree cohorts, thus the stem number of trees within a cohort has to be taken into account in the calculations when summing up the values of RDF and RDFL for a stand.

4.3 Prediction of natural regeneration and ingrowth

The model for natural regeneration consists of four sub-models for

1) the number of new trees per hectare under the next 5-year period
2) tree species distribution of the new trees
3) the birth year of the new trees, and
4) ingrowth model (Ingrowth means height growth until the tree reaches breast height.).

Number of new trees is predicted with a heuristic model based on the average stand conditions in sample plots of 7th National Forest Inventory (NFI7):

$$\begin{aligned} iN = {} & c_{BA} \cdot ((0.6 + 0.8 \cdot \xi) \cdot N_{ref} - N) \cdot \\ & (1.0 - 0.5 \cdot SCRUB) \cdot (1 - 0.95 \cdot WASTE) \cdot (1 + 0.2 \cdot SP)\ ' \end{aligned} \tag{24}$$

where

iN = number of the new trees per hectare under the next 5-year period
N_{ref} = average number of trees per hectare in NFI7 sub-strata
N = actual number of trees per hectare
ξ = random variable from rectangular distribution with closed interval 0–1
SP = categorical variable referring to accomplished soil preparaton during the preceding 10 years. SP = 1, if soil preparation has been done, othermise SP = 0
c_{BA} = coefficient of the density effect as a function of stand basal area (BA).

$$c_{BA} = \begin{cases} 0.01 + 0.2475 \cdot BA & \text{if}(BA < 3.9\text{m}^2) \\ 1.0 & \text{if}(3.9\text{m}^2 \leq BA < 8.0\text{m}^2) \\ 1.471 - 0.05882 \cdot BA & \text{if}(8.0\text{m}^2 \leq BA < 25.0\text{m}^2) \\ 0 & \text{if}(BA \geq 25.0\text{m}^2) \end{cases}$$

Average number of trees per hectare (N_{ref}) is given in a Table 15 based on NFI7 sample plots fulfilling the following stand conditions:

- dominant height is over 1.3 m
- mean diameter weighted with basal area is under 8 cm
- total age is under 50 years in Southern Finland, and under 120 years in Northern Finland
- stand is not in under-productive condition according to the other reasons than unsuitable tree species for the site.

N_{ref} is calculated for sub-strata that are defined according to soil type (mineral or organic), fertility class, regeneration method, and dominant tree species (Table 15). In natural regeneration, dominant tree species is the dominating species among the seed trees, and in artificial regeneration the planted or the seeded tree species. If the dominating tree species is not known, it is determined as a function of soil type and site type according to Table 16.

Table 15. Average number of trees per hectare (N_{ref}) in Equation 24. Following notations are used for tree species: 1 = Scots pine, 2 = Norway spruce, 3 = silver birch, 4 = pubescent birch, 5 = aspen, 6 = alder, 7 = other coniferous, 8 = other deciduous; and for soil type: 1 = mineral soil, 2 = peatland.

Soil type	Fertility class	Dominant tree species							
		1	2	3	4	5	6	7	8
		Natural regeneration							
1	SC1-2	5988.4	6917.0	6992.1	8235.7	12067.9	12067.9	5988.4	12067.9
1	SC3	5988.4	5529.3	6992.1	8235.7	12067.9	12067.9	5988.4	12067.9
1	SC4	4009.5	4009.5	7136.6	7136.6	12067.9	12067.9	4009.5	12067.9
1	SC5-6	3444.1	3444.1	3444.1	3444.1	3444.1	3444.1	3444.1	3444.1
1	SC7-8	1493.6	1493.6	1493.6	1493.6	1493.6	1493.6	1493.6	1493.6
2	SC1-2	5988.4	6917.0	6992.1	10337.8	12067.9	12067.9	5988.4	12067.9
2	SC3	5988.4	5777.2	6992.1	10337.8	12067.9	12067.9	5988.4	12067.9
2	SC4	4583.5	4583.5	7136.6	8347.6	12067.9	12067.9	4583.5	12067.9
2	SC5-6	3475.3	3475.3	3475.3	3475.3	3475.3	3475.3	3475.3	3475.3
2	SC7-8	4307.3	4307.3	4307.3	4307.3	4307.3	4307.3	4307.3	4307.3
		Artificial regeneration							
1	SC1-2	5153.0	5677.9	6128.3	3249.2	17715.8	17715.8	5153.0	17715.8
1	SC3	5153.0	4814.8	6128.3	3249.2	17715.8	17715.8	5153.0	17715.8
1	SC4	4158.1	4158.1	7136.6	7136.6	17715.8	17715.8	4158.1	17715.8
1	SC5-6	2557.1	2557.1	2557.1	2557.1	2557.1	2557.1	2557.1	2557.1
1	SC7-8	1493.6	1493.6	1493.6	1493.6	1493.6	1493.6	1493.6	1493.6
2	SC1-2	5153.0	5677.9	6128.3	1315.2	17715.8	17715.8	5153.0	17715.8
2	SC3	5153.0	6546.6	6128.3	1315.2	17715.8	17715.8	5153.0	17715.8
2	SC4	3737.9	3737.9	7136.6	8347.6	17715.8	17715.8	3737.9	17715.8
2	SC5-6	3774.7	3774.7	3774.7	3774.7	3774.7	3774.7	3774.7	3774.7
2	SC7-8	4307.3	4307.3	4307.3	4307.3	4307.3	4307.3	4307.3	4307.3

Table 16. Dominant tree species as a function of soil type and site type.

Soil type	Fertility class				
	SC1, SC2	SC3	SC4	SC5, SC6	SC7, SC8
Mineral soil	Pubescent birch	Norway spruce	Scots pine	Scots pine	Scots pine
Peatland	Pubescent birch	Pubescent birch	Pubescent birch	Pubescent birch	Pubescent birch

Table 17. Relative proportion of different tree species in regeneration areas. Following notations are used for tree species: 1 = Scots pine, 2 = Norway spruce, 3 = silver birch, 4 = pubescent birch, 5 = aspen, 6 = alder, 7 = other coniferous, 8 = other deciduous; and for soil type: 1 = mineral soil, 2 = peatland.

Dominant tree species	Soil type	Fertility class	Tree species							
			1	2	3	4	5	6	7	8
						Natural regeneration				
1, 7	1, 2	SC1-3	0.3423	0.0828	0.0353	0.4633	0.0078	0.0593	0.0000	0.0092
2	1, 2	SC1-2	0.0064	0.3582	0.0208	0.3075	0.0339	0.1373	0.0000	0.1359
3	1, 2	SC1-3	0.0138	0.0211	0.7204	0.1808	0.0355	0.0234	0.0000	0.0050
4	1	SC1-3	0.0293	0.0557	0.0041	0.7587	0.0750	0.0294	0.0000	0.0478
4	2	SC1-3	0.0217	0.0466	0.0027	0.8869	0.0081	0.0255	0.0000	0.0085
5, 6, 8	1, 2	SC1-4	0.0047	0.0075	0.0487	0.0648	0.1925	0.5391	0.0003	0.1424
2	1	SC3	0.0181	0.4796	0.0556	0.2626	0.1051	0.0322	0.0000	0.0468
2	2	SC3	0.0845	0.3775	0.0315	0.4717	0.0026	0.0227	0.0005	0.0090
1, 2, 7	1	SC4	0.5581	0.1041	0.0573	0.1982	0.0305	0.0160	0.0007	0.0351
1, 2, 7	2	SC4	0.4823	0.0576	0.0225	0.4316	0.0019	0.0036	0.0005	0.0000
3, 4	1, 2	SC4	0.0411	0.0288	0.0026	0.9018	0.0052	0.0040	0.0000	0.0165
1-8	1	SC5, 6	0.9148	0.0347	0.0045	0.0395	0.0000	0.0065	0.0000	0.0000
1-8	2	SC5, 6	0.7273	0.0061	0.0050	0.2615	0.0000	0.0001	0.0000	0.0000
1-8	1, 2	SC7, 8	0.4900	0.1507	0.0969	0.0854	0.1056	0.0000	0.0078	0.0636
						Artificial regeneration				
1, 7	1, 2	SC1-3	0.3957	0.0643	0.1010	0.3232	0.0347	0.0376	0.0112	0.0323
2	1, 2	SC1-2	0.0164	0.2135	0.0192	0.1525	0.0601	0.3754	0.0069	0.1560
3	1, 2	SC1-3	0.0032	0.0286	0.6608	0.0997	0.1521	0.0161	0.0000	0.0395
4	1	SC1-3	0.0000	0.0000	0.0108	0.7715	0.2177	0.0000	0.0000	0.0000
4	2	SC1-3	0.0000	0.0000	0.0000	0.9032	0.0000	0.0968	0.0000	0.0000
5, 6, 8	1, 2	SC1-4	0.0000	0.0115	0.0000	0.0000	0.6763	0.3122	0.0000	0.0000
2	1	SC3	0.0268	0.3998	0.0147	0.1753	0.0160	0.1152	0.0000	0.2522
2	2	SC3	0.1117	0.1140	0.0037	0.7551	0.0000	0.0155	0.0000	0.0000
1, 2, 7	1	SC4	0.6104	0.0518	0.0549	0.2006	0.0398	0.0247	0.0001	0.0177
1, 2, 7	2	SC4	0.4300	0.0153	0.0000	0.5547	0.0000	0.0000	0.0000	0.0000
3, 4	1, 2	SC4	0.2542	0.0000	0.0000	0.4916	0.2542	0.0000	0.0000	0.0000
1-8	1	SC5, 6	0.9948	0.0000	0.0052	0.0000	0.0000	0.0000	0.0000	0.0000
1-8	2	SC5, 6	0.4378	0.0000	0.0000	0.5622	0.0000	0.0000	0.0000	0.0000
1-8	1, 2	SC7, 8	0.3003	0.1095	0.0975	0.0000	0.0000	0.0000	0.0000	0.4927

The sub-model for distribution of tree species is presented in table format (Table 17). It is based on distributions of tree species of NFI7 sample plots in the same sub-strata as N_{ref} in the first sub-model (Equation 24). The species composition of new trees is generated with separate algorithms for natural regeneration and for artificial regeneration.

To predict the *natural regeneration* immediately after regeneration felling, five new sample trees are established. Each sample tree receives a stem number equal to one fifth of the predicted total stem number (iN in Equation 24). Tree species of the first sample tree is the same as that of the dominant tree species of the seed trees. Tree species for the other sample trees are obtained randomly. The probabilities for different tree species to be chosen for a sample tree are presented in Table 17.

In *artificial regeneration*, new sample trees are established according to user-defined rules regarding regeneration (tree species, stem number). In addition to seeded or planted sample trees, one complementary naturally regenerated sample tree is established. Stem number for that sample tree is obtained with the model for iN (Eq. 24), and tree species is determined randomly using the probabilities presented in Table 17.

To predict the natural regeneration during the simulation in any other point of in time, except for the time period next to regeneration felling, one new sample tree is formed. The stem number and tree species for that sample tree is determined as described above with the help of model for iN (Eq. 24), and Table 17 for determining tree species.

Some restrictions are used when generating the new sample trees. New sample trees are not established, if the stem number of existing stand (N) is over 3 500 ha^{-1}, or if it is over 90 % of N_{ref}. Further, a new sample tree will not be generated, if the stem number represented by the sample tree is less than 100 ha^{-1}. If the dominant canopy layer is younger than 20, or if the age of the understory is more than 60 years, no new sample trees will be generated.

A theoretical age (a_0) for a new tree in the beginning of the 5 years simulation step is predicted with the following model:

$$a_0 = -(\beta \cdot (1 - TS/1400) + SY_{1400}) - \iota, \qquad (25)$$

where

SY_{1400} = seed year interval with temperature sum 1400 dd
β = scaling parameter for the effect of temperature sum
ι = a random integer from rectangular distribution with closed interval between 0–4.

Negative value for age (a_0) means that the sample tree will be born during the five year simulation period. Parameter values for b and SY_{1400} are given in Table 18.

The ingrowth sub-model consists of two sub-models: a model for height growth and a model for the initial diameter of a tree at breast height.

First, the annual height growth (ih) under breast height is

$$ih = \left(\frac{LSS \cdot 1.3}{th}\right) \cdot (0.6 + 0.8 \cdot \xi), \qquad (26)$$

where

th = the time that it takes for a new tree to reach the breast height (Equation 27)
LSS = number of years from beginning of the simulation step that it takes for a tree to reach breast height (≤ 5)
ξ = random variable from rectangular distribution with closed interval between 0–1.

Time that it takes for a tree to reach breast height (th) is a function of tree species, fertility class, temperature sum and basal area of the stand as follows:

$$\mathrm{th} = \left\{ \mathrm{thref} \cdot \left[\frac{1300}{\mathrm{TS}}\right] \cdot \left(1-\left[\frac{\mathrm{CULT}*2600}{\mathrm{TS}+1300}\right]\right) + 0.005\cdot \mathrm{BAth}^2 \right\} \cdot (0.9+0.2\cdot\xi)\,, \qquad (27)$$

where

thref = reference time that it takes for a new tree to reach breast height, year

CULT= dummy variable, that separate cultivate stands

BAth = transformation of BA:

$$\begin{cases} 0 & \mathrm{if}(\mathrm{BA} < 10\mathrm{m}^2\mathrm{ha}^{-1}) \\ \mathrm{BA}-10 & \mathrm{if}(\mathrm{BA} \geq 10\mathrm{m}^2\mathrm{ha}^{-1}) \end{cases}.$$

The variable *thref* is given in Table 19 as a function of tree species and fertility class. The table is based on TVVK data and on the tables for the difference between total age and age at breast height used in NFI7. Initial diameter (dh13) of a tree that has reached the breast height is predicted with the following formula

$$\mathrm{dh13} = \left(\frac{\mathrm{dhref}}{1+0.01\cdot\mathrm{BA}^{1.5}}\right)\cdot(0.6+0.8\cdot\xi)\,. \qquad (28)$$

The reference diameters (*dhref*) are given in Table 20.

Table 18. Parameter values of Equation (25).

Tree species	β	SY_{1400}
Scots pine	6	1
Norway spruce	10	2
Deciduous tree sp.	4	1

Table 19. The reference time (thref in Equation 27) that it takes for a tree to reach the breast height according to data from TVVK and NFI7.

Forest site	Scots pine	Norway spruce	Silver birch	Other deciduous
SC1–SC2	7.9	12.2	6.0	7.2
SC3	8.4	12.9	7.5	8.2
SC4	8.9	13.8	9.0	9.2
SC5	10.2	14.8	10.2	10.2
SC6	12.0	14.0	12.0	12.0
SC7–SC8, SCRUB and WASTE	10.2	14.0	10.2	10.2

Table 20. The initial reference diameter (dhref in Equation 28) of a tree that has reached the breast height.

	Forest site		
Tree species	SC1	SC2	SC3– SC8, SCRUB and WASTE
Scots pine	0.7	0.6	0.3
Norway spruce	0.7	0.6	0.3
Silver birch	0.6	0.5	0.2
Pubescent birch	0.3	0.3	0.1
Alder	0.3	0.3	0.1
Other deciduous	0.4	0.3	0.1

4.4 Growth prediction

4.4.1 Tree growth on mineral soils

General description of the growth simulation is presented in Figure 4. On mineral soils, growth is predicted with models for tree basal area growth and height growth. In order to apply the growth models, all the required background information have to be included in tree and stand description referring to the time at the beginning of five-year growth period. Most of the information is included in the measured stand and tree variables. The most important required variables not provided by inventory data are a) variables of stand density and within-stand competition, b) site index, c) tree crown ratio. In growth models, stand density and competitive status of a tree within a stand are described with relative density factors (RDF – by tree species, and RDFL). They have to be calculated for each plot and tree according to methods presented in Chapter 4.2. The most important measure for site productivity is site index, which is presented in Chapter 4.1. The prediction of individual-tree height growth is driven by height development of dominant trees, which is predicted with model presented in Chapter 4.1.

Tree crown ratio is one of the driving variables in the tree basal area growth model. Although it is widely measured variable, it is not always present in inventory data. For those cases, as well as for updating tree crown ratio during the simulation, models for tree crown ratio by tree species are presented in Chapter 4.6.1.

4.4.1.1 Tree basal area growth

Tree diameter growth is predicted with models for tree basal area growth. Separate growth models were developed for Scots pine, Norway spruce, and birch species. Growth of other deciduous tree species are predicted with model of pubescent birch, calibrated according to the National Forest Inventory data (see Chapter 5.2).

The dependent variable in all the models is natural logarithm of tree basal area growth during the coming five-year growth period (i_{ba5}). If the time interval between successive measurements in the modelling data was not exactly five years, the measured growth was divided with the ratio of five and the corrected growing period (see Chapter 3.2.1). It was assumed that the effect of growth factors on tree growth is multiplicative.

The models were constructed as mixed linear models with random plot effect. The fixed variables in the models can be grouped in to variables referring to site, phase of stand development, tree size, stand density, within-stand competition and stand treatment. There were two criteria for selecting the final modifications of the variables during the model building. First, the goal was to develop models with unbiased behaviour throughout the modelling data. Second, the chosen formulation has to be capable for logical behaviour also outside the variation of modelling data (Tables 21, 22, 23).

The most important variable describing site productivity is site index. In addition to that, categorical variables referring to fertility classes are employed as complementary site variables. The reason for including categorical site type variables into the tree basal area growth models is, that site index basically describes the relation between site and height growth. However, it can be assumed that the effect of site on tree diameter growth may not be exactly similar to the effect of site on tree height growth. The effect of climate was incorporated in the model with temperature sum.

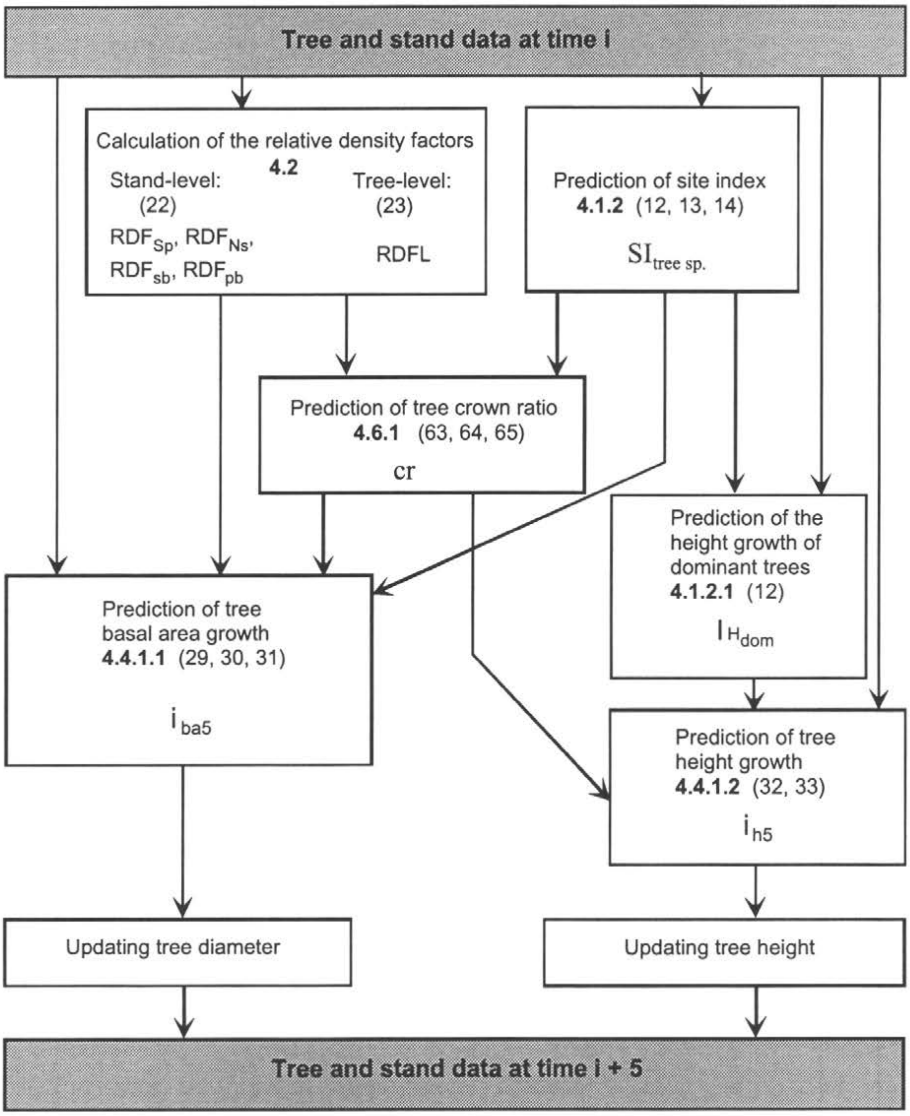


Figure 4. Tree growth prediction on mineral soils. Bold numbers refer to chapters. Numbers in the parentheses refer to model numbers.

Table 21. Model (29) for tree basal area growth of Scots pine on mineral soils.

Dependent variable is $\ln(i_{ba5})$. (Model 29)

Variable	Coefficient	Std. error	t-value
Intercept	-2.74332	0.12541	-21.87
$\ln(SI_{Sp})$	0.75638	0.05169	14.63
SC1, SC2	0.11721	0.05988	1.96
SC3	0.05213	0.02081	2.50
SC5-SC8	-0.13549	0.02549	-5.32
$1/H_{dom}$	6.46997	0.38195	16.94
$1/H_{dom}^2$	-4.22774	0.69121	-6.12
$\ln(d)$	1.57123	0.02027	77.53
d^2	-0.00088	0.00004	-22.70
$1/(d+0.1)$	1.09423	0.06243	17.53
$\ln(cr)$	0.56858	0.05051	11.26
RDFL	-0.40647	0.03639	-11.17
$\ln(RDF_{Sp}+1)$	-0.89384	0.07072	-12.64
$\ln(RDF_{Ns}+1)$	-0.97311	0.15613	-6.23
$\ln(RDF_{sb+pb+od}+1)$	-0.94614	0.22358	-4.23
$(cr \cdot TS)/1000$	0.38051	0.09031	4.21
$THIN_{0\text{-}5}$	0.11976	0.01647	7.27
$THIN_{5\text{-}10}$	0.08060	0.02025	3.98
Predicted mean	3.0260		
std(u)	0.2907		
std(e)	0.4400		
Observations	22811		

Table 22. Model (30) for tree basal area growth of Norway spruce on mineral soils.

Dependent variable is $\ln(i_{ba5})$ (Model 30)

Variable	Coefficient	Std. error	t-value
Intercept	-5.08998	0.27741	-18.35
$\ln(SI_{Ns})$	0.66849	0.09414	7.10
SC1	0.14526	0.08911	1.63
SC2	0.11475	0.03619	3.17
SC4-SC8	-0.10130	0.04480	-2.26
$1/(\ln(H_{dom}))$	7.10363	0.42799	16.60
$1/H_{dom}^2$	-25.3565	2.12405	-11.94
$\ln(d)$	0.61162	0.04945	12.37
d^2	-0.00063	0.00006	-10.88
$(\ln(d))^2$	0.19257	0.01508	12.77
$\ln(cr)$	-0.35418	0.14069	-2.52
RDFL	-0.42997	0.05318	-8.08
$\ln(RDF_{Sp}+1)$	-0.67742	0.12312	-5.50
$\ln(RDF_{Ns}+1)$	-0.78516	0.10187	-7.71
$\ln(RDF_b+1)$	-0.30546	0.18003	-1.70
$(cr\ TS)/1000$	1.71107	0.17677	9.68
$THIN_{0\text{-}5}$	0.11804	0.02100	5.62
Predicted mean	3.2491		
std(u)	0.2936		
std(e)	0.4709		
Observations	9285		

Table 23. Model (31) for tree basal area growth of silver birch (*Betula pendula* Roth.) and pubescent birch (*Betula pubescens* Ehrh.) on mineral soils.

Dependent variable is $\ln(i_{ba5})$ (Model 31)

Variable	Coefficient	Std. error	t-value
Intercept	-3.98207	0.44486	-8.95
$\ln(SI_{sb/pb})$	0.76027	0.14657	5.19
$1/H_{dom}$	14.97845	1.76386	8.49
$1/H_{dom}^2$	-32.15540	5.22331	-6.16
$\ln(d+1)$	1.314906	0.06156	21.36
d^2	-0.00053	0.00013	-4.22
$\ln(cr)$	0.37444	0.05102	7.34
RDFL	-0.96221	0.10019	-9.60
$\ln(RDF+1)$	-0.59253	0.16883	-3.51
TS/1000	1.16996	0.18158	6.44
PLANT	0.36701	0.01616	5.96
$THIN_{0-10}$	0.19411	0.03366	5.77
SP_{bb}	-0.16571	0.04362	-3.80
Predicted mean			
std(u)	0.33827		
std(e)	0.50537		
Observations	3757		

The effect of phase of stand development is described with average height of dominant trees, i.e. average height of the trees with breast height diameter larger than mean diameter.

Tree diameter and tree crown ratio are applied to describe tree size. In growth models for conifers, there is an interactive effect of tree crown ratio and temperature sum. The purpose of interaction is to take into account the effect of geographical variation in tree crown ratio on tree growth. It is known that trees in Northern Finland have, in general, larger crown ratio than trees in Southern Finland.

Relative stand density factor (RDF) is applied to describe stand density (see Chapter 4.2). In order to take into account different effect of different tree species on tree growth, relative density factor is expressed by tree species. However, in growth model for birch, species-specific expression of RDF did not prove to be statistically significant.

The competitive status of individual tree compared to other trees in the stand is described with relative density factor calculated for trees larger than subject tree (RDFL).

Variables referring to stand treatment (THIN) are categorical variables for thinning treatment in all the models, and categorical variable referring to stand regeneration method (PLANT) in model for birch. For Scots pine and birch, explicit effect of thinning was statistically significant for 10 years after thinning, and for spruce only for five years. Categorical thinning variables were needed to depict the thinning response during the time period instantly after thinning, because the tree variables that are sensitive to growing space and competition (e.g. crown ratio) do not immediately adapt to sudden changes in stand density caused by thinning, and therefore cannot reflect growth response in the model.

In birch stands, the effect of regeneration method on tree growth is included with categorical planting variable. In fact, the variable includes the combined effect of planting itself, and the effect of genetically improved seedling material used in planting.

4.4.1.2 Tree height growth

Height growth of an individual tree is predicted with a model, in which potential growth is multiplied with a modifier function. Predicted height development of dominant trees serves as potential (reference) growth, to which the prediction of individual-tree height growth is restricted. Thus, the average growth rate of the stand is predicted with models for height development of dominant trees, which is presented in Chapter 4.1.2.1.

Individual-tree height growth model for Scots pine and Norway spruce is as follows:

$$\hat{i}_{h5} = IH_{dom5}[d/D_{dom}]^{\left(\alpha_1 IH_{dom5}{}^{\alpha_2} + \alpha_3(cr/CR_{dom}) + \alpha_4 cr + \alpha_5 RDFL\right)}, \tag{32}$$

and for birch:

$$\hat{i}_{h5} = IH_{dom5}[d/D_{dom}]^{(\alpha_1 + \alpha_2 PLANT)RDFL}, \tag{33}$$

where i_{h5} is height increment in the next five years (m), IH_{dom5} five-year height increment of the mean dominant tree, and CR_{dom} is mean crown ratio of the dominant trees (Table 24).

Models for tree height growth allocate height growth between the trees within a stand. The modifier function predicts tree growth in relation to the height growth of dominant trees. Predicted tree height growth can be greater or smaller than the average height growth of dominant trees depending on relative tree size. Relative tree size is described with the ratio between tree diameter and average diameter of the dominant trees (d/D_{dom}).

The effect of relative tree size on tree height growth directly affects height growth differentiation among the trees within a stand. A strong effect of relative tree size results in large variation in predicted height growths among the trees. The effect of relative tree size on predicted height growth of Scots pine and Norway spruce depends on growth rate of dominant trees, crown ratio, and degree of competition within a stand. The differentiation in height growth among trees of varying size is greatest in stands with fast-growing dominant trees, i.e. in young stands.

The effect of tree crown ratio on height growth depends on relative tree size. Among small trees, height growth is the better the larger is tree crown ratio, whereas among the largest trees, the relationship is the opposite.

Relative density factor of larger trees (RDFL) is applied to describe the status of a tree in within-stand competition and the degree of within-stand competition. Differentiation of height growth between trees within a stand increases with increasing RDFL.

In the model for birch, the effect of planting is included in the model. According to the model (33), the within-stand variation in height growth is greater in naturally regenerated stands than in birch plantations.

Table 24. Parameters of individual-tree height growth models for mineral soils (Equations 32 and 33).

Parameter	Estimate	Asymptotic Std. deviation	Asymptotic 95 % confidence interval Lower	Upper
Scots pine				(Model 32)
α_1	0.80171	0.02644	0.74988	0.85355
α_2	0.43530	0.01470	0.40648	0.46412
α_3	-0.49724	0.03198	-0.55993	-0.43454
α_4	-0.64383	0.03855	-0.71938	-0.56827
α_5	0.08193	0.02251	0.037815	0.12605
Predicted mean	1.2454			
RMSE	0.3746			
Observations	23992			
Norway spruce				(Model 32)
α_1	1.78842	0.09034	1.61134	1.96550
α_2	0.25440	0.01365	0.22764	0.28117
α_3	-0.38878	0.11898	-0.62201	-0.15555
α_4	-1.96189	0.11764	-2.19248	-1.73129
α_5	0.53034	0.06157	0.40938	0.65103
Predicted mean	1.1779			
RMSE	0.5117			
Observations	9577			
Birch				(Model 33)
α_1	1.54405	0.1325	1.284	1.804
α_2	-0.81202	0.1875	-1.180	-0.444
Predicted mean				
RMSE	0.5623			
Observations	2572			

4.4.2 Tree growth on peatlands

The flow chart of growth prediction on peatlands is illustrated on Fig. 5. On peatlands, tree diameter increment is predicted with a model for tree basal area growth. But, the prediction of tree height growth is different from that on mineral soils. On peatland, a static model for tree height is applied. With that model, tree height is predicted in the beginning of each simulation period. Tree height growth is then calculated as a difference between tree height at the beginning of two successive simulation periods.

4.4.2.1 Yield classes and site drainage condition

In the models for peatlands, the yield classes are defined by grouping the initial site classes used in the data collection into few larger classes. The initial 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 distinguishes five 'site quality classes' for the first main group and six for the others to reflect the differences in site nutrient status. Huikari (1952) also gives supplementary definitions for a more detailed classification.

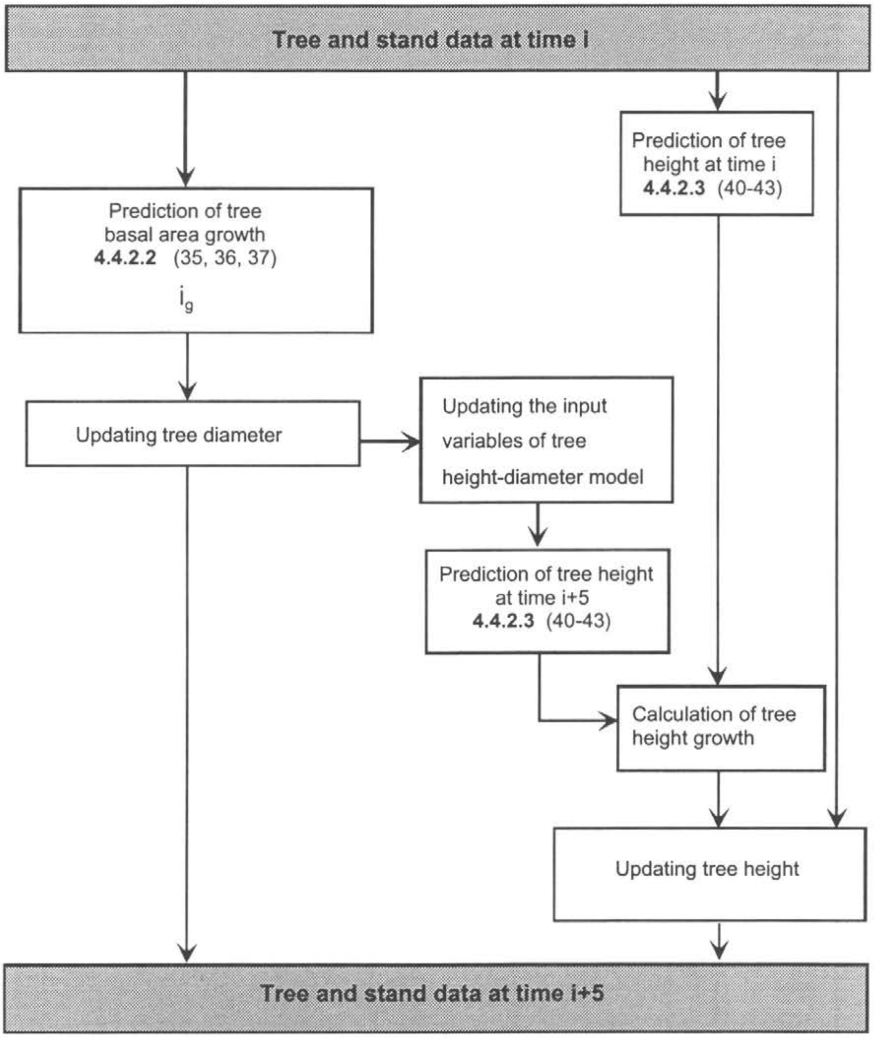


Figure 5. Tree growth prediction on peatlands. Bold numbers refer to chapters. Numbers in the parentheses refer to model numbers.

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 25. Several tests with different combinations of initial sites resulted in a system in which the yield classes were specific to each tree species (Table 26).

An additional dummy variable was defined in the model for pine to indicate the significant occurrence of either *Sphagnum fuscum* hummocks or pools or both (FUSC) in the site (Huikari 1952, 1974).

The condition of site drainage after ditching is described with two factors: dummy variables for time from the last ditching ($DR_{x.y}$, x-y indicate time from the original ditching) and a dummy variable indicating the need for complementary ditching or ditch cleaning (PDR).

Table 25. Classification of forested peatland site types according to Huikari (1952, 1974) and the occurrence of tree species (pb = pubescent birch, Sp = Scots pine, Ns = Norway spruce) in different sites.

Main site group		Site	Initial	
K-sites (*Korpi*)	R-sites (*Räme*)	quality class	site class	Trophic class
Ns, pb, (Sp)	Sp, pb, (Ns)	eutrophic	KI, RI	eutrophic
Ns, pb, Sp	Sp, pb, Ns	herb-rich	KII, RII	mesotrophic
Ns, pb, Sp	Sp, v, Ns	*V. myrtillus* / tall sedge	KIII, RIII	oligo-mesotrophic
Ns, pb, Sp	Sp, v, Ns	*V. vitis idea* / low sedge	KIV, RIV	oligotrophic
–	Sp	dwarf-shrub / Cottongrass	RV	poor oligotrophic/ ombrotrophic
–	Sp	*S. fuscum*	RVI	ombrotrophic

Table 26. Yield classes for different tree species as a function of the initial site classes, see Table 25.

Tree species	Yield class	Initial site class
Scots pine	$Y1_{Sp}$	KI-IV
	$Y2_{Sp}$	RI-RII
	$Y3_{Sp}$	RIII-RIV
	$Y4_{Sp}$	RV-RVI
Pubescent birch	$Y1_{pb}$	KI-KIV, RIII
	$Y2_{pb}$	RI-RII
	$Y3_{pb}$	RIV
Norway spruce	$Y1_{Ns}$	KI-KIII, RI-RIII
	$Y2_{Ns}$	KIV, RIV-RV

Table 27. Logistic regression model for predicting the need of improvement ditching on drained peatland sites, which corresponds to the variable PDR in the basal area growth models (Tables 28–30). (Model 34)

Variable	Coefficient	Std. error	T
Intercept	-13.5728	4.1176	-3.29
LAT	0.00201	0.00057	3.52
DR_{1-5}	-3.2307	0.7929	-4.07
DR_{6-10}	-2.513	0.4473	-5.62
DR_{11-25}	-1.3532	0.2976	-4.55
Observations	215		

Stands with good drainage conditions had a higher level of growth. In simulations, the value (0/1) of variable PDR may change in time. A specific model was developed and implemented in the MELA simulator version 1999 to predict the probability of poor condition of the ditch network (Hökkä et al. 2000). When the condition of the drainage ditches in the site is poor, the corresponding dummy variable in the peatland basal area growth models (PDR) should be used to decrease growth in predictions. In simulations, the probability for poor ditch condition is repeatedly predicted with a logistic regression model (Table 27). The probability becomes higher as the time since drainage increases and the location becomes more northern. With a specified probability level (default = 0.5), the model suggests when the dummy variable in the growth models should indicate poor drainage conditions. Later, if ditch network maintenance is made, the value of the dummy variable should indicate good conditions.

4.4.2.2 Tree basal area growth

The dependent variable is logarithm of tree basal area growth. A constant was added to the basal area growth before taking the logarithm (ln(ig+cons), where cons is specified for each tree species). At tree level, tree diameter in transformed form was the most important independent variable. Between-tree competition is accounted for by the total basal area of trees larger than the subject tree (BAL). For all tree species, high BAL results in the significantly lower growth of a tree. The relationship is described with a linear and quadratic component for pine. For spruce and birch, only the linear component was significant (Tables 28–30). At stand level, stand basal area serves as a broad measure of competition. In stands with high basal area, pine growth is significantly lower (Table 28). Stand-level indicators of competition were insignificant in explaining the growth of spruce and birch. For spruce, the greater proportion of spruce of the total basal ($BA\%_{Ns}$) area shows up as lower growth. For birch, both the proportion of birch ($BA\%_{pb}$) and the proportion of spruce of the total basal area have a similar decreasing effect on growth (Tables 29 and 30).

In all models, tree growth is higher with a higher temperature sum (TS), but for birch the linear coefficient is considerably lower than for conifers. For the pine model, the temperature sum is included as an interactive effect with the square root of tree diameter. Thus, the slope of the relationship between tree growth and tree diameter varies according to the average growing conditions. The immediate proximity of seacoast as defined by sea index (SEA) significantly increase the growth of birch.

Table 28. Model for the tree basal area growth of Scots pine on peatland.

Response variable ln(ig +1) (Model 35)

Variable	Coefficient	Std. error	T
Intercept	-1.217101	0.16012	-7.77
ba	0.00187	0.00011	-17.00
BAL	-0.00892	0.00392	-2.27
BAL^2	-0.00153	0.00014	-10.81
ln(BA)	-0.2468	0.02625	-9.40
$(TS*d^{0.50})^{0.5}$	0.06915	0.00497	13.89
$Y1_{Sp}$	-0.6115	0.10818	-5.65
$Y2_{Sp}$	0.301425	0.05305	5.68
$Y1_{Sp}$ * ln(d)	0.664339	0.07410	8.96
$Y2_{Sp}$, 4_{Sp} * ln(d)	0.314616	0.06257	5.02
$Y3_{Sp}$*ln(d)	0.388967	0.05878	6.62
DR_{0-5}	-0.23774	0.08344	-2.85
DR_{11-25}	0.093963	0.02977	3.16
PDR	-0.155569	0.02829	5.50
$THIN_{0-5}$	0.12766	0.03452	-3.70
FUSC	0.258215	0.06924	3.73
std(u)	0.410967		
std(e)	0.576062		
Observations	20644		

Table 29. Model for the tree basal area growth of pubescent birch on peatland.

Response variable ln(ig +3) (Model 36)

Variable	Coefficient	Std. error	T
Intercept	0.6394	0.1697	3.77
d^2	-0.00074	0.000093	-7.95
BAL	-0.03533	0.001244	-28.40
TS	0.0005473	0.000168	3.26
$BA\%_{Ns}$	-0.003167	0.0006813	-4.65
$BA\%_{pb}$	-0.003626	0.0004418	-8.21
SEA	0.005155	0.002312	2.23
$Y1_{pb}$, 4_{pb} *ln(d)	1.016	0.02049	49.58
$Y2_{pb}$*ln(d)	1.048	0.02546	41.16
$Y3_{pb}$*ln(d)	0.9442	0.02437	38.74
DR_{0-5}	-0.1955	0.09113	-2.14
DR_{11-25}	0.06322	0.03186	1.98
PDR	-0.1028	0.03144	-3.27
$THIN_{0-5}$	0.1777	0.03702	4.80
std(u)	0.1052		
std(e)	0.2413		
Observations	16609		

Table 30. Model for the tree basal area growth of Norway spruce on peatland.

Response variable ln(ig +7) (Model 37)

Variable	Coefficient	Std. error	T
Intercept	1.223	0.1517	8.06
$d^{2.9}$	-0.00001747	0.000002938	-5.95
BAL	-0.01503	0.001512	-9.94
$BA\%_{Ns}$	-0.00441	0.00057	-7.74
$Y1_{Ns} * d^{0.5}$	0.5141	0.01311	11.75
$Y2_{Ns} * d^{0.5}$	0.4279	0.01626	26.32
$DR_{0\text{-}5}$	-0.2639	0.09509	-2.78
$DR_{25\text{-}}$	-0.04874	0.03549	-1.37
PDR	-0.06852	0.03427	-2.00
$THIN_{0\text{-}5}$	0.1621	0.04057	3.99
std(u)	0.08562		
std(e)	0.1241		
Observations	5645		

For Scots pine, the yield classes $Y1_{Sp}$ and $Y2_{Sp}$ have a different intercept compared to the others (Table 28). Different slopes are determined for yield classes $Y1_{Sp}$ and $Y3_{Sp}$, while yield classes $Y2_{Sp}$ and $Y4_{Sp}$ have equal slopes.

For birch, the K-sites are grouped into one yield class ($Y1_{pb}$, which also included site RIII (Table 26)). Classes $Y1_{pb}$, $Y2_{pb}$ and $Y3_{pb}$ all have different slopes.

For spruce, only two yield classes ($Y1_{Ns}$, $Y2_{Ns}$) were formed (Table 26). For yield class $Y1_{Ns}$, the slope is greater than for $Y2_{Ns}$ (Table 30). Yield classes $Y1_{Ns}$ and $Y2_{Ns}$ correspond to Huikari's site quality classes I–III and IV, respectively.

The site variable FUSC results in a significantly lower growth rate for pine.

The effect of time since drainage (DR) is different for each species. Stands drained less than 6 years earlier have the lowest level of growth for all species (Tables 28–30). Similarly, the highest growth rate occur 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 is equal for pine and birch, so these classes are combined. For spruce, growth in the oldest age class (> 25 years since drainage) is slightly lower than during in the preceding 20 years.

Stands with poor drainage conditions (PDR) have a lower level of growth. Thinning treatment during the past 5 years, indicated by a dummy variable ($THIN_{0\text{-}5}$), significantly increases the growth of trees of all species.

In all models, the random stand effect (u) was significant, indicating that the level of growth varies randomly from stand to stand.

4.4.2.3. Tree height

The height formula used here is the common exponential model:

$$\ln(h-1.3) = a - bd^{-c} \tag{38}$$

where h is tree height in decimeters. When the parameters of the height model are assumed to vary from stand to stand, the height of tree i in stand k can be described with model:

$$\ln(h_{ki}-1.3)=a_k-b_k d_{ki}^{-c}+e_{ki} \tag{39}$$

where e_{ki} is an error term. With respect to parameters a_k, b_k and tree diameter, the model was parameterised according to Lappi (1997):

$$\ln(h_{ki}-1.3) = A_k - B_k x_{ki} + e_{ki} \tag{40}$$

$$\text{where } x_{ki} = ((d_{ki}^{-c})-(30^{-c}))/((10^{-c})-(30^{-c})) \tag{41}$$

Using this expression, A_k can be interpreted as the expected value of ln(h-1.3) for trees with a diameter of 30 cm and B_k as the expected difference of ln(h-1.3) between trees with diameters of 30 cm and 10 cm (Lappi 1997).

Parameters A and B assumed to be functions of variables describing growing stock and site. Another basic assumption was that height-diameter curves vary randomly from stand to stand with respect to both intercept (A) and slope (B) (Lappi 1997). 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 is expressed as a function of stand and site characteristics.

Sub-model for parameter A is

$$\begin{aligned} A_k &= \alpha_{0,0}+\alpha_{0,1}\cdot\ln(DgM_k)+\alpha_{0,2}\cdot\ln(BA_k)+\alpha_{0,3}\cdot\ln((BA\%B_k/100)+1) \\ &\quad+\alpha_{0,4}\cdot LAT_k+\alpha_{0,5}\cdot ALT_k+\alpha_{0,6}\cdot TH_k+\alpha_{0,7}\cdot(SQ24_{Sp})_k+u_{0k}+e_{0ki} \end{aligned} \tag{42}$$

and for parameter B it is

$$B_k = \alpha_{1,0}+\alpha_{1,1}\cdot\ln(DgM_k)+\alpha_{1,2}\cdot BA+u_{1k}+e_{1ki}\cdot(\dot{d}_{ki})\,, \tag{43}$$

where DgM_k is basal area median diameter in the stand k, and $\dot{d}_{ki}$ is $\max(d_{ki}, p)^q$. The search for the appropriate values for the parameters p and q was done with trial-and-error method. For Scots pine and pubescent birch, the determined values are 9 and -2 for p and q, respectively. For Norway spruce $\dot{d}_{ki} = 0$.

Tree height is assumed to depend on tree diameter according to Equation (39), the exponent c being specific to each species. The appropriate value for parameter c was determined by tree species by fitting model 40 to each stand. The minimum sum of squares of the residuals was used as an indicator of the best exponent, which were 0.4 for Norway spruce and Scots pine, and 0.7 for pubescent birch.

For *Norway spruce*, the logarithm of the diameter of the tree of median basal area (DgM), logarithm of stand basal area, and north coordinate (divided by1000) explain the variation in intercept (Table 31). DgM and tree diameter explain the slope of the curve.

For *pubescent birch*, fixed stand-level variables explaining intercept A are the logarithm of DgM, north coordinate (divided by1000), elevation above sea level, the logarithm of the total basal area of birch, and a dummy variable which have value 1 if the stand had been thinned during the past five years, or 0 otherwise (Table 31). The slope of the curve (B) is explained by tree diameter, DgM, and stand basal area.

Table 31. Model for the height-diameter curve. The independent variable is ln(h-1.3). Variable x is a function of tree diameter, given in Equation 41. Estimates of the values (value) of the fixed parameters and standard deviations (std.) as well as correlations (cor) of the random parameters are presented. Also standard errors of the fixed parameters (std. err.) and the approximated t-values (t-value) for the variances or covariances of the random parameters are presented. The approximated t-values were calculated by dividing the variance by its standard error.

	Para-	Scots pine		Norway spruce		Pubescent birch	
Variable	meter	Value	Std. err.	Value	Std. err.	Value	Std. err.
Cons	$\alpha_{0,0}$	5.369	0.3139	5.789	0.4095	6.465	0.417
ln(DgM)	$\alpha_{0,1}$	0.3566	0.03451	0.1889	0.05092	0.4743	0.03084
ln(BA)	$\alpha_{0,2}$	0.1177	0.01672	0.1665	0.0222		
$\ln((BA\%_{pb}/100)+1)$	$\alpha_{0,3}$					0.1339	0.01302
LAT	$\alpha_{0,4}$	-0.02638	0.004088	-0.02381	0.00491	-0.0433	0.00542
ALT	$\alpha_{0,5}$					-0.000436	0.000134
$THIN_{0-5}$	$\alpha_{0,6}$	0.05115	0.01649			0.06447	0.01824
$SQ24_{Sp}$	$\alpha_{0,7}$	0.0984	0.01719				
	c	0.4		0.4		0.7	
x	$\alpha_{1,0}$	0.3742	0.03857	0.4502	0.09459	-0.05942	0.04247
x * ln(DgM)	$\alpha_{1,1}$	0.141	0.01831	0.1622	0.03583	0.2123	0.01955
x * (BA)	$\alpha_{1,2}$	0.0984	0.001274			-0.004922	0.000838
Parameter		Std/cor	T-value	Std/cor	T-value	Std/cor	T-value
$std(u_0)$		0.155145	89.31	0.05945	2.34	0.133116	53.75
$std(u_0, u_1)$		0.6554	14.08			0.579	15.38
$std(u_1)$		0.07345	32.47	0.005127	2.47	0.004265	24.57
$std(e_0)$		0.071937	36.50	0.15691	17.64	0.059958	22.74
$std(e_1)$		1.389244	241.09			0.923038	87.93
Plots		458		131		279	
Observations		3450		769		2133	

For *Scots pine*, the intercept is explained by the logarithm of DgM, the north coordinate, the logarithm of the stand basal area, and the dummy variable for thinning (Table 31). In contrast to the other models, a dummy variable indicating site quality according to Huikari's (1952) classification system proved to significant. The curve is higher for medium productive sites, i.e., KII – KIV and RII – RIV, indicated by a dummy variable $SQ24_{Sp}$. For pine, tree diameter, the logarithm of DgM, and stand basal area explain the variation in the slope of the curve.

When the height model is applied in arithmetic scale, the prediction is

$$\hat{h}_{ki} = \exp(\overline{\ln(h_{ki} - 13)} + (std(u_0)^2 + std(u_1)^2 \cdot \dot{d}_{ki}{}^2) + 13, \tag{44}$$

where $\overline{\ln(h_{ki} - 13)}$ is fixed prediction for height in logarithmic scale.

4.5 Prediction of mortality

Mortality is predicted with two-phase procedure (Fig. 6). In the beginning of the simulation period, survival probability is calculated for each tree with the help of two sub-models: within stand competition model (Eq. 46, 47) and life-span model (Eq. 48, 49).

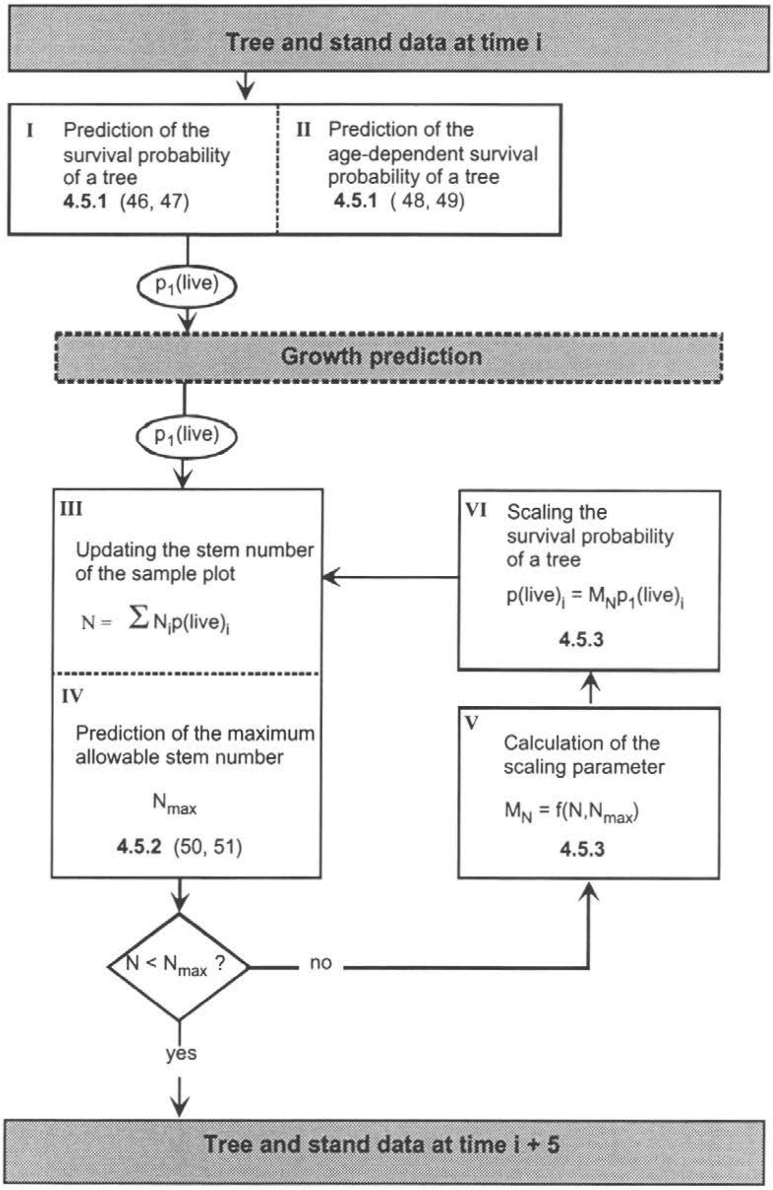


Figure 6. Prediction of mortality in MELA-System. Bold numbers refer to chapters. Numbers in the parenthesis refer to model numbers.

In the end of the simulation period, simulated stocking level is checked to ensure that it falls within the reasonable limits. The maximum allowable stem number in a stand with a given mean diameter, is predicted with the self-thinning models (Eq. 50, 51). Then, the ratio of maximum stem number and simulated stem number is calculated. If this ratio is less than one, the predicted stem number of each sample tree, will be multiplied with the ratio to decrease the survival, and increase mortality rates until the simulated stem number equals the maximum allowable stem number.

4.5.1 Individual-tree survival

Individual-tree survival rate is obtained with models predicting the probability of a tree to die during the coming five-year growth period. The total probability for a tree to die during the coming five-year period (p_{tot5}) can be predicted with the following formula including the predicted probabilities of models 46, 47 and 48.

$$p_{tot5}(age) = 1 - (1 - p_{comp5})(1 - p_{old5}), \tag{45}$$

in which p_{comp5} is mortality probability caused by within stand competition and p_{old5} the life-span mortality.

For mortality caused by within stand competition, separate models were used for conifers and deciduous tree species. For Scots pine and Norway spruce, the following model developed and documented by Haapala (1983) is applied:

$$p_{comp5} = \left(\frac{1}{1 + \exp(\alpha_0 + \alpha_1 \cdot d + \alpha_2 \cdot BA + \alpha_3 \cdot BAL)} \right), \tag{46}$$

where

p_{comp5} = probability of a tree to die during the coming five-year period.

Model was fitted separately for Scots pine and Norway spruce, and within tree species, separately for different fertility classes Table 32. The survival rate for deciduous tree species is predicted with the following model (Table 32).

$$p_{comp5} = \left(\frac{1}{1 + \exp(\alpha_0 + \alpha_1 \cdot d_s + \alpha_2 \cdot RDFL + \alpha_3 \cdot d_s \cdot RDFL)} \right), \tag{47}$$

According to the survival models caused by within stand competition, the probability of a tree to die during the coming five-year is largest among the smallest and suppressed trees (Figure 7).

The probability of a tree to die due to aging is predicted using the following heuristic logistic model:

$$p_{old}(\mathrm{age}) = \frac{e^{\left(-10+10\left(\frac{10\cdot \mathrm{age}}{0.82\cdot A_{max}}\right)\right)}}{1+e^{\left(-10+10\left(\frac{10\cdot \mathrm{age}}{0.82\cdot A_{max}}\right)\right)}}. \qquad (48)$$

where P_{old} (age) is probability of a tree to die due to aging at a given age.

Table 32. Parameter values of the individual-tree mortality models for Scots pine and Norway spruce (Equation 46) and for deciduous tree species (Equation 47).

Tree species	Fertility class	Parameter α_0	α_1	α_2	α_3
Scots pine	SC1,2	3.133	0.2087	-0.0189	-0.0847
	SC3	2.2388	0.5089	-0.0303	-0.0794
	SC4	3.9458	0.1445	-0.0444	-0.069
	SC5	2.9774	0.3274	0.0591	-0.1875
	SC6-8	3.476	0.0071	0.1692	-0.1867
Norway spruce	SC1,2	4.3958	0.2042	0.0956	-0.199
	SC3	4.3552	0.094	0.0867	-0.1637
	SC4	2.891	0.1772	0.809	-0.9307
	SC5-8	1.696	0.092	-0.0154	0.5883
Deciduous	SC1-8	3.014	0.1015	-9.313	0.4073

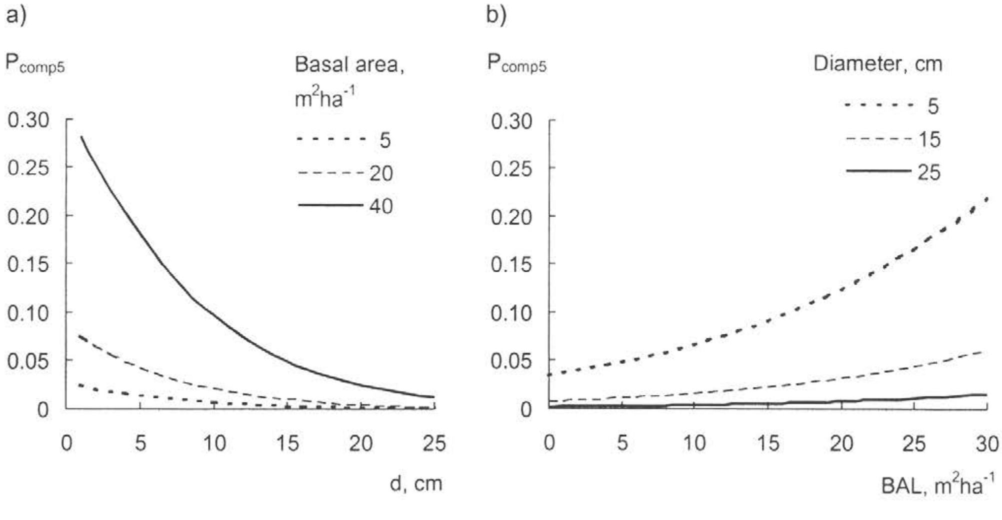


Figure 7. Probability of a tree to die during the next five-year period in a Scots pine stand on sub-dry site class (Vaccinium site type) a) as a function of tree diameter with varying stand basal area (BA), and basal area of larger than the subject tree (BAL = 0.5 BA), and b) as a function of BAL with varying tree diameter with fixed stand basal area (BA = 30 $m^2 ha^{-1}$).

Survival rate of trees decreases with increasing age so that at the maximum age, 10 % of trees are still alive (Fig. 8). The maximum age of a tree varies according to tree species and geographical location of a tree. The values for maximum ages of tree species are based on the information from literature and from personal communications with experienced researchers (Table 33).

The maximum age of a tree with a given temperature sum, can be calculated using the maximum ages presented in Table 33, and assuming the linear relationship between maximum age and temperature sum. The life-span related probability of a tree to die during the coming five-year period is as follows:

$$p_{old5} = \frac{\left(p_{old}(age+5) - p_{old}(age)\right)}{\left(1 - p_{old}(age)\right)} . \tag{49}$$

where p_{old5} is probability of a tree to die due to aging during the coming 5-year growth period.

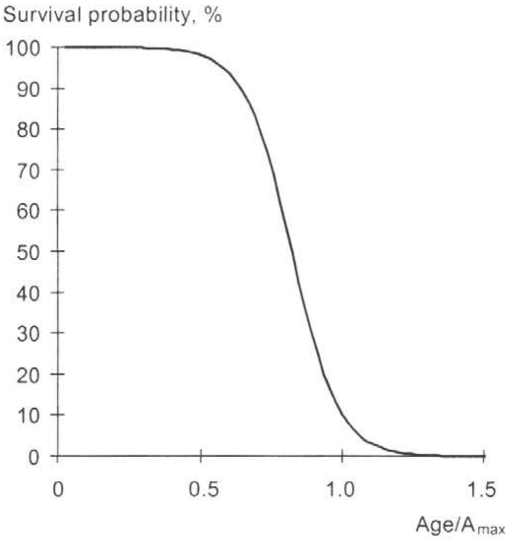


Figure 8. Survival probability of a tree as a function of relative tree age, predicted with the heuristic model (48).

Table 33. Maximum ages of tree species (A_{max}) with varying temperature sum used in Equation 48.

Tree species	Temperature sum, ddy	
	1200	800
	Maximum age, years	
Scots pine (*Pinus sylvestris* L.)	450	750
Norway spruce (*Picea abies* L. Karsten)	350	450
Silver birch (*Betula pendula* Roth.)	200	300
Pubescent birch (*Betula pubescens* Ehrh.)	150	225
Aspen (*Populus tremula* L.)	180	270
Grey alder (*Alnus incana* L.)	100	150
Common alder (*Alnus glutinosa* L. Gaertner)	150	225
Mountain ash (*Sorbus aucuparia* L.)	80	120
Goat-willow (*Salix caprea* L.)	80	120
Other coniferous sp.	350	400

4.5.2 Self-thinning

In order to ensure that the amount of growing stock remains within reasonable limits during the simulation, an upper allowable level for growing stock is set. Stand density is controlled between five-year intervals during the simulation by applying the modified form of the self-thinning model of Hynynen (1993) based on the relationship first introduced by Reineke (1933).

The model for self-thinning describes the relationship between stem number and mean diameter in an unthinned stand undergoing self-thinning. Separate models, estimated as mixed linear models, were developed for four major tree species (Tables 34 and 35).

Two set of self-thinning models were developed. First, site-independent self-thinning model developed for conifers and birch species is as follows (Table 34):

$$\ln(N_{ij}) = \alpha_0 + \alpha_1 \ln(D_{gsij}) + u_i + e_{ij} . \qquad (50)$$

Second, the site-dependent model for conifers is as follows (Table 35):

$$\ln(N_{ij}) = \alpha_0 + \alpha_2 \ln(SI_i) + \alpha_1 \ln(D_{gsij}) + u_i + e_{ij} . \qquad (51)$$

Site-dependent model for birch species has not been presented, because the effect of site index proved not to be statistically significant in the analysis.

Mean diameter at stump height (weighted with stand basal area at stump height) was applied in the models instead of mean diameter at breast height in order to stabilise model behaviour when applied in the young stands. The stump height diameter was calculated as a function of dbh according Equation 3.

Table 34. Site-independent models for self-thinning (50).

Dependent variable: ln (N)	Estimate	Standard error	t-value
Scots pine			
α_0	13.9189	0.1515	91.90
α_1	-2.0551	0.0469	-43.78
std(u)	0.202		
std(e)	0.078		
Norway spruce			
α_0	12.6161	0.2048	61.59
α_1	-1.5538	0.0632	-24.60
std(u)	0.087		
std(e)	0.056		
Silver birch			
α_0	14.1979	0.2853	49.77
α_1	-2.2178	0.0942	-23.55
std(u)	0.160		
std(e)	0.106		
Pubescent birch			
α_0	13.1659	0.4141	31.79
α_1	-1.8545	0.1438	-12.90
std(u)	0.156		
std(e)	0.040		

According to the models for self-thinning, Norway spruce is the most shade-tolerant tree species. In a stand with a given mean diameter, maximum stem number attained in spruce stand is higher than in stands of other species. Silver birch is the most shade-intolerant of the major tree species (Fig. 9).

Table 35. Site-dependent models for self-thinning for conifers (51).

Dependent variable: ln (N)	Estimate	Standard error	t-value
Scots pine			
α_0	12.3758	0.4666	26.53
α_2	0.5710	0.1657	3.45
α_1	-2.0670	0.0460	-44.91
std(u)	0.158		
std(e)	0.078		
Norway spruce			
α_0	11.8686	0.4411	26.91
α_2	0.2919	0.1558	1.87
α_1	-1.5928	0.0663	-24.01
std(u)	0.076		
std(e)	0.056		

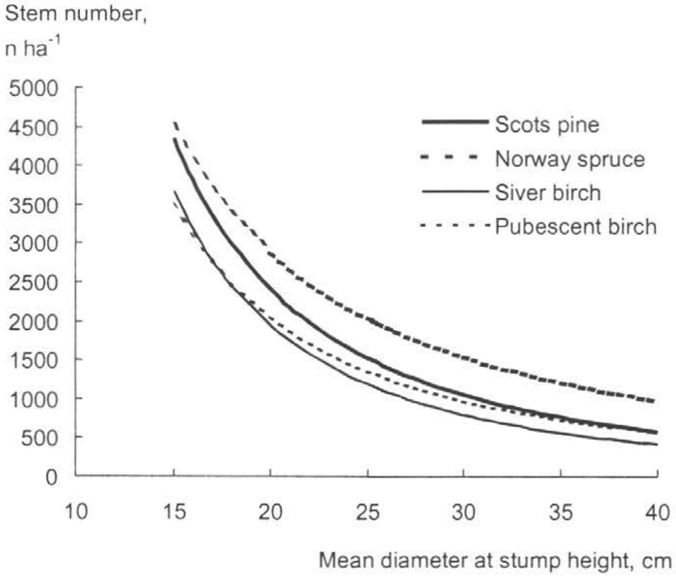


Figure 9. The relationship between stem number and mean diameter at stump height (weighted with stand basal area at stump height) predicted with site-independent self-thinning model 50.

4.5.3 Applying the self-thinning models during the simulation

During the simulation of stand development in MELA System, self-thinning models are applied to calculate I) relative density and II) maximum allowable stem number of a stand.

I Calculation of the relative stand density variables (RDF, RDFL)

1. Site-independent self-thinning models (47) are applied in calculation of RDF and RDFL, when input variables of the model for dominant height increment (Table 14) and site index models (Eq. 13, 14) are determined.
2. Site-dependent self-thinning models are applied in calculation of RDF, and RDFL for input variables of
   - tree basal area growth model (on mineral soils) [29, 30, 31],
   - tree height growth model (on mineral soils) [32, 33],
   - model for tree crown ratio [63, 64, 65]

II Calculation of the maximum stem number in stands undergoing self-thinning
In the prediction of mortality, self thinning models are applied in the determination of the upper allowable limit for growing stock, i.e. maximum stem number at a given mean diameter. In the simulation, mortality models are applied simultaneously according to the procedure illustrated in Figure 6 with the following steps:

1. *Calculation of individual-tree mortality rates for sample trees*
   Individual-tree mortality rate during the coming five-year period (p_{tot5}) is calculated with models 45 to 49 as described in 4.5.1.
2. *Calculation of the total stem number (N) and the stem number represented by each sample tree (n_j) at the end of simulation period*
   Stem number represented by every sample tree ($Ntree_{actual}$), as well as the total stem number of the stand ($Ntot_{actual}$) at the end of five-year growth period are calculated by subtracting the predicted mortality from the stem number at the beginning of growth period.
3. *Calculation of stand mean diameter at stump height D_{gs}*
   Mean stand diameters at stump height (weighted with stand basal area) in the beginning and in the end of five-year growth growth period are calculated according to the formula similar to Eq. 3.

   $$D_{gs} = 2.0 + 1.25 * D_g. \qquad (52)$$
4. *Calculation of the maximum allowable stem number (N_{max})*
   The maximum stem number in the end of five-year period for each tree species (N_{max}(sp.)) in the stand is calculated with site dependent self-thinning models (51) for conifer stands on mineral soils, and with site-independent models (50) for deciduous stands and for peatlands.
   - Prediction of maximum stem number for mixed stands

     Maximum stem number is predicted for each tree species of the stand. In a stand with only one tree species, maximum stem number is obtained directly from the self-thinning model of the tree species in question.

     In mixed stands, it is assumed that maximum stem number is affected by all the tree species growing in the stand. The following principles concerning the inter-species effects are applied.

The effect of competing tree species is determined by their shade-tolerance with respect to the shade-tolerance of subject tree species.

Appearance of less shade-tolerant competing tree species does not affect the self-thinning of subject tree species. Thus, the maximum stem number of Norway spruce, which is the most shade-tolerant tree species, is not affected by any other species.

Appearance of more shade-tolerant competing species in the stand increase the shade-tolerance (shifts up the self-thinning line) of a subject tree species. For example, if we consider a silver birch tree growing in a spruce dominated stand, the self-thinning line for that silver birch tree is higher compared to the situation, in which all the competitors are silver birch trees.

In calculating the N_{max} for mixed species, each tree species of higher shade-tolerance is assumed to affect to N_{max} with the weight determined by its relative density factor. Thus, the maximum allowable stem number for different tree species in a mixed stand is obtained with the following procedure.

Tree species are ordered by their shade-tolerance.

For Norway spruce:

$$N_{max}(Ns) = N_{max\,i}(Ns) \tag{53}$$

For Scots pine:

$$N_{max}(Sp) = \frac{(RDF_{Sp} + RDF_{sb} + RDF_{pb})}{RDF_{tot}} \cdot N_{max\,i}(Sp) + \frac{RDF_{Ns}}{RDF_{tot}} \cdot N_{max\,i}(Ns) \tag{54}$$

For pubescent birch:

$$\begin{aligned} N_{max}(pb) = {} & \frac{(RDF_{Sp})}{RDF_{tot}} \cdot N_{max\,i}(Sp) + \frac{RDF_{Ns}}{RDF_{tot}} \cdot N_{max\,i}(Ns) + \\ & \frac{(RDF_{Ssb} + RDF_{pb})}{RDF_{tot}} \cdot N_{max\,i}(pb) \end{aligned} \tag{55}$$

For Silver birch:

$$\begin{aligned} N_{max}(sb) = {} & \frac{(RDF_{Sp})}{RDF_{tot}} \cdot N_{max\,i}(Sp) + \frac{RDF_{Ns}}{RDF_{tot}} \cdot N_{max\,i}(Ns) + \\ & \frac{(RDF_{sb})}{RDF_{tot}} \cdot N_{max\,i}(sb) + \frac{(RDF_{pb})}{RDF_{tot}} \cdot N_{max\,i}(pb) \text{ ,} \end{aligned} \tag{56}$$

where N_{max}(tree species) is calculated with the model (51) for conifers, and with model (50) for deciduous tree species.

For other deciduous tree species, model for pubescent birch is applied. For other conifers, model for Scots pine is applied.

- Prediction of maximum stem number for stands with mean diameter (D_{gs}) under 12 cm.

In the modelling data of self-thinning models, stands with mean diameter under 10 cm were poorly represented, because most of these young stands had not yet reached the stage of self-thinning. Therefore, the predicted maximum stem number obtained with models 50 and 51 may not be realistic for young stand with small mean diameter. For the stands with mean diameter at stump height less than 12 cm, the relationship between stem number and mean diameter was assumed to be linear. It was described with straight line equals to tangent of the model 50, with value of D_{gs} equals to 12 cm (Fig. 10).

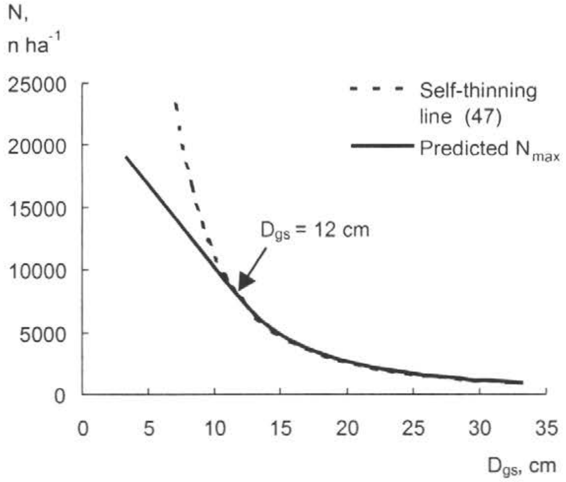


Figure 10. Prediction of maximum stem number.

- Prediction of the maximum stem number for two-storey stands

  In this context, a stand is defined as two-story stand, if the mean height of upper-storey tree species is more than 20 % greater than the arithmetic average height of a stand.

  In two-storied stands, it is assumed that the stem number of lower storey will not affect the self-thinning (maximum stem number) of upper-storey trees. Therefore, self-thinning of upper-storey does not occur until the the maximum stem number of upper-storey is greater than maximum allowable stem number calculated on the basis of upper-storey trees only.

- Maximum allowable decrease in stem number during 5-year simulation step

  If data are obtained from small sample plots or with angle cauge sampling, the estimate of stem number of individual sample plot is unprecise. In National Forest Inventory, sample plot data is obtained using angle cauge sampling with the angle cauge factor 2. In young stands with small sample trees, angle cauge sampling may result in illogically high stem numbers, i.e. high above maximum allowable stem number predicted with self-thinning model. For those cases, a maximum allowable reduction of stem number during one 5-year simulation step is set in order to prevent catastrophic mortality in the beginning simulation.

  Maximum allowable reduction in stem number for a given tree species (ΔN_{max} (sp.)) with a given increase in mean stand diameter is set to be equal to 1.5-times the reduction in stem numbers as a function of mean diameter development according the self thinning model ($\Delta N_{selfth.}$).

5. *Calculation of the scaling factor for mortality*

   The ratio between maximum stem number (N_{max}(sp.)) and the actual stem number N_{actual} (calculated in step 2) is calculated for each tree species growing in the stand.

$$N_{ratio} = \frac{N_{max}(sp.)}{N_{actual}} . \tag{57}$$

- Calculation of N_{ratio} for data sampled with angle cauge method

  If data is obtained with angle cauge sampling the following restrictions are applied in determination of maximum stem number, and its change.

  For stands with stem number under 2000 trees per hectare, N_{ratio} is calculated as presented above.

  For stands with stem number over 5000 trees per hectare, measured stand basal area is applied in calculation of N_{ratio} instead of stem number. Before calculation of N_{ratio}, a theoretical maximum stand basal area is calculated for stand undergoing self-thinning as a function of mean diameter of the sample plot (D_g) and maximum stem number (N_{max}) predicted with self-thinning model:

$$G_{max} = N_{max} \cdot \pi \cdot \left(\frac{D_g}{200}\right)^2 . \tag{58}$$

Then, N_{ratio} is calculated as a ratio between maximum stand basal (G_{max}) area and measured (or predicted) basal area of the sample plot (G_{actual}):

$$N_{ratio} = \frac{G_{max}}{G_{actual}} . \tag{59}$$

For stands with stem number between 2000 and 5000 trees per hectare, N_{ratio} is calculated twice; based on stem numbers and based on basal areas. The final value of N_{ratio} is then calculated as their weighted average as follows:

$$N_{ratio} = weight \cdot \frac{G_{max}}{G_{actual}} + (1 - weight) \cdot \left(\frac{N_{max}}{N_{actual}}\right), \tag{60}$$

in which

$$weight = 1/3 \cdot (N_{actual}/1000) - 2/3.$$

6. *Scaling of the mortality rates of sample trees.*

   If the calculated N_{ratio} is less than one, i.e. actual predicted stem number is greater than maximum allowable stem number, N_{ratio} is applied in the calculation of the final stem numbers. The final value of the stem number represented by a sample tree is obtained by multiplying the predicted stem number with N_{ratio}.

$$Ntree = N_{ratio} \cdot Ntree(actual) . \tag{61}$$

Because maximum stem number N_{max} is species specific, also the value of N_{ratio} varies according to tree species. Therefore, the scaling multiplier (N_{ratio}) varies among sample trees of different tree species even within a sample plot.

4.6 Auxiliary models

4.6.1 Tree crown ratio

Tree crown ratio (cr) is defined as the ratio between the length of the live crown to tree height. Live crown base is determined as the height of lowest living branch over which the number of death nodes is less than two.

For predicting tree crown ratio, the following non-linear model form was applied:

$$\hat{cr} = 1 - e^{-f(x)} \tag{62}$$

The applied model formulation restricts the predicted values between 0 and 1. The effects of site, geographical location, and stand and tree characteristics are included in the function f(x).

Separate models were developed for Scots pine, Norway spruce and deciduous tree species. For Scots pine, the model for tree crown ratio has the following form:

$$\hat{cr} = 1 - \exp\left(\begin{matrix} -\left(\alpha_1 - \alpha_{11}\cdot \mathrm{THIN}_{0-5} - \alpha_{12}\cdot \mathrm{THIN}_{5-10}\right)\cdot \mathrm{H}_{\mathrm{dom}}^{-\alpha_2}\cdot \mathrm{d}^{\alpha_3}\cdot \\ \exp\left(-\alpha_4\cdot \mathrm{RDFL}\right)\cdot \mathrm{TS}^{\alpha_5}\cdot \exp\left(-\alpha_6\cdot \mathrm{RDF}\right) \end{matrix}\right). \tag{63}$$

For Norway spruce the model is as follows:

$$\hat{cr} = 1 - \exp(-\left(\alpha_1 - \alpha_{11}\cdot \mathrm{THIN}_{0-5}\right)\cdot \mathrm{H}_{\mathrm{dom}}^{-\alpha_2}\cdot \mathrm{d}^{\alpha_3}\cdot \exp\left(-\alpha_4 \mathrm{RDF}\right)\cdot \mathrm{TS}^{\alpha_5}\cdot \mathrm{SI}_{\mathrm{Ns}}^{\alpha_6}\cdot$$
(64)

For birch, and other deciduous tree species, the analysis resulted in a following model form:

$$\hat{cr} = 1 - \exp\left(\begin{matrix} -\left(\alpha_1 + \alpha_{11}\cdot \mathrm{PLANT}\right)\cdot \ln\left(\mathrm{H}_{\mathrm{dom}}\right)^{-\alpha_2}\cdot \mathrm{d}^{\alpha_3}\cdot \ln(\mathrm{h})^{-\alpha_4}\cdot \\ \exp\left(-\left(\alpha_5 + \alpha_{12}\cdot \mathrm{PLANT}\right)\cdot \mathrm{RDF}\right) \end{matrix}\right) \tag{65}$$

The parameter values of models are presented in Tables 36, 37, and 38.

For all tree species, crown ratio follows a general age-dependent pattern. Crown ratio decreases as a tree grows older. The stage of stand development is described with stand dominant height.

Within a stand at the given point of time, tree crown ratio varies according to the absolute and relative tree size. Tree size is described with diameter and height (in the models for deciduous tree species). Crown ratio increases with increasing tree diameter.

Tree crown ratio is known to be sensitive to stand density. In the models, stand density is described with the relative density factor (RDF) including all the tree species in the stand. The relative tree size in a stand is expressed with relative density factor of trees larger than a subject tree (RDFL). Tree crown ratio decreases with increasing stand density. Suppressed trees have smaller crown ratios compared to dominant trees.

Table 36. The parameter values of tree crown ratio model for Scots pine (63).

Parameter	Estimate	Asymptotic Std. deviation	Asymptotic 95 % confidence interval Lower	 Upper
α_1	4.90911	0.05438	4.80274	5.01548
α_2	0.76199	0.00737	0.74754	0.77643
α_3	0.14438	0.00495	0.13466	0.15409
v_4	0.1180	0.01456	0.08942	0.14651
α_5	-0.47057	0.01077	-0.49179	-0.44946
α_6	0.29490	0.01321	0.26902	0.32079
α_{11}	0.28807	0.02786	0.23348	0.34271
α_{12}	0.21357	0.03297	0.14894	0.27820
Predicted mean	0.6192			
RMSE	0.103			
Observations	32 943			

Table 37. The parameter values for tree crown ratio model of Norway spruce (64).

Parameter	Estimate	Asymptotic Std. deviation	Asymptotic 95 % confidence interval Lower	 Upper
α_1	2.05788	0.10368	1.85465	2.26111
α_2	0.71419	0.01275	0.68920	0.73919
α_3	0.25755	0.00739	0.24306	0.27204
α_4	0.38242	0.01371	0.35554	0.40931
α_5	-0.54008	0.03996	-0.61841	-0.4617
α_6	0.42485	0.01927	0.38708	0.46261
α_{11}	0.16547	0.01556	0.13496	0.19598
Predicted mean	0.7578			
RMSE	0.099			
Observations	10 708			

Table 38. The parameter values for tree crown ratio model of birch (65).

Parameter	Estimate	Asymptotic Std. deviation	Asymptotic 95 % confidence interval Lower	 Upper
α_1	2.02622	0.07423	1.88069	2.17174
α_2	0.62383	0.05735	0.51140	0.73627
α_3	0.54674	0.01992	0.50769	0.58578
α_4	1.67423	0.06640	1.54405	1.80441
α_5	0.32816	0.02689	0.27546	0.38087
α_{11}	1.71650	0.12112	1.47905	1.95396
α_{12}	0.64030	0.06298	0.51683	0.76377
Predicted mean	0.5668			
RMSE	0.100			
Observations	5 235			

In thinning, growing space of remaining trees increases rapidly. However, in recently thinned stands tree crown ratios are not yet adapted to increased growing space. Instead, crown ratios are smaller compared to those in unthinned, but otherwise similar stands. Therefore a categorical variable referring to the effect of recent thinning is included in the models for Scots pine and Norway spruce.

The effect of geographical location on tree crown ratio was incorporated into the models for conifers using temperature sum (TS). Predicted crown ratio decreases with increasing temperature sum.

Site index is used to describe the site the model for Norway spruce. In fertile sites, predicted tree crown ratios are greater than crown ratios on poorer sites, when other regressor variables are kept constant. The effect of site index proved not to be significant in modelling crown ratio for Scots pine.

In crown ratio model for birch, a categorical variable referring to regeneration method (PLANT) was included among the regressors. The regeneration methods affects tree crown ratio so, that in planted birch stands tree crown ratios, on the average, are greater than in naturally regenerated stands.

Models for tree crown ratio are non-linear regression models, which were fitted with SAS PROC NLIN program (SAS 1989). Marquardt method was applied in parameter estimation with conversation criterion set to 10^{-8}.

4.6.2 Stem volume and volumes of different timber assortments

Volumes of stems are predicted applying the polynomial model for stem curve of Laasasenaho (1982). The stem curve is predicted using the information on tree diameter and height. Timber assortments are determined as a function of stem dimensions. The minimum diameter for pulpwood is 6 cm and the minimum length is 2 m.

Log volumes obtained from timber assortment model is based on stem dimensions. In practice it provides an overestimate of log volumes, because it ignores all the defects of different kinds, which generally appear in stems. In order to produce more reliable prediction for actual log volumes, an empirical model for log volume reduction can be applied in simulation. That model is bounded to the used definition for log timber.

The model is based on sample tree measurements of 7th National Forest Inventory (NFI7). It predicts proportional reduction to log volume based on tree dimensions as a function of tree species, tree diameter and age (Fig. 11).

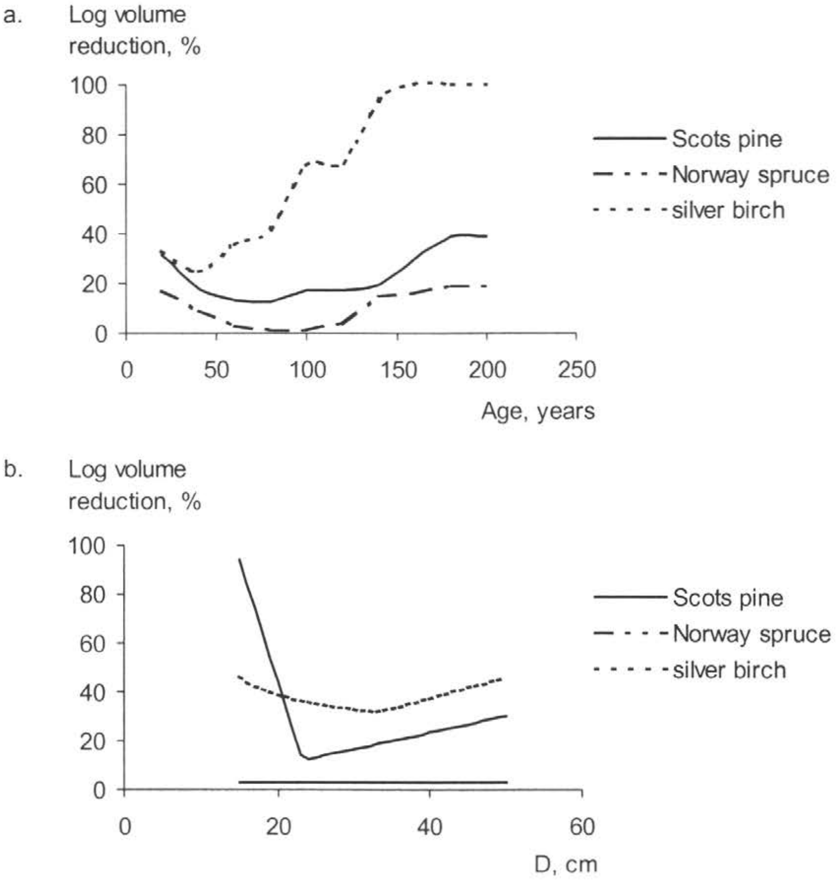


Figure 11. Proportional log volume reduction predicted by empirical model based on NFI7 sample tree measurements.

a) Reduction as a function of age with fixed tree diameter of 25 cm.

b) Reduction as a function of diameter with fixed tree age of 60 years.

5 Evaluation and calibration of the models

5.1 Purpose of the model evaluation and calibration

The primary requirement for growth and yield models applied in MELA System, is capability to produce unbiased prediction for the development of the forest resources. The measurement data from INKA and TINKA sample plots were the most representative material that was available for modelling purposes. However, the temporary sample plots measured in National Forest Inventory form even more extensive data to represent the forest resources in Finland. Nevertheless, these temporary sample plot data were not suitable for model development, because of unreliable stand information caused by small relascope plots, and unsuitable sample tree selection for description of stand dynamics. Instead, they were used as test material in order to study the performance of the models in independent data, and in order to find out right growth level for different tree species in different growing situations.

The goal of the evaluation and calibration was to end up with a set of models that would behave in a satisfactory manner when applied in NFI8 data, before they can be applied in MELA System.

With the data from temporary sample plots of NFI8, the models were first evaluated by comparing the predicted and observed growth of sample tree data. Then, based on the results of these analyses, models were calibrated in order to result the best possible fit in NFI8 data. The description of the methods applied in calibration is provided in the Chapter 5.4.

5.2 Test material

Models were evaluated and calibrated with 8th National Forest Inventory data (NFI8) (Tomppo et al. 2001). NFI8 was a clustered systematic sample with L-shaped or square-shaped clusters. The layout varied in different parts of country according the forest districts (Table 39) with respect to

- distance between two clusters in the east-west and north-south directions,
- number of sample plots with potential sample trees per cluster, and
- relative frequency on sample trees from all trees on the plots.

In NFI8, temporary relascope sample plots were used. The relascope factor was different in different areas. In forest districts 10–19, except for the three northernmost municipalities (Utsjoki, Enontekiö and Inari), the maximum radius of relascope plots was 12.45 m. On the plots, trees were measures as tally trees or as sample trees. The tally trees were measured for tree diameter, and some tree classifications were made. From the sample trees, tree height, height of the living crown, double bark thickness, and diameter increment during the past five years without bark were measured among others variables. In the forest districts 0–9 of Southern Finland, on three sample of each cluster, all the trees were measured as sample trees. The rest of the plots within a cluster served as tally tree sample plots. In the Northern Finland (districts 10–19) every seventh tree of each sample plot was measured as a sample tree.

Forest inventory of the northernmost Finland (Inari, Utsjoki and Enontekiö municipalities) based on stratified sampling. The stratification was made based on satellite image interpretation. The squared clusters were placed systematically in the field according the stratification. Circular sample plots were used for tally tree measurements and sample trees were chosen with relascope.

The test and calibration of the dominant height model was based on tree height observations at the measurement instance. Sample plots that fulfilled the following criteria were included into the calibration data:

- plot locates in whole in one stand compartment
- plot is on mineral soil
- stand is one-storied
- dominant height is over 1.3 m
- stand quality is not regarded as under-productive
- stand is healthy.

Furthermore, only trees fulfilling the following criteria were used:

- tree species is the same than the dominating tree species, excluding other deciduous tree species than birch
- diameter is larger than stand mean diameter weighted by tree basal area
- tree is healthy.

Some statistics of the calibration data for dominant height models are given in Table 40.

The test and calibration of the tree basal area growth model, height growth model and crown ratio model are based on sample trees on sample plots with the following characters:

- the whole plot is located in one stand compartment
- stand dominant height is over 1.3 m.

Examination of crown ratio model is based directly on the measured tree and stand variables. In case of the growth models, the examinations are based on 5-year growth period preceding the time of inventory. Thus, the sample plots had to be reconstructed in the beginning of the 5-year growth period with the help of growth measurements (radial growth without bark during the last five years, height growth, and double bark thickness) made from the sample trees. The reconstruction required information from the initial diameters of all the trees on the plot and initial crown ratio of the sample trees. Furthermore, the diameter increment with bark was needed.

In all calculations, cross-section of tree stem was assumed to be circular.

The measured sample tree variables were diameter over bark at measurement time (d_m), double bark thickness ($2b_m$), and radial increment under bark during the preceding five years. The radial increment was transformed to diameter increment (id_{wb}) by multiplied it with two.

Sample tree diameter under bark (d_{wb}) in beginning of the growth period is

$$d_{wb} = d_m - 2b_m - id_{wb}\,. \tag{66}$$

Sample tree diameter over bark in the beginning of the growth period (d) was calculated by adding the predicted double bark thickness ($\dot{2b}$) to d_{wb}.

$$d = d_{wb} + 2\dot{b} . \tag{67}$$

Table 39. Characteristics of the sampling layout of NFI8.

	South Finland	North Finland	Northermost Finland
Cluster form	L-shaped	Square	Square
Cluster distance: North-South,	7	7–10	Varies
East-West, km	8	8–10	
Number of plots in a cluster	21	21–15	8
Plot interval in the cluster, m	1200	300	750
Basal area factor, m^2	2	1.5	Cluster of three circular sample plots with radius of 5.15 m
Sample tree selection	All trees from three systematic selected plots in each cluster	Every 7th tree throughout the whole inventory	Sampled by angle-cauge from the trees on the plot with basal area factor of 6 m^{2}ha^{-1}

Table 40. Statistics of the calibration data for height model of the dominant trees.

	Scots pine			Norway spruce			Deciduous		
	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
Tree									
h	5.4	14.9	30.5	2.2	20.6	33	4.3	17.5	32.5
d/D	0.70	1.00	2.32	0.71	0.99	1.30			
Stand – growing stock									
Age	8	63.9	347	8	65.3	210	9	48.0	141
RDF	0.009	0.477	1.542	0.018	0.516	1.281	0.100	0.546	1.433
Stand – site									
TS	640	1110	1360	630	1172	1360	750	1162	1360
ALT	0	126	360	0	114	40	0	112	300
LAKE	0.00	0.12	0.71	0	0.10	0.63	0.00	0.14	0.55
SEA	0.00	0.04	0.82	0	0.09	0.85	0.00	0.04	0.97
SC1	0	0.001	1	0	0.009	1	0	0.086	1
SC2	0	0.050	1	0	0.457	1	0	0.373	1
SC3	0	0.386	1	0	0.528	1	0	0.438	1
SC4	0	0.458	1		0.001		0	0.084	1
SC5	0	0.045	1				0	0.005	1
SC6	0	0.002	1						
SC7	0	0.055	1	0	0.003	1	0	0.015	1
SC8	0	0.002	1	0	0.002	1			
SCRUB	0	0.033	0				0	0.011	1
STONY	0	0.193	1	0	0.115	1	0	0.073	1
PALU	0	0.039	1	0	0.073	1	0	0.041	1
HUMUS	0	0.002	1	0	0.005	1	0	0.002	1
N		3246			1818			533	

Prediction of $\dot{2b}$ was done in two phases. First, a double bark thickness at measurement instance was modelled as a function of diameter under bark at time of measurement (d_{wb}) and fertility class. Second, this model was used to predict double bark thickness in the beginning of the growth period ($\hat{2b}$). Finally, this prediction was calibrated for each tree according to following formula:

$$\dot{2b} = \hat{2b} + \frac{d_{wb}}{d_{mwb}} \cdot (2b_m - \hat{2b}_m), \tag{68}$$

where d_{mwb} is diameter under bark at measurement instance.

Diameter increment over bark for sample trees was then calculated as follows:

$$id = d_m - d. \tag{69}$$

For tally trees, diameters over bark in beginning of the growth period were calculated by subtracting the predicted five-year diameter increment over bark from the measured diameter over bark. Five-year diameter growth was predicted with a regression model based on sample trees. In this model, measured diameter over bark, stand basal area, temperature sum, and forest site type were used as independent variables. The model was developed separately for each tree species.

Crown ratio and some competition measures in the beginning of the growth period are used as independent variables in basal area growth model. Crown ratio was predicted to the beginning of the growth period with regression model. The model was done for a logistic transformation of crown ratio ($\ln(1/cr-1)$) for measurement time. For calibration, residuals of the model were calculated for each tree. The logistic crown ratio in the beginning of the growth period was predicted for each tree. The calibration of the predicted crown ratio was made by adding the treewise logistic residual to the prediction.

Diameter increments were corrected with growth indexes by Henttonen (2000). The indexes are based on sample trees of NFI8, and the method is based on mixed linear model technique (Henttonen 1990). Indexes for Scots pine, Norway spruce and birch were available. The birch indexes were used for other deciduous tree species. Separate indexes were available for tree different geographical areas: a) forest districts 1–9, b) 16–17, and c) 18–19. For Norway spruce and birch, a common index was used for areas b and c (districts 16–19). Average indexes of the areas a and b were used for forest districts 10–15. The indexes refer to the time period of 1965–1994 for area a, 1965–1992 for area b, and 1965–1993 for area c. Height growth measurements were not corrected with any index.

Statistics of the calibration data of tree basal area growth models are given in Tables 41 to 44.

Table 41. Information about tree and stand characteristics in the test data from Scots pine stands of the 8th National Forest Inventory temporary sample plots.

Characteristic	Mineral soils				Peatlands			
	Mean	Std.dev.	Min.	Max.	Mean	Std.dev.	Min.	Max.
Tree								
d	17.5	9.0	0.01	67.0	11.9	6.2	1.0	41.8
h	13.5	6.2	0.3	30.8	9.41	4.5	1.4	27.9
cr	0.566	0.157	0.053	0.990	0.551	0.143	0.027	0.951
Stand – growing stock								
H_{dom}	18.0	7.1	1.0	38.3	16.2	5.5	1.0	35.4
A	79.5	46.3	0	412	70.4	27.3	0	239
BA	19.1	13.0	0	82.6	10.6	8.7	0.04	56.8
RDF	0.45	0.29	0.003	2.03	0.27	0.21	0.005	1.31
D_g	20.5	7.8	0.2	58.7	14.2	5.2	1.1	34.7
Stand – site								
SI_{Sp}	17.8	2.7	5.8	23.5	17.6	2.4	6.9	23.3
TS	1087	172	590	1360	1084	107	730	1350
LAT	7020	238	6642	7738	7027	159	6656	7517
ALT	132	71.9	0.0	410.0	123	52.7	0	300
Number of observations		17331					5534	

Table 42. Information about tree and stand characteristics in the test data from Norway spruce stands of the 8th National Forest Inventory temporary sample plots.

Characteristic	Mineral soils				Peatlands			
	Mean	Std.dev.	Min.	Max	Mean	Std.dev.	Min.	Max
Tree								
d	18.2	9.3	0.0	57.6	15.1	7.7	1.0	45.9
h	17.8	6.4	0.8	34.7	12.7	5.7	1.5	27.8
cr	0.785	0.120	0.025	0.989	0.755	0.122	0.159	0.989
Stand – growing stock								
H_{dom}	21.7	6.5	1.6	39.6	21.7	5.7	1.9	37.1
A	86.6	42.0	3	349	85.2	30.5	5	239
BA	25.2	13.2	0.02	75.7	20.8	11.5	0.06	57.7
RDF	0.48	0.23	0.01	1.66	0.44	0.20	0.01	1.31
D_g	23.1	6.8	0.7	50.0	19.0	5.7	1.3	41.1
Stand – site								
SI_{Ns}	19.8	4.0	6.1	29.0	20.1	3.2	9.2	29.5
TS	1136	147	630	1370	1139	113	730	1350
LAT	6946	194	6648	7587	6947	165	6680	7496
ALT	124	70	0	460	115	53	0	300
Number of observations		14933				2574		

Table 43. Information about tree and stand characteristics in the test data from silver birch stands of the 8th National Forest Inventory temporary sample plots.

Characteristic	Mineral soils				Peatlands			
	Mean	Std.dev.	Min.	Max.	Mean	Std.dev.	Min.	Max.
Tree								
d	17.6	9.2	0.0	47.2				
h	16.5	6.4	0.6	30.1				
cr	0.617	0.139	0.137	0.990				
Stand – growing stock								
H_{dom}	20.6	7.2	1.75	39.1				
A	74.0	39.8	2	280				
BA	22.0	13.9	0.0	81.5				
RDF	0.56	0.32	0.00	1.68				
Dg	21.8	7.8	0.2	43.6				
Stand – site								
SI_{sb}	25.4	4.2	8.6	42.6				
TS								
LAT	6905	179	6650	7587				
ALT	108	62	0	360				
Number of observations		1503						

Table 44. Information about tree and stand characteristics in the test data from pubescent birch stands of the 8th National Forest Inventory temporary sample plots.

Characteristic	Mineral soils				Peatlands			
	Mean	Std.dev.	Min.	Max.	Mean	Std.dev.	Min.	Max.
Tree								
d	11.3	7.3	0.0	44.1	9.4	5.6	1.0	37.9
h	11.1	5.7	0.1	27.7	9.9	4.3	1.1	27.6
cr	0.613	0.139	0.03	0.984	0.602	0.134	0.05	0.979
Stand – growing stock								
H_{dom}	18.2	7.1	1.0	38.4	17.4	5.7	1.0	34.6
A	76.4	46.1	0	323	65.0	28.5	0	240
BA	17.2	11.8	0.0	70.1	12.7	8.9	0.1	57.7
RDF	0.43	0.26	0.01	1.61	0.36	0.21	0.01	1.31
Dg	18.9	7.7	0.4	53.2	14.3	5.2	1.4	34.7
Stand – site								
SI_{pb}	20.4	4.6	5.8	36.2	21.2	3.2	6.9	34.7
TS	1060	183	520	1370	1087	107	730	1350
LAT	7036	247	6650	7733	7034	166	6656	7537
ALT	139	83	0	560	116	55	0	330
Number of observations		3935				2767		

5.3 Model performance in NFI sample plots

Model evaluation was first carried out by calculating the predicted five-year growth for every sample tree in NFI8 data. Then the model biases (observed – predicted growth) were analysed visually with the help of residual plots. Biases were plotted against the following tree and stand characteristics:

- *absolute tree size*: diameter at breast height
- *relative tree size*: tree diameter/mean diameter
- *stand density*: stand basal area
- *stage of stand development*: stand age and stand dominant height
- *site*: site type
- *geographical location*: temperature sum, forestry district.

The evaluation was done separately for mineral soils and for drained peatlands for each tree species (Scots pine, Norway spruce, silver birch, pubescent birch and other deciduous tree species). The results are presented in Figures 12 to 16 for mineral soils, and in Figures 17 to 20 for drained peatlands.

The evaluation revealed some serious trends in the residual plots. The biased behaviour of the models were most frequent with respect to site variation (site type) and variation in geographical location and climatic region (temperature sum). These kinds of trends were also expected, because the variation in modelling data was significantly narrower compared to that in the NFI8 test data. Therefore, it was considered to be necessary to perform the model calibration with respect to these variables.

5.4 Calibration of growth models

5.4.1 Calibration method

Model calibration was performed based on the results of model evaluation against the data from NFI8 temporary sample plots.

The purpose of the calibration was to

- calibrate the predicted growth to the same average level obtained from the growth measurements of National Forest Inventory
- take into account the effect of climatic variation on tree growth
- obtain the growth predictions for trees
  - of tree species not included in the modelling data
  - growing on extreme sites not included in the modelling data.

Calibration was done for each major tree species, and separately for stand growing on mineral soils and stands growing on peatlands.

Calibration was carried out for the

a) models for the dominant height increment
b) models for tree basal area growth
c) models for tree crown ratio
d) models for tree height on peatlands.

NFI8-data included also measurements for five-year height growth of individual trees. However, the measurement error connected to height growth observations for short periods is known to be quite large (Päivinen et al. 1992). Therefore, the height growth information of individual trees was regarded to be too unreliable for calibration purposes. Nevertheless, the calibration of models for the dominant height development was assumed to correct the most serious biases in height growth prediction.

The following basic procedure was adopted in the calibration of the models:

1. Dependent variable for of all the trees in the calibration data was predicted with the models.
2. The prediction bias was calculated as a difference between the observed and the predicted values.
3. A linear regression model for bias was developed with the most important stand variables as regressors.
4. The final, calibrated prediction was obtained by adding the predicted bias to the initial prediction.

The main principle in the selection of regressors to the models for bias was to include the stand variables referring to variation in site and geographical location and climatic conditions. These included the variables such as:

- site type defined as categorical site type classes
- specifications reflecting the reduced yield capacity (stoniness etc.)
- temperature sum
- altitude
- sea and lake indexes.

The variables referring to stand dynamics (dominant height, stand age, tree size) were added to the model only, if serious biases were still present after the models were calibrated with respect to site and location variables. The purpose was to maintain the initial model structure and model behaviour with respect to growth dynamics whenever it was possible.

In some cases model bias with respect to stand dominant height was so severe (e.g. Fig 14d), that it had to be included into the model (e.g. Table 51). For extreme site types poorly represented in the modelling data, calibration was needed with respect to tree size (e.g. Table 49), because original model failed to describe the relationship between tree size and growth rate as it was observed in the test data.

5.4.2 Calibration of models for height development of dominant trees

Calibration of the model for height development for dominant trees was carried out stepwise as follows:

1. Height of dominant tree was predicted in linearized scale, where the dependent variable y was $\ln(h - 1.3 + (D_{dom}/d - 1))$. The fixed part of Model 12 was used.
2. The prediction bias was calculated as the difference between observed and predicted tree height transformed into linearized scale: $bias = y - \hat{y}$.
3. A linear regression model for the bias was developed for Scots pine, Norway spruce, birch and all deciduous together (Models 70–73 in Tables 45–48). In the calibration

models for birch and all deciduous tree species, tree species are separated with the help of categorical (dummy) variables. Because of the lack of data, calibration coefficients for some forest site types are defined in a heuristic manner.

4. Predicted bias was added to predicted height in a linearized scale as follows: $\hat{y}(\mathrm{cal}) = \ln(\hat{y}) + \ln\left(\hat{\mathrm{B}}\mathrm{ias}\right)$.

5.4.3 Calibration of the models for tree basal area growth

Calibration of the models for tree basal area growth was carried out as follows:

1. Tree basal area growth of all the trees in the calibration data was predicted with the tree basal area growth models (29–31, 35–37) presented in 4.4.1.1 and 4.4.2.2.
2. The prediction bias was calculated as the difference between observed and predicted tree basal area growth transformed into a logarithmic scale as follows: $\mathrm{Bias} = \ln(i_g + 1) - \ln\left(\hat{i}_g + 1\right)$. A constant (=1) was added to logarithms of observed and predicted growth in order to avoid problems, when logarithms are taken from values near zero.
3. A linear regression model for bias (*Bias*) was developed for major tree species separately for mineral soils and peatlands.
4. Predicted bias was then added to the predicted growth (in a logarithmic scale), and their sum was transformed into an arithmetic scale as follows: $\hat{i}_g(\mathrm{cal}) + 1 = \exp\left(\ln\left(\hat{i}_g + 1\right) + \hat{\mathrm{B}}\mathrm{ias}\right)$.
5. An empirical variance correction term for bias due to transformation into an arithmetic scale was done. In order to obtain unbiased growth predictions for trees of different sizes, a correction term was calculated separately for 5-cm diameter classes as follows:
   - trees were classified into diameter classes
   - the mean observed growth ($\overline{i_g(\mathrm{obs}) + 1}$) and predicted and calibrated growth ($\hat{i}_g(\mathrm{cal}) + 1$) within each diameter class was calculated
   - the following ratio for the diameter class was calculated: $C_{\mathrm{ratio}} = \dfrac{\overline{i_g(\mathrm{obs}) + 1}}{\overline{\hat{i}_g(\mathrm{cal}) + 1}}$
   - the final calibrated growth prediction for a tree within a given diameter class was obtained applying the following formula $i_g(\mathrm{cal}) = \left(C_{\mathrm{ratio}} \cdot \left(\hat{i}_g + 1\right) \cdot \exp\left(\hat{\mathrm{B}}\mathrm{ias}\right)\right) - 1$.

Correction terms for each diameter classes together with other model parameters are presented in Tables 49–57 (Models 74–82).

5.4.4 Calibration of the models for tree height on peatlands

On peatlands, tree height is predicted with static height models, as presented in chapter 4.4.2.3. Models for tree height were calibrated as follows:

1. Tree height was predicted with the models (40–44) presented in 4.4.2.3.
2. The prediction bias was calculated as a difference between observed and predicted

tree height transformed into a logarithmic scale as follows:
$\text{Bias} = \ln(h) - \ln(\hat{h})$.

3. A linear regression model for bias (*Bias*) was developed separately for three major tree species on peatlands, and for other broadleaved tree species (Tables 58–61).

4. Prediced bias was added to predicted height (in a logarithmic scale), and their sum was transformed into an arithmetic scale as follows: $\hat{h}(\text{cal}) = \exp(\ln(\hat{h}) + \hat{\text{B}}\text{ias})$.

5. An empirical variance correction term for bias due to transformation into an arithmetic scale was done in a similar manner as in the tree basal area growth calibration (see 5.4.3). The final calibrated tree height prediction for a tree within a given diameter class was obtained as follows: $h(\text{cal}) = C_{\text{Ratio}} \cdot \hat{h} \cdot \exp(\hat{\text{B}}\text{ias})$.

Correction terms (C_{ratio}) for each diameter classes together with other model parameters are presented in Tables 58–61 (Models 83–86).

5.4.5 Calibration of the models for tree crown ratio

Models to predict tree crown ratios were calibrated in the following manner:

1. Tree crown ratios of trees in the calibration data were predicted with the models presented in 4.6.1.

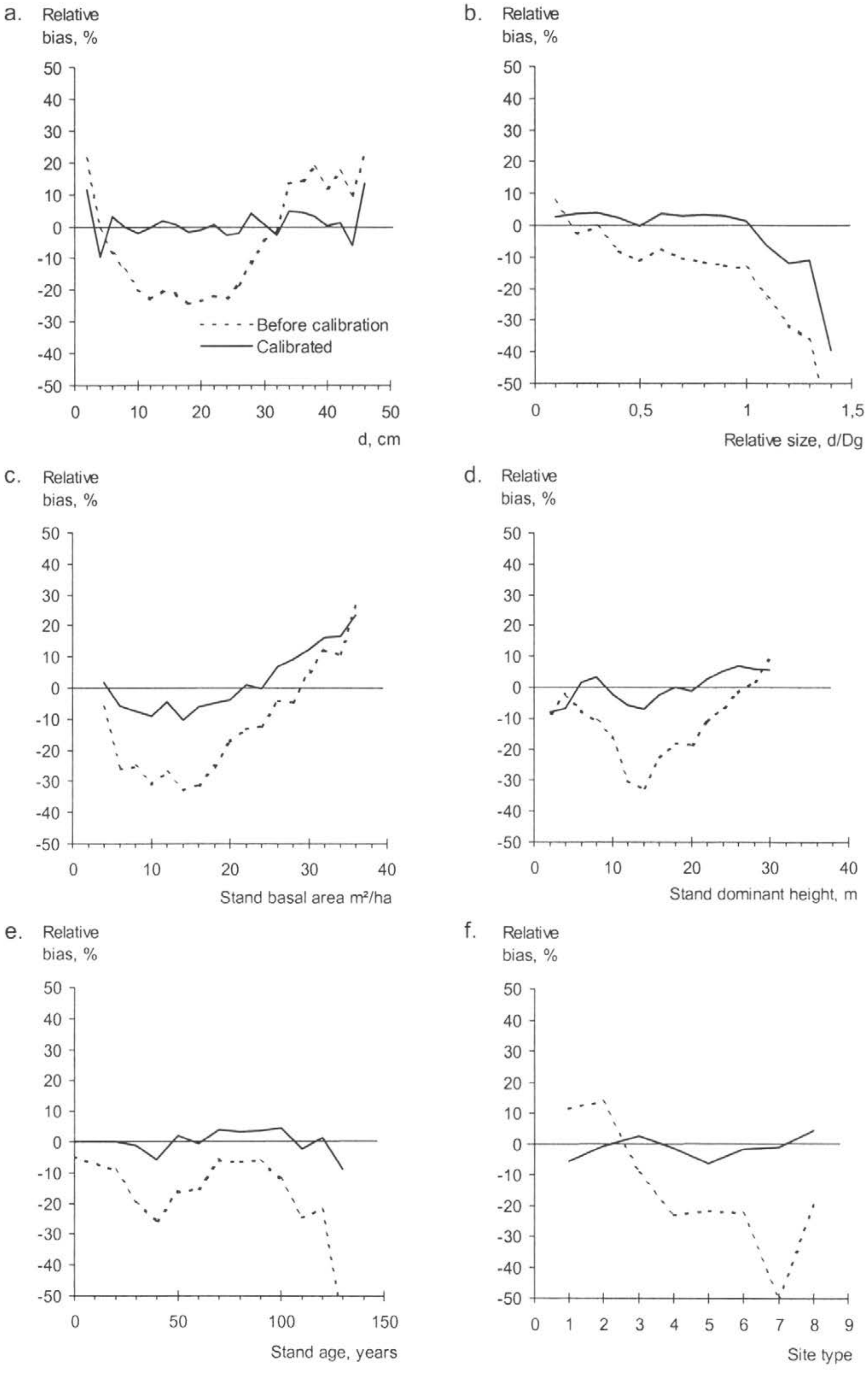
2. The prediction bias was calculated as a difference between observed and predicted tree basal area growth transformed into a logarithmic scale as follows:
$\text{Bias} = \text{cr} - \hat{\text{c}}\text{r}$ ·

3. A linear regression model for bias (*Bias*) was developed for major tree species on mineral soils (Models 87–91 in Tables 62–66).

4. Predicted bias was then added to predicted crown ratio $\hat{\text{c}}\text{r}(\text{cal}) = \hat{\text{c}}\text{r} + \hat{\text{B}}\text{ias}$.

5. The following restrictions were applied into the final predicted and calibrated crown ratio before applying it in the simulations:
   - predicted tree crown ratio has to be less than one ($\hat{\text{c}}\text{r}(\text{cal}) < 1.0$)
   - if $\hat{\text{c}}\text{r}(\text{cal}) \le 0.5 \cdot \hat{\text{c}}\text{r}$, then $\hat{\text{c}}\text{r}(\text{cal}) = 0.5 \cdot \hat{\text{c}}\text{r}$
   - if $\hat{\text{c}}\text{r}(\text{cal}) \ge 1.5 \cdot \hat{\text{c}}\text{r}$, then $\hat{\text{c}}\text{r}(\text{cal}) = 1.5 \cdot \hat{\text{c}}\text{r}$.

Notice! Figures 12–20 p. 74–91, and
Tables 45–66 p. 92–105.


a.
Relative bias, %
50
40
30
20
10
0
-10
-20
-30
-40
-50
0
10
20
30
40
50
d, cm
Before calibration
Calibrated
b.
Relative bias, %
0
0,5
1
1,5
Relative size, d/Dg
c.
Relative bias, %
0
10
20
30
40
Stand basal area m²/ha
d.
Relative bias, %
0
10
20
30
40
Stand dominant height, m
e.
Relative bias, %
0
50
100
150
Stand age, years
f.
Relative bias, %
0
1
2
3
4
5
6
7
8
9
Site type

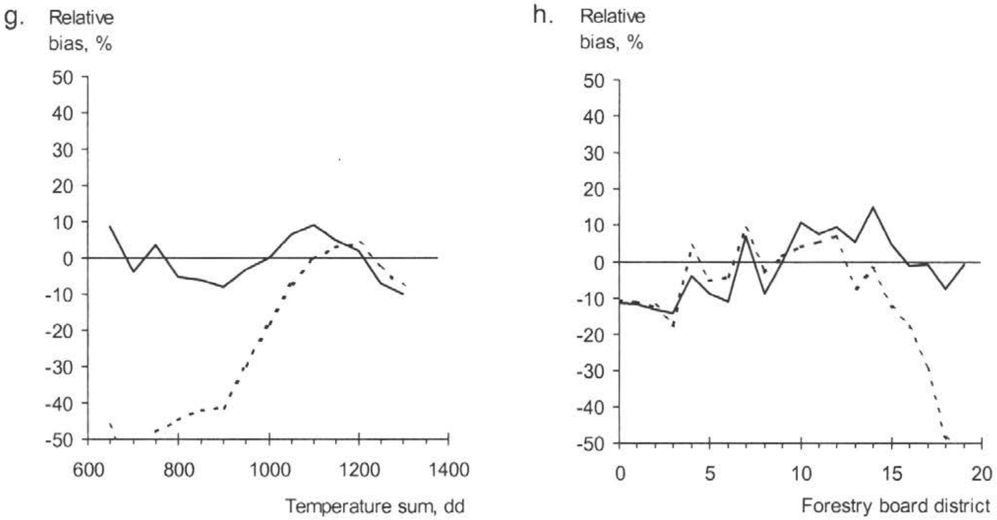
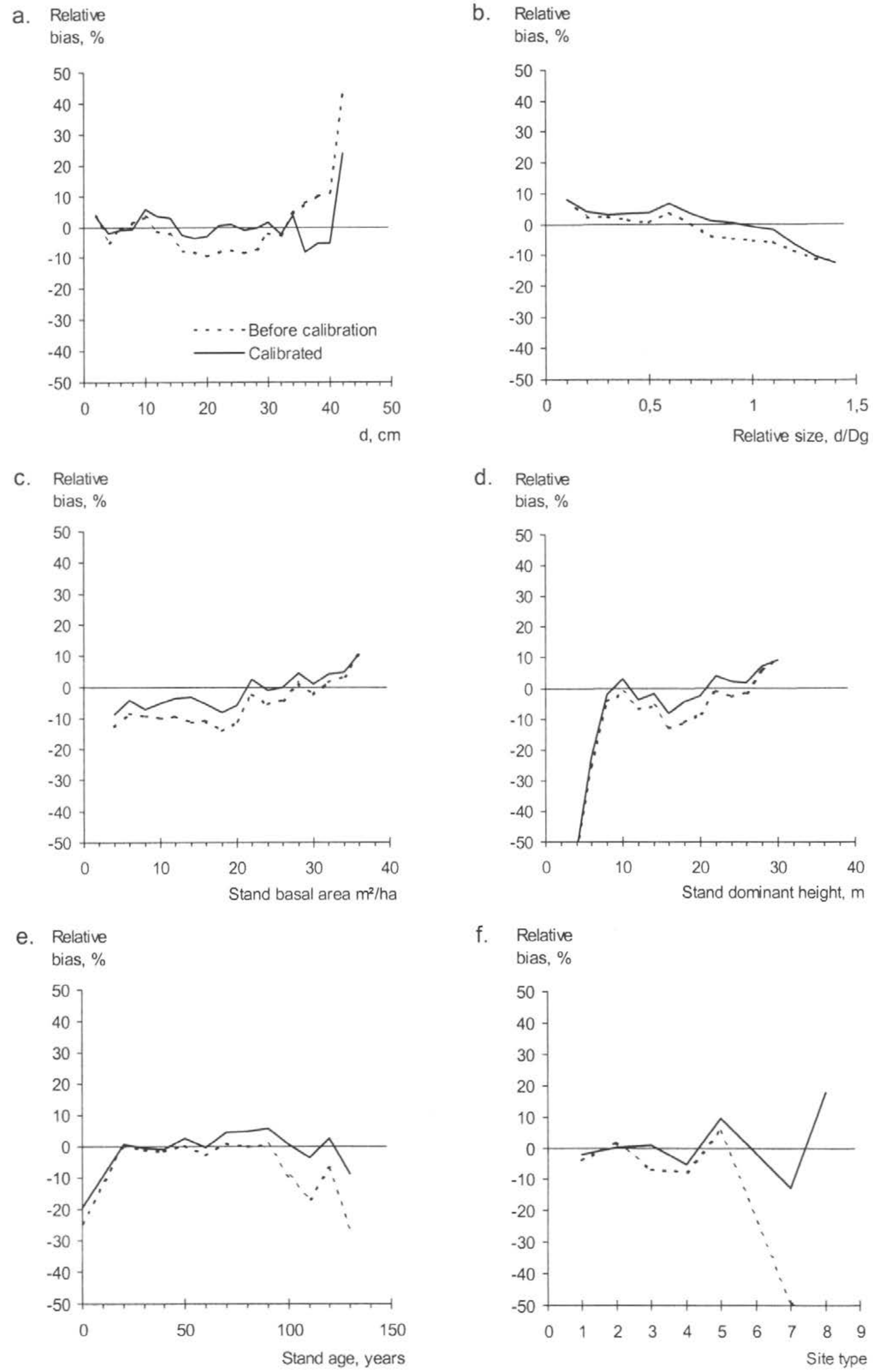


Figure 12. Relative bias of tree basal area growth model for Scots pine before and after calibration plotted against dree diameter (a), relative tree size (d/Dg) (b), stand basal area (c), stand dominant height (d), stand age (e), site type (f), temperature sum (g), and forestry board district (h). Stands on mineral soils.


a.
Relative bias, %
50
40
30
20
10
0
-10
-20
-30
-40
-50
0
10
20
30
40
50
d, cm
Before calibration
Calibrated
b.
Relative bias, %
0
0,5
1
1,5
Relative size, d/Dg
c.
Relative bias, %
0
10
20
30
40
Stand basal area m²/ha
d.
Relative bias, %
0
10
20
30
40
Stand dominant height, m
e.
Relative bias, %
0
50
100
150
Stand age, years
f.
Relative bias, %
0
1
2
3
4
5
6
7
8
9
Site type

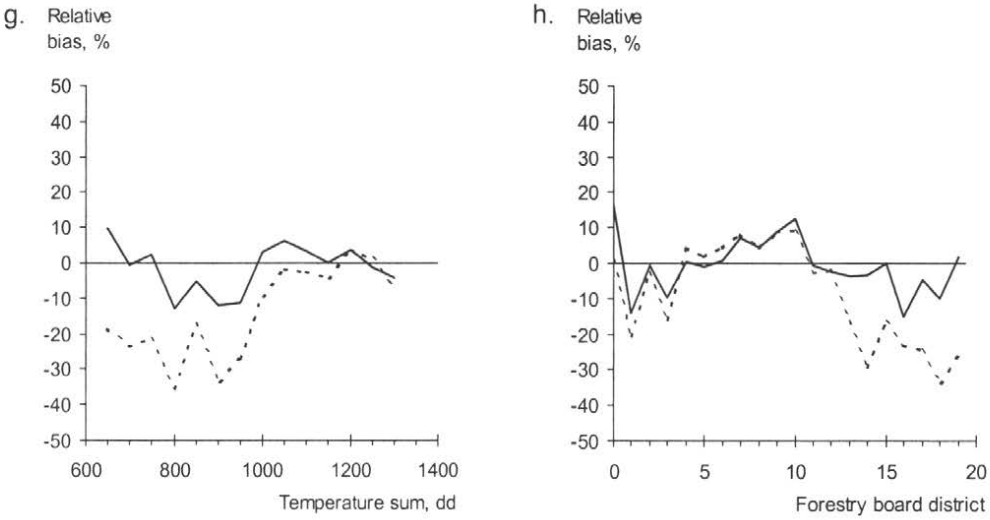
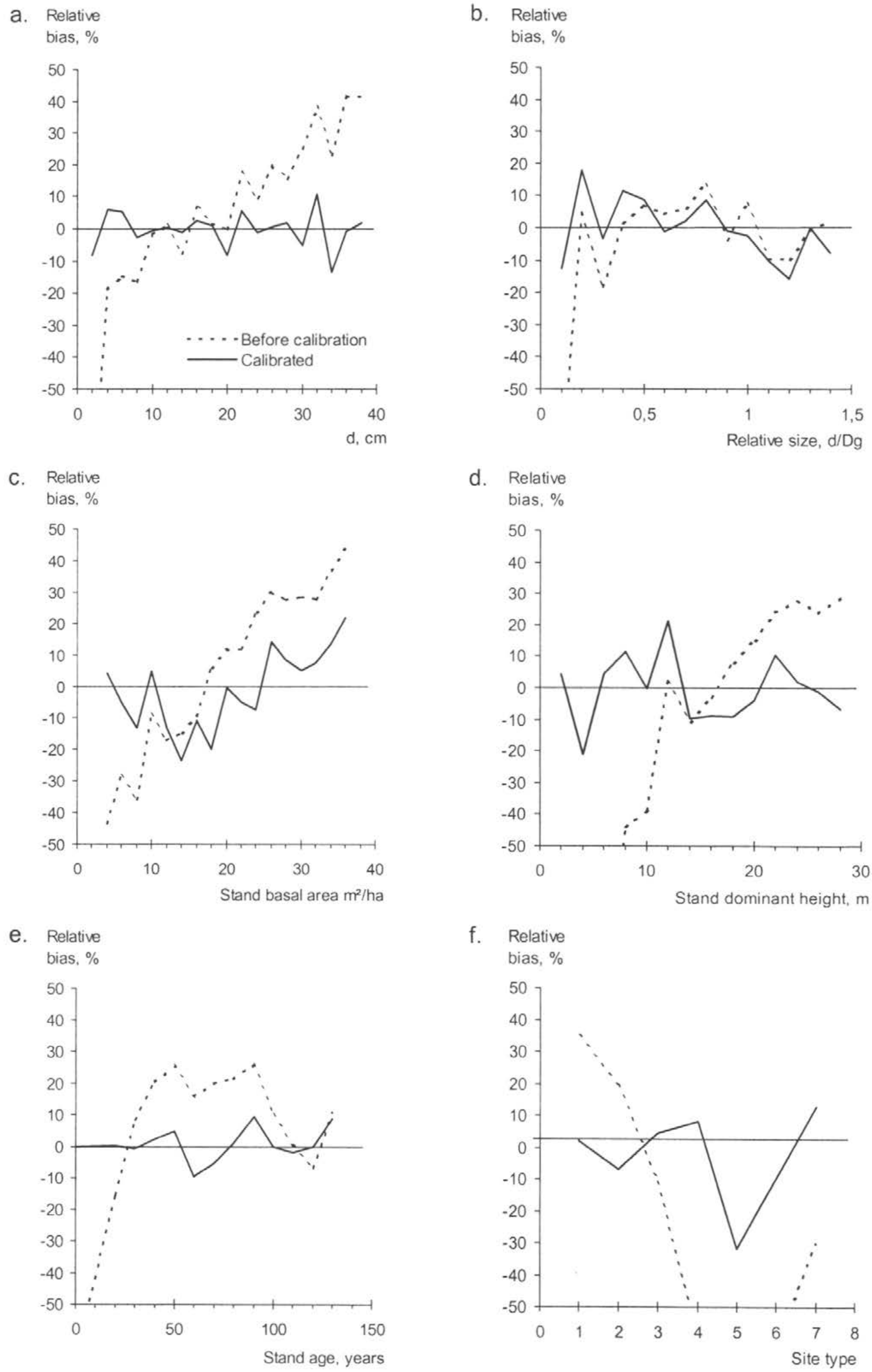


Figure 13. Relative bias of tree basal area growth model for Norway spruce before and after calibration plotted against dree diameter (a), relative tree size (d/Dg) (b), stand basal area (c), stand dominant height (d), stand age (e), site type (f), temperature sum (g), and forestry board district (h). Stands on mineral soils.


a.
Relative bias, %
50
40
30
20
10
0
-10
-20
-30
-40
-50
0
10
20
30
40
d, cm
Before calibration
Calibrated
b.
Relative bias, %
0
0,5
1
1,5
Relative size, d/Dg
c.
Relative bias, %
Stand basal area m²/ha
d.
Relative bias, %
Stand dominant height, m
e.
Relative bias, %
0
50
100
150
Stand age, years
f.
Relative bias, %
0
1
2
3
4
5
6
7
8
Site type

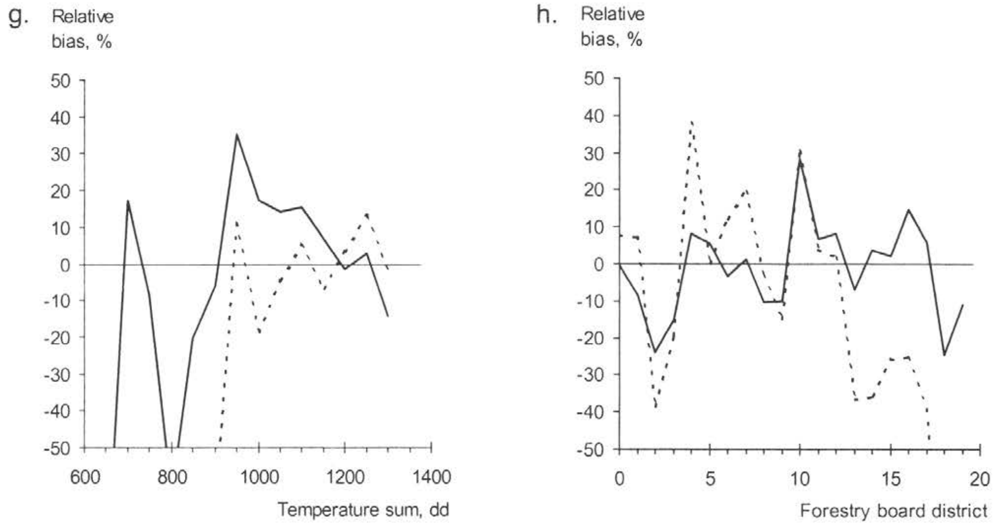
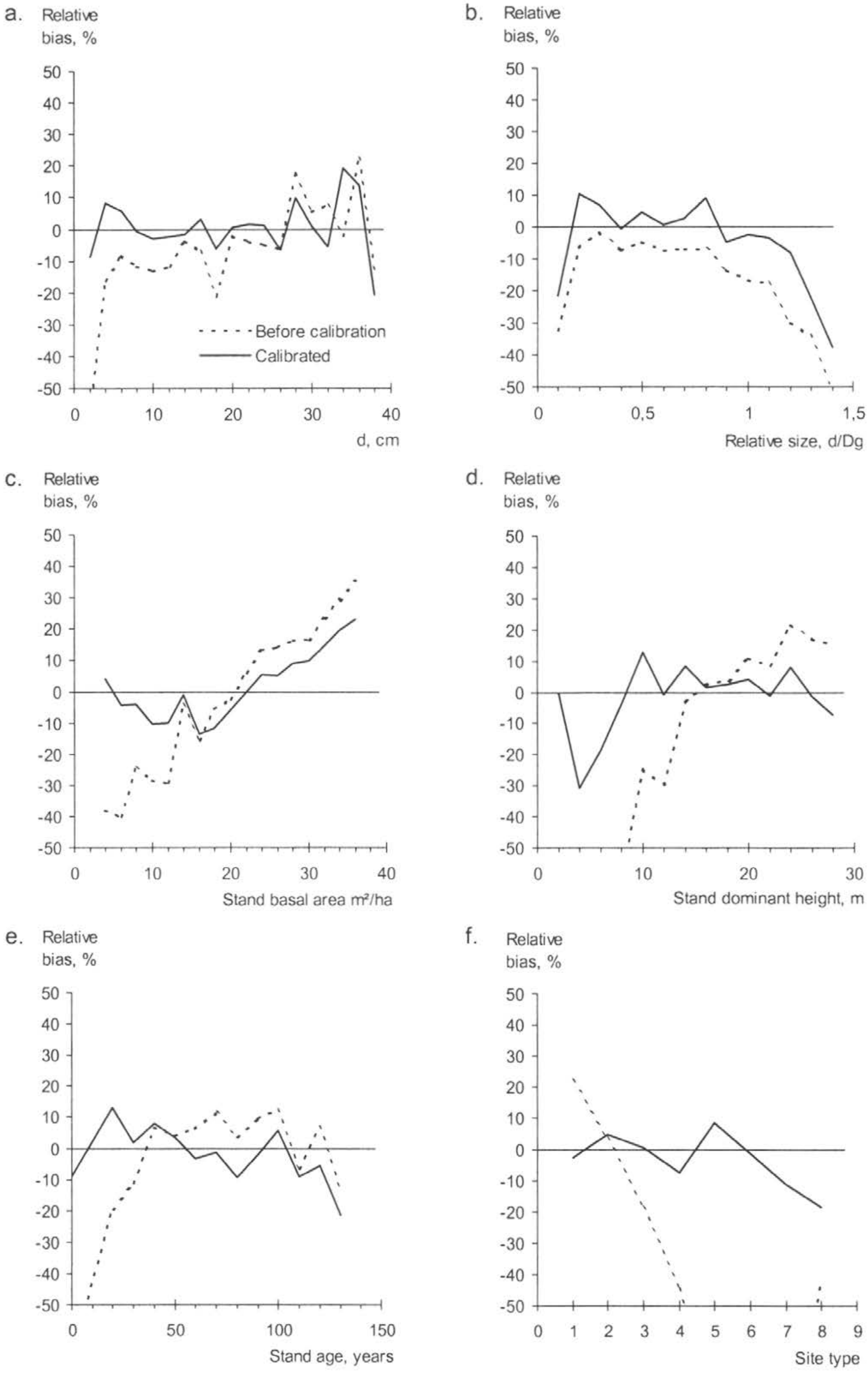


Figure 14. Relative bias of tree basal area growth model for silver birch (*Betula pendula*) before and after calibration plotted against dree diameter (a), relative tree size (d/Dg) (b), stand basal area (c), stand dominant height (d), stand age (e), site type (f), temperature sum (g), and forestry board district (h). Stands on mineral soils.


a.
Relative bias, %
50
40
30
20
10
0
-10
-20
-30
-40
-50
0
10
20
30
40
d, cm
Before calibration
Calibrated
b.
Relative bias, %
0
0,5
1
1,5
Relative size, d/Dg
c.
Relative bias, %
0
10
20
30
40
Stand basal area m²/ha
d.
Relative bias, %
0
10
20
30
Stand dominant height, m
e.
Relative bias, %
0
50
100
150
Stand age, years
f.
Relative bias, %
0
1
2
3
4
5
6
7
8
9
Site type

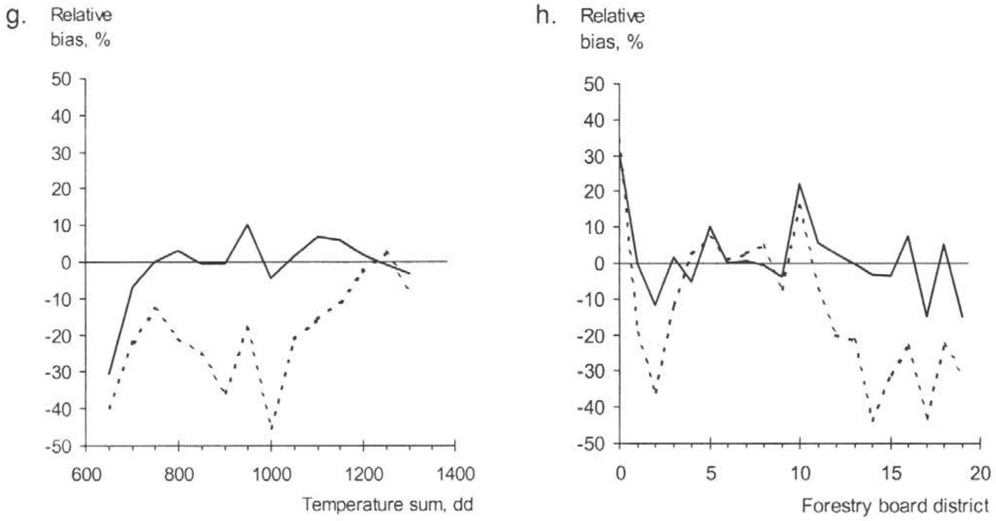
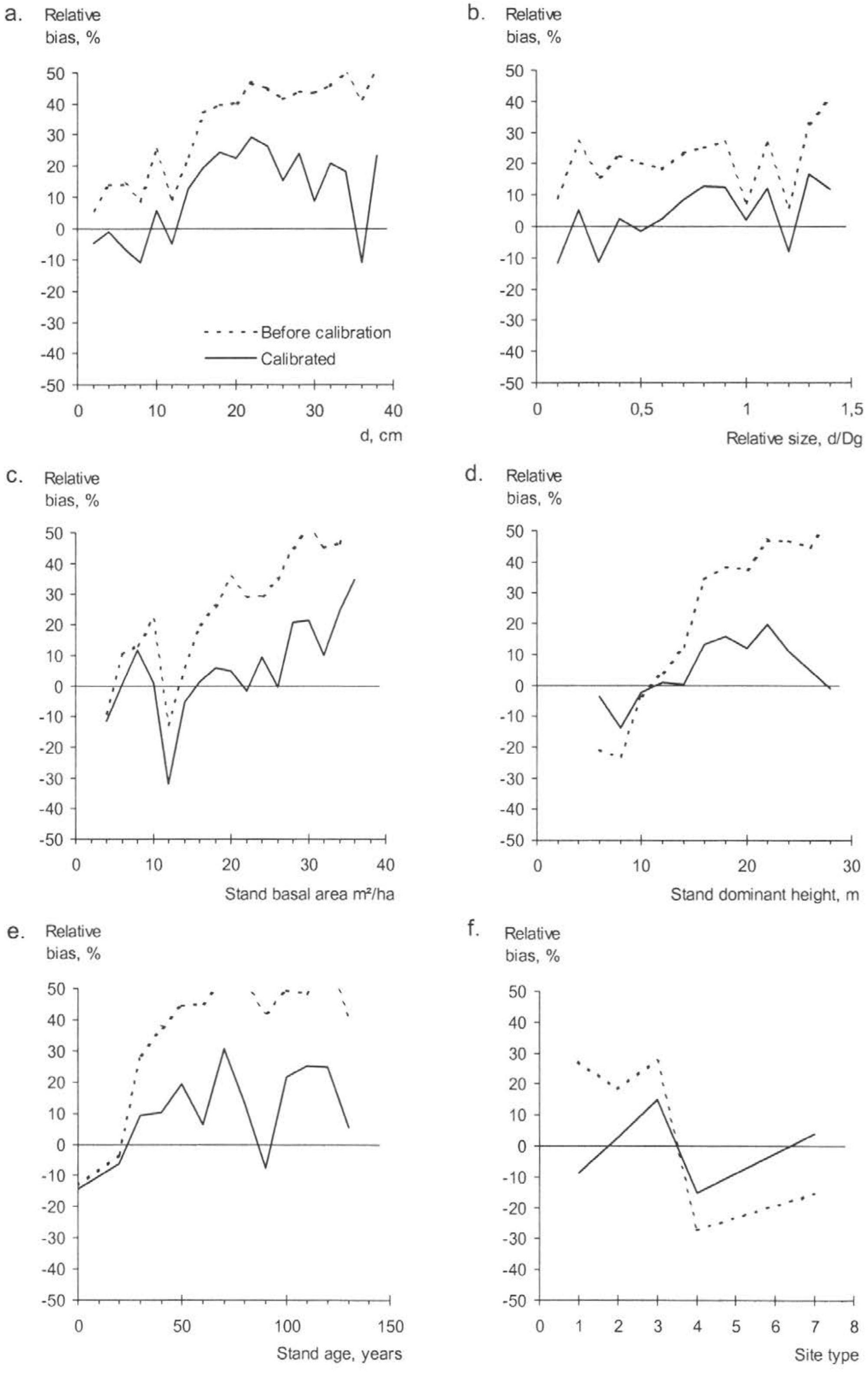


Figure 15. Relative bias of tree basal area growth model for pubescent birch (*Betula pubescens*) before and after calibration plotted against dree diameter (a), relative tree size (d/Dg) (b), stand basal area (c), stand dominant height (d), stand age (e), site type (f), temperature sum (g), and forestry board district (h). Stands on mineral soils.


a.
Relative bias, %
50
40
30
20
10
0
-10
-20
-30
-40
-50
0
10
20
30
40
d, cm
Before calibration
Calibrated
b.
Relative bias, %
0
0,5
1
1,5
Relative size, d/Dg
c.
Relative bias, %
0
10
20
30
40
Stand basal area m²/ha
d.
Relative bias, %
0
10
20
30
Stand dominant height, m
e.
Relative bias, %
0
50
100
150
Stand age, years
f.
Relative bias, %
0
1
2
3
4
5
6
7
8
Site type

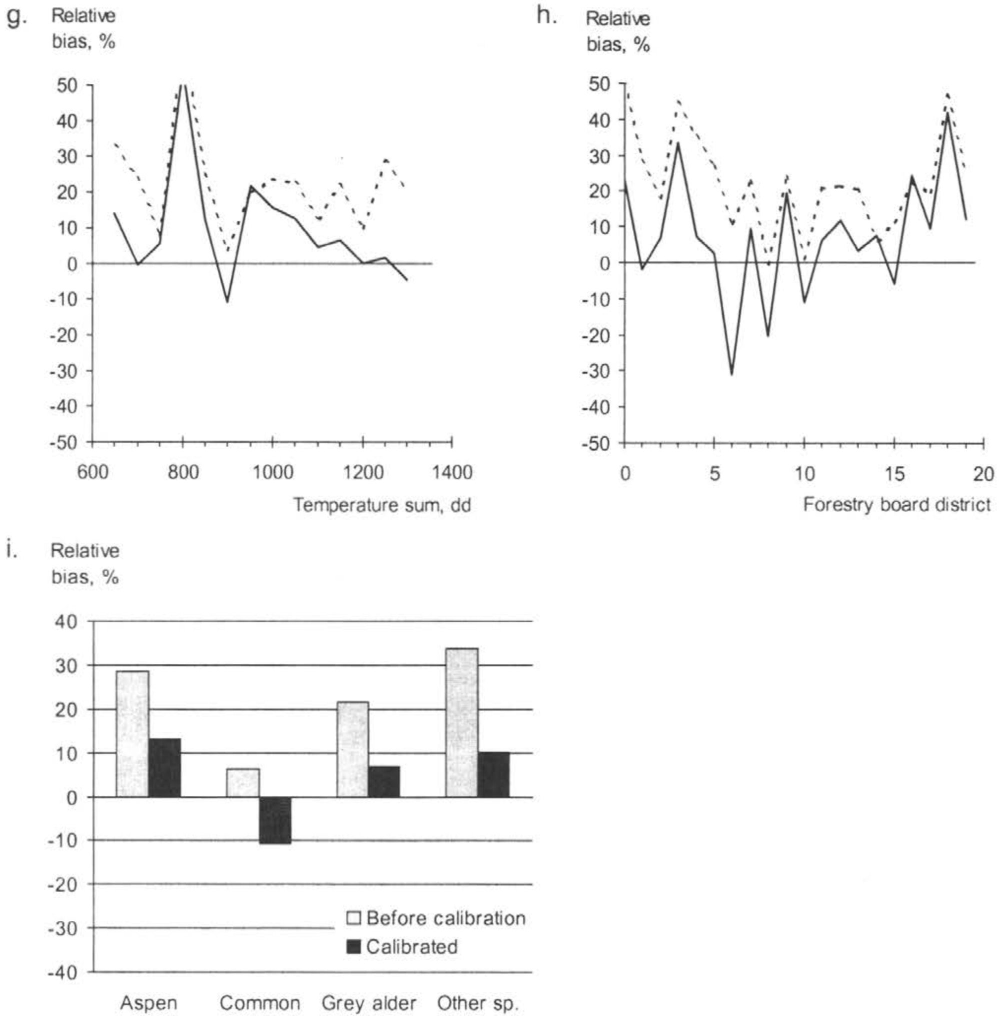
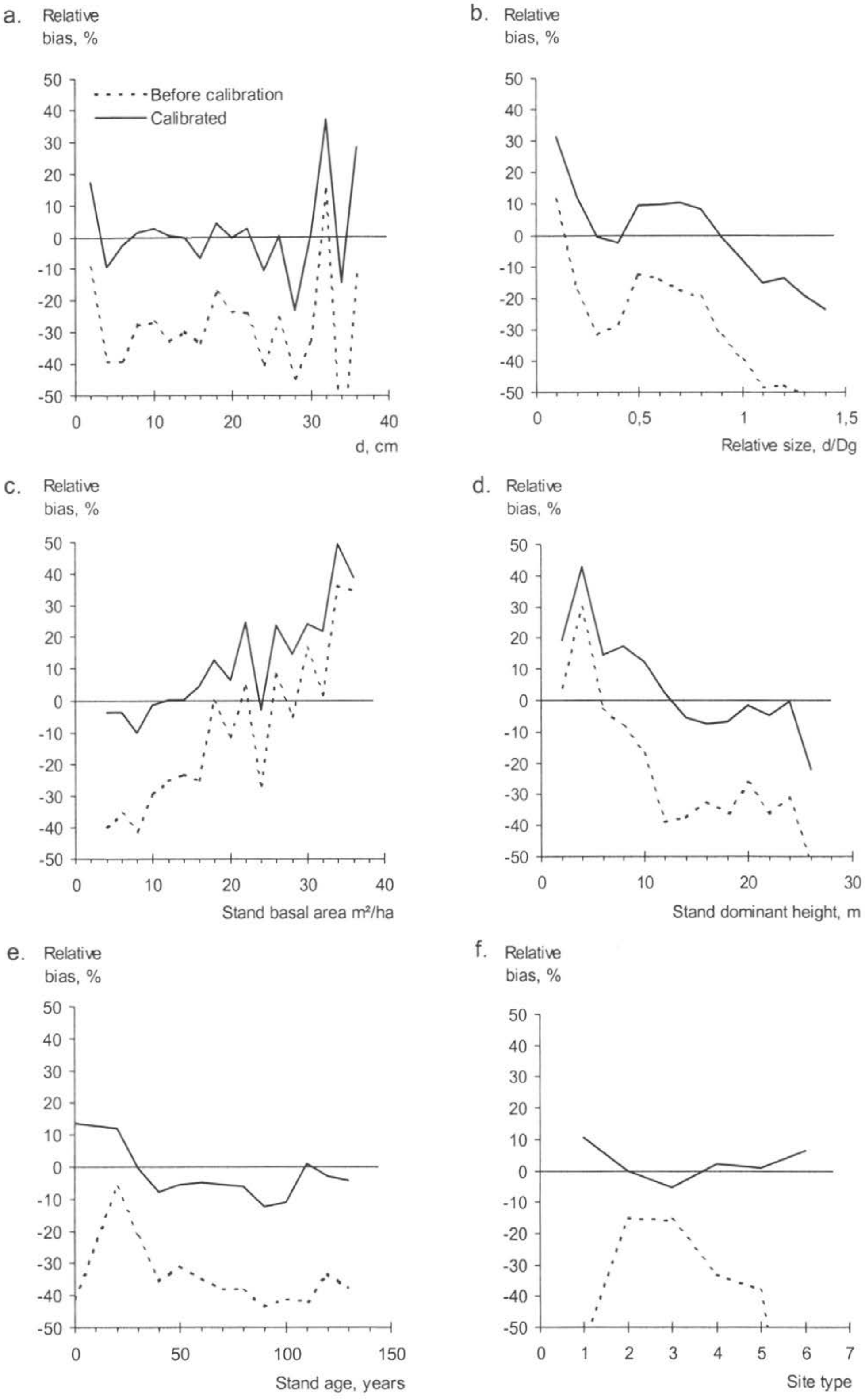


Figure 16. Relative bias of tree basal area growth model for other deciduous tree species before and after calibration plotted against dree diameter (a), relative tree size (d/Dg) (b), stand basal area (c), stand dominant height (d), stand age (e), site type (f), temperature sum (g), forestry board district (h), and mean residuals by tree species (i). Stands on mineral soils.


a.
Relative bias, %
Before calibration
Calibrated
50
40
30
20
10
0
-10
-20
-30
-40
-50
0
10
20
30
40
d, cm
b.
Relative bias, %
0
0,5
1
1,5
Relative size, d/Dg
c.
Relative bias, %
0
10
20
30
40
Stand basal area m²/ha
d.
Relative bias, %
0
10
20
30
Stand dominant height, m
e.
Relative bias, %
0
50
100
150
Stand age, years
f.
Relative bias, %
0
1
2
3
4
5
6
7
Site type

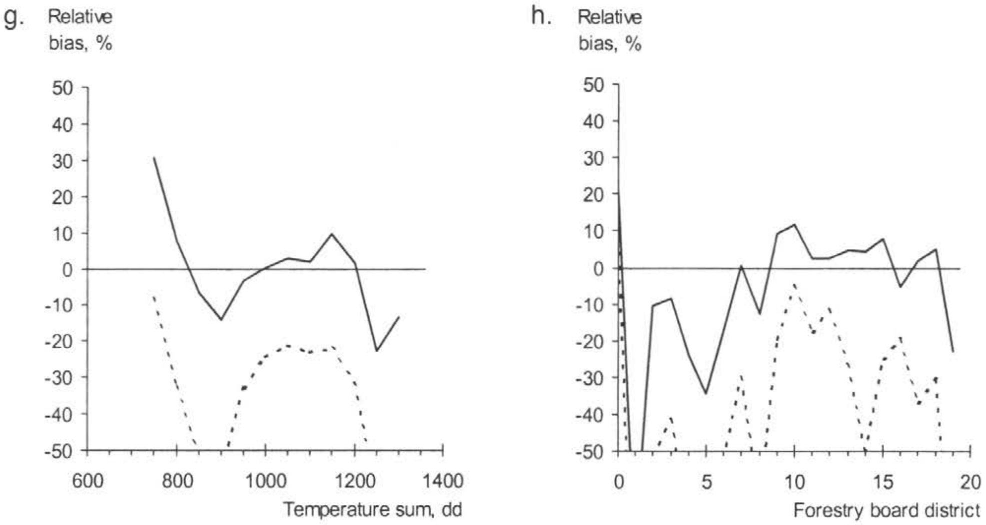
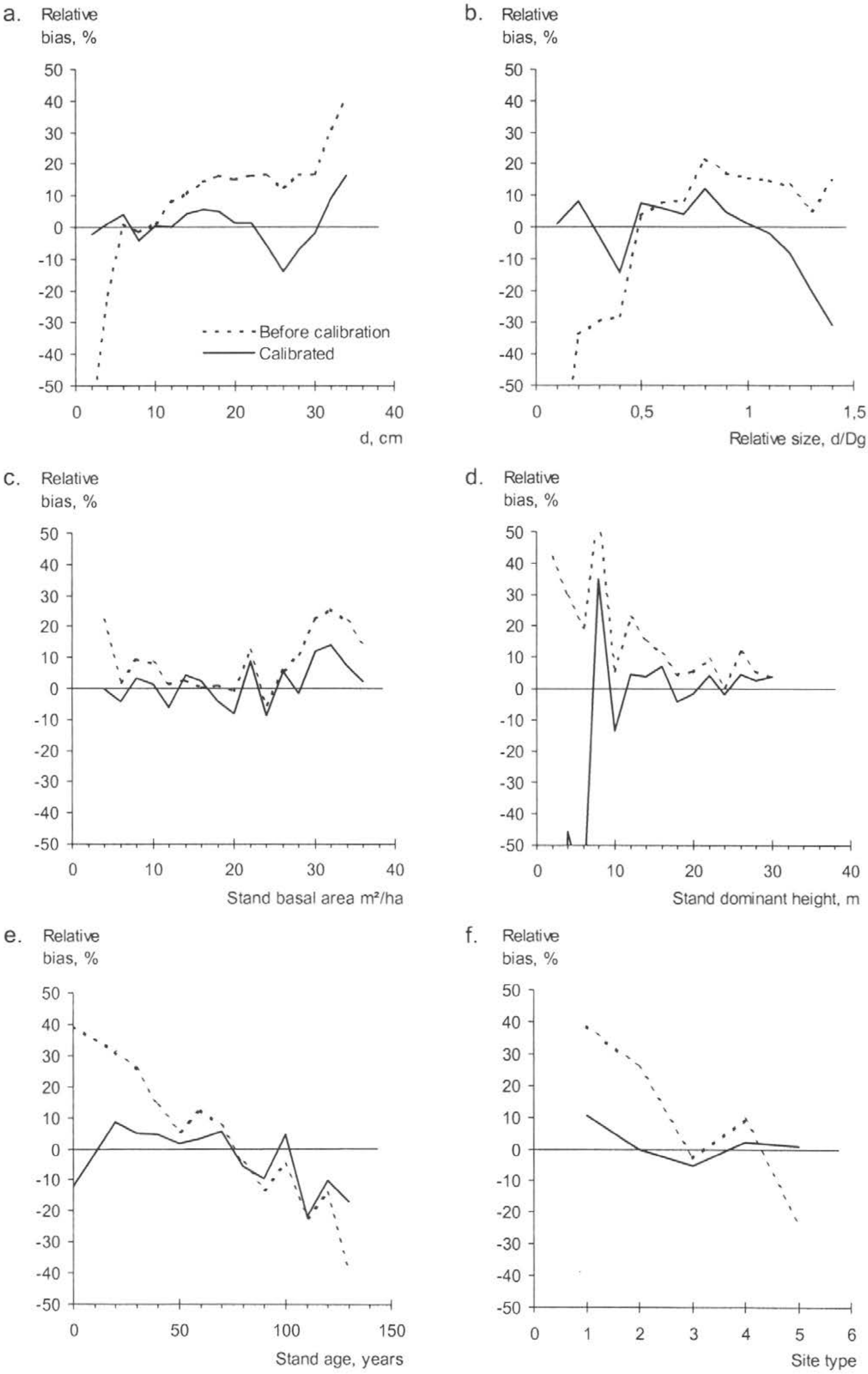


Figure 17. Relative bias of tree basal area growth model for Scots pine before and after calibration plotted against dree diameter (a), relative tree size (d/Dg) (b), stand basal area (c), stand dominant height (d), stand age (e), site type (f), temperature sum (g), and forestry board district (h). Stands on drained peatlands.


a.
Relative bias, %
50
40
30
20
10
0
-10
-20
-30
-40
-50
0
10
20
30
40
d, cm
Before calibration
Calibrated
b.
Relative bias, %
0
0,5
1
1,5
Relative size, d/Dg
c.
Relative bias, %
Stand basal area m²/ha
d.
Relative bias, %
Stand dominant height, m
e.
Relative bias, %
0
50
100
150
Stand age, years
f.
Relative bias, %
0
1
2
3
4
5
6
Site type

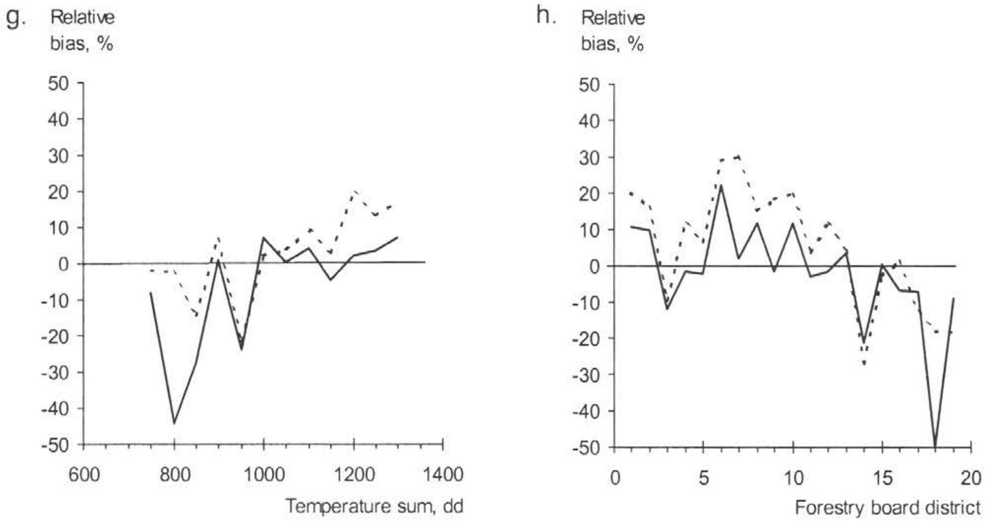
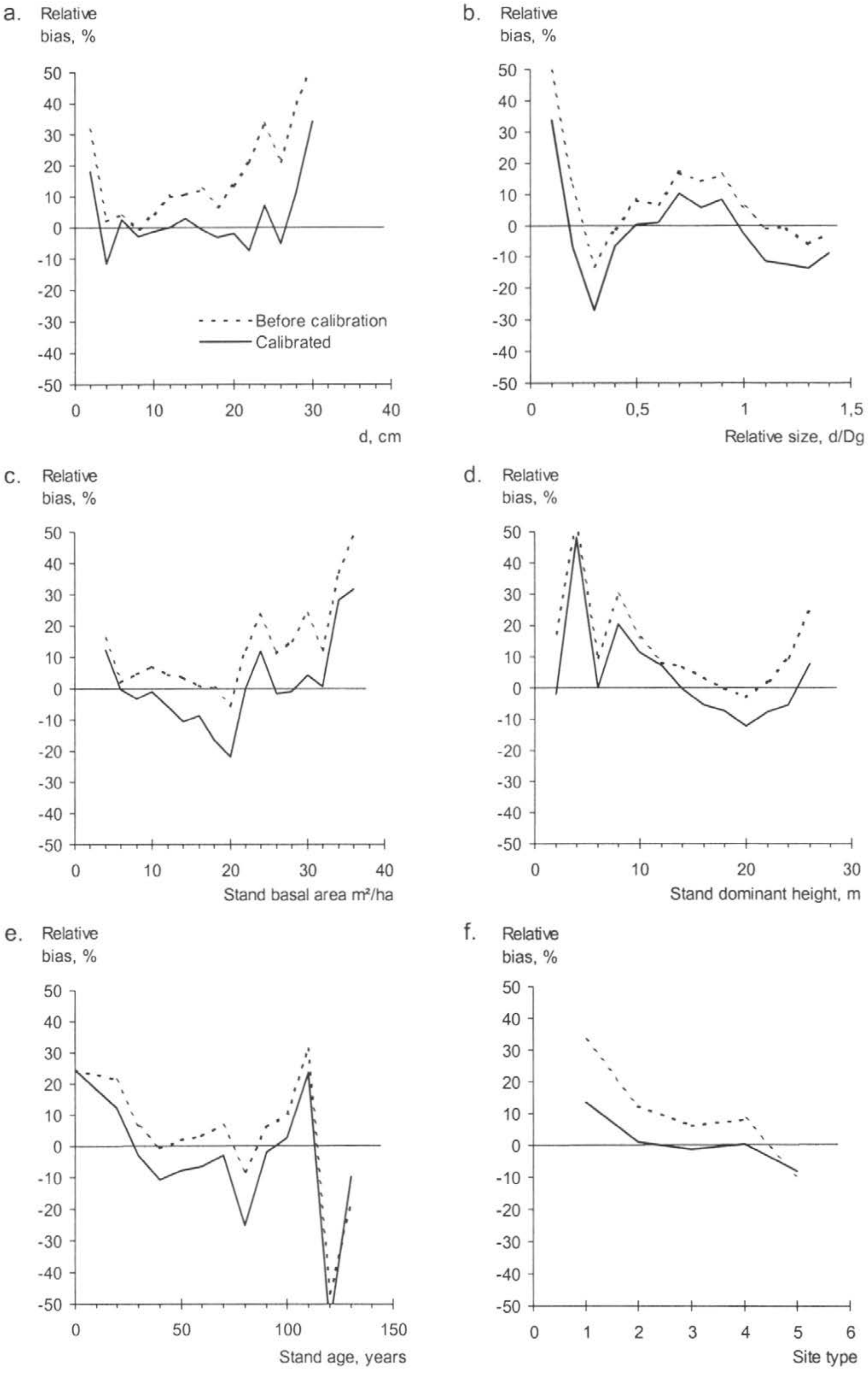


Figure 18. Relative bias of tree basal area growth model for Norway spruce before and after calibration plotted against dree diameter (a), relative tree size (d/Dg) (b), stand basal area (c), stand dominant height (d), stand age (e), site type (f), temperature sum (g), and forestry board district (h). Stands on drained peatlands.


a.
Relative
bias, %
50
40
30
20
10
0
-10
-20
-30
-40
-50
0
10
20
30
40
d, cm
Before calibration
Calibrated
b.
Relative
bias, %
0
0,5
1
1,5
Relative size, d/Dg
c.
Relative
bias, %
0
10
20
30
40
Stand basal area m²/ha
d.
Relative
bias, %
0
10
20
30
Stand dominant height, m
e.
Relative
bias, %
0
50
100
150
Stand age, years
f.
Relative
bias, %
0
1
2
3
4
5
6
Site type

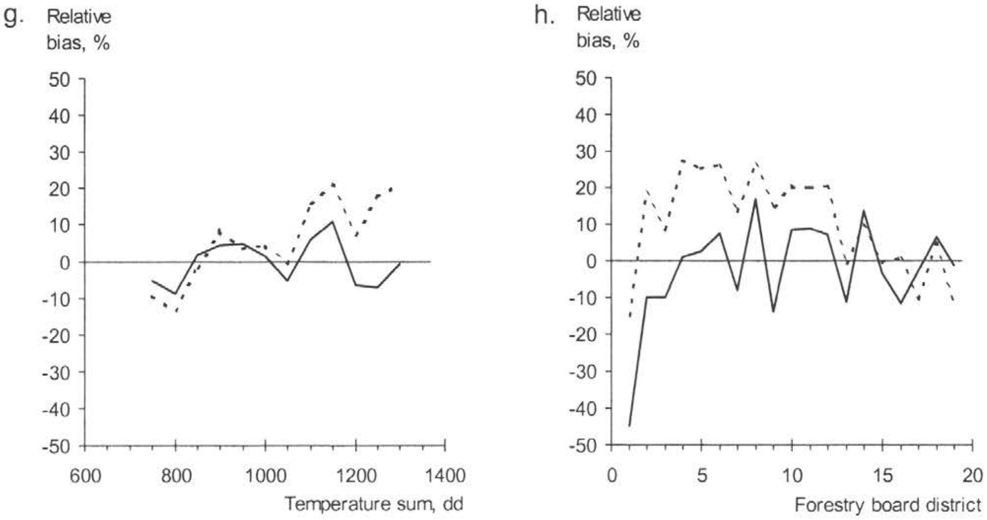
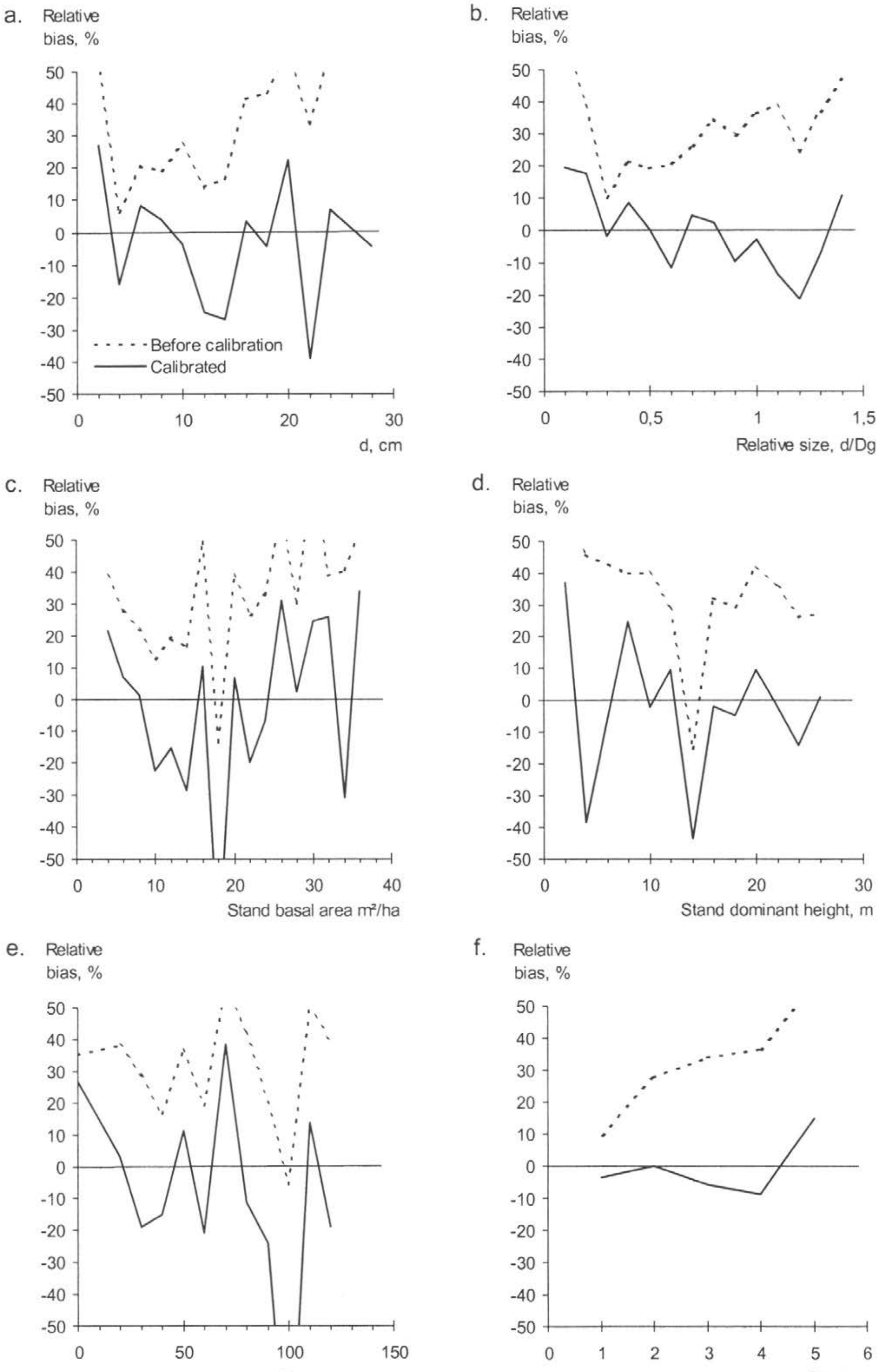


Figure 19. Relative bias of tree basal area growth model for pubescent birch (*Betula pubescens*) before and after calibration plotted against dree diameter (a), relative tree size (d/Dg) (b), stand basal area (c), stand dominant height (d), stand age (e), site type (f), temperature sum (g), and forestry board district (h). Stands on drained peatlands.


a.
Relative bias, %
50
40
30
20
10
0
-10
-20
-30
-40
-50
0
10
20
30
d, cm
Before calibration
Calibrated
b.
Relative bias, %
0
0,5
1
1,5
Relative size, d/Dg
c.
Relative bias, %
0
10
20
30
40
Stand basal area m²/ha
d.
Relative bias, %
0
10
20
30
Stand dominant height, m
e.
Relative bias, %
0
50
100
150
Stand age, years
f.
Relative bias, %
0
1
2
3
4
5
6
Site type

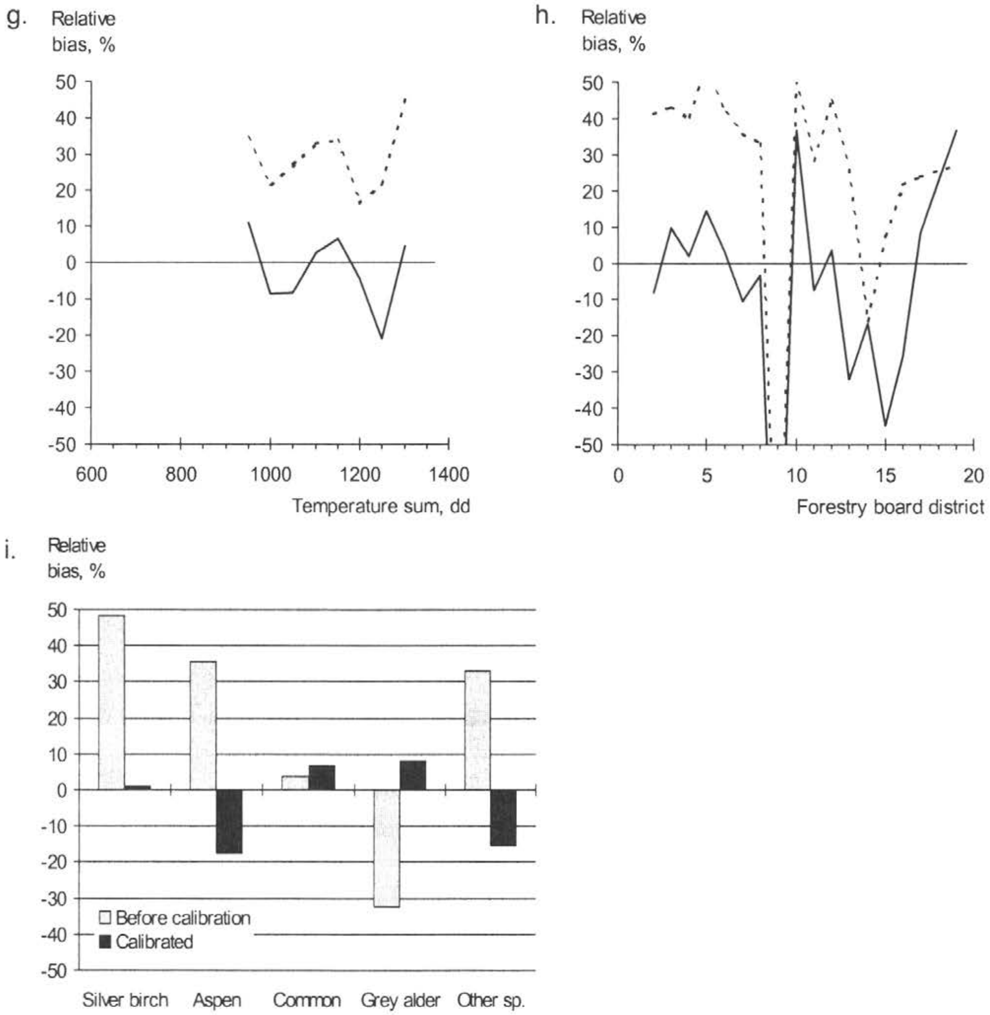


Figure 20. Relative bias of tree basal area growth model for other deciduous tree species before and after calibration plotted against dree diameter (a), relative tree size (d/Dg) (b), stand basal area (c), stand dominant height (d), stand age (e), site type(f), temperature sum (g), forestry board district (h), and mean residuals by tree species (i). Stands on drained peatlands.

Table 45. Model for bias. Height of dominant trees in Scots pine stands on mineral soils.

Independent variable: $y-\hat{y}$, where $y = \ln(h-1.3-((D_{dom} / d)-1))$. (Model 70)

Variable	Coefficient	Std. error	T
Intercept	0.149241	0.16853399	0.89
TS/1000	0.680	0.30298	2.24
$(TS/1000)^2$	-0.562	0.140	-4.01
ALT	-0.00194	0.00011417	-16.99
LAKE	-0.358054	0.03984176	-8.99
SEA	0.176556	0.04484722	3.94
SC_4	0.020707	0.00874088	2.37
SC_5	0.068819	0.02019731	3.41
SC_6	0.0		
SC_7	-0.170542	0.02544781	-6.70
SC_8 or SCRUB	-0.402331	0.03142211	-12.80
WASTE	-0.7		
(SC_{1-4})*STONY	-0.252109	0.05180961	-4.87
(SC_{1-4})*PALU	-0.106470	0.03530306	-3.02
(SC_{3-8})*PALU	-0.706770	0.23611883	-2.99
R^2	0.2965		
RMSE	0.23581		
Dep. Mean	0.13413		
No. of trees	3246		

Table 46. Model for bias. Height of dominant trees in Norway spruce stands on mineral soils.

Independent variable: $y-\hat{y}$, where $y = \ln(h-1.3-((D_{dom} / d)-1))$. (Model 71)

Variable	Coefficient	Std. error	T
Intercept	-2.055512	0.35880285	-5.73
TS/1000	3.980	0.61590	6.46
$(TS/1000)^2$	-1.839	0.27	-6.81
ALT	0.000970	0.00013434	7.22
LAKE	-0.037887	0.04742902	-0.80
SEA	0.664343	0.05848584	11.36
SC_1	0.017290	0.04728875	0.37
SC_2	-0.070675	0.00905928	-7.80
SC_4	0.019196	0.04165068	0.46
SC_5	0.0		
SC_6	-0.1		
SC_7	0.196336	0.10765049	1.82
SC_8	-0.187849	-0.187849	1.00
SCRUB	0.187935	0.18286085	1.03
WASTE	-0.2		
STONY	-0.0744049	0.01457200	-5.11
PALU	-0.099341	0.01732625	-5.73
HUMUS	-0.083910	0.07886342	-1.06
R^2	0.1829		
RMSE	0.18605		
Dep. Mean	0.13644		
No. of trees	1818		

Table 47. Model for bias. Height of dominant trees in birch stands on mineral soils. The basic level is for pubescent birch.

Independent variable: $y-\hat{y}$, where $y = \ln(h-1.3-((D_{dom} / d)-1))$. (Model 72)

Variable	Coefficient	Std. error	T
Intercept	-1.557652	0.60029153	-2.59
sp_4	0.063115	0.02407163	2.62
TS/1000	1.986	1.06484	1.87
$(TS/1000)^2$	-0.513	0.48	-1.07
ALT	0.001080	0.00027389	3.94
LAKE	-0.110713	0.08991807	-1.23
SEA	-0.108478	0.09681434	-1.12
SC_1	-0.027724	0.04246118	-0.65
SC_2	0.075057	0.02168131	3.46
SC_4	0.234759	0.03402435	6.90
SC_5	0.597830	0.14468187	4.13
SC_6	-0.1		
$SC_{7,8}$	0.169286	0.14159980	1.20
SCRUB	-0.249864	0.17077640	-1.46
WASTE	-0.3		
STONY	-0.067949	0.03518582	-1.93
STONY. sp_4	0.012180	0.04932565	0.25
PALU	0.279850	0.14704774	1.90
PALU. sp_4	-0.433211	0.15493058	-2.80
HUMUS	0.246037	0.15009759	1.64
R^2	0.2285		
RMSE	0.19817		
Dep. Mean	0.10064		
No. of trees	444		

Table 48. Model for bias. Height of dominant trees in stands of deciduous tree species on mineral soils.

Independent variable: y- $\hat{y}$, where y = ln(h-1.3-((D_{dom} / d)-1)). (Model 73)

Variable	Coefficient	Std. error	T
$\text{Intercept}_{B\ Pen}$	-1.426887	0.63821994	-2.24
sp_4	0.058216	0.02643895	2.20
sp_5	0.144658	0.03570269	4.05
sp_6	-0.080327	0.05407480	-1.49
sp_7	0.091600	0.11608854	0.79
sp_8	-0.20		
sp_9	-0.41		
TS/1000	1.838	1.12025	1.64
$(TS/1000)^2$	-0.540	0.50	-1.08
ALT	0.000860	0.00028332	3.04
LAKE	-0.082521	0.09315088	-0.89
SEA	-0.390489	0.09066244	-4.31
SC_1	0.012887	0.03938578	0.33
SC_2	0.064706	0.02258472	2.87
SC_4	0.257001	0.03669536	7.00
SC_5	0.599669	0.16265042	3.69
SC_6	-0.1		
$SC_{7,8}$	0.163237	0.15921247	1.03
SCRUB	0.316935	0.18573645	1.71
WASTE	-0.2		
STONY	-0.53425	0.05202951	-10.27
PALU	-0.14812	0.11463938	-1.29
R^2	0.2547		
RMSE	0.22307		
Dep. Mean	0.11460		
No. of trees	533		

Table 49. Model for bias. Tree basal area growth model for Scots pine on mineral soils.

Independent variable: $\ln(\text{Bias}) = \ln(\text{ig} + 1) - \ln(\hat{\text{i}}\text{g} + 1)$ (Model 74)

Variable	Coefficient	Std. error	T
Intercept	-1.88386	0.12808	-14.344
TS/1000	1.65420	0.24251	6.821
$(TS/1000)^2$	-0.28099	0.11950	-2.351
ALT	0.00145	0.00010	14.456
SEA	0.18180	0.04194	3.958
$SC_1 \cdot (d^2)$	0.00040	0.00012	3.170
$SC_2 \cdot (d^2)$	0.00043	0.00003	13.879
SC_3	0.05210	0.00897	5.811
SC_5	0.08097	0.01855	4.364
SC_7	-0.20553	0.02825	-7.275
SC_8	0.31621	0.07755	4.077
SCRUB	-0.14429	0.04102	-3.590
R^2	0.1382		
RMSE	5.2498		
Dep. Mean	-0.25931		
No. of Obs.	17 330		
Variance correction terms:			
C_{ratio}: < 5 cm	1.36562		
C_{ratio}: 5–10 cm	1.11041		
C_{ratio}: 10–20 cm	1.04251		
C_{ratio}: 20–30 cm	1.01429		
C_{ratio}: > 30 cm	1.15160		

Table 50. Model for bias. Tree basal area growth model for Norway spruce on mineral soils.

Independent variable: $\ln(\text{Bias}) = \ln(\text{ig} + 1) - \ln(\hat{\text{i}}\text{g} + 1)$ (Model 75)

Variable	Coefficient	Std. error	T
Intercept	-1.22666	0.06249	-19.001
TS/1000	0.7629	0.04617	16.523
ALT	0.00155	0.00010	15.367
$d \cdot SC_2$	0.00288	0.00055	5.213
$(1/d) \cdot SC_{4+}$ 1)	0.19087	0.01970	9.691
SCRUB	-0.52581	0.06036	-8.712
R^2	0.0600		
RMSE	5.07508		
Dep. Mean	-0.16511		
No. of Obs.	14932		
Variance correction terms:			
C_{ratio}: < 5 cm	1.13425		
C_{ratio}: 5–10 cm	1.17624		
C_{ratio}: 10–20 cm	1.10393		
C_{ratio}: 20–30 cm	1.03971		
C_{ratio}: 30–40 cm	1.08988		
C_{ratio}: >35 cm	1.24833		

1) VT (Vaccinium site type) and less productive sites.

Table 51. Model for bias. Tree basal area growth model for silver birch (*Betula pendula*) on mineral soils.

Independent variable: $\ln(\text{Bias}) = \ln(i_g + 1) - \ln(\hat{i}_g + 1)$ (Model 76)

Variable	Coefficient	Std. error	T
Intercept	-1.97241	0.16917	-11.239
TS/1000	0.32670	0.12837	2.545
H_{dom}	0.11402	0.00873	13.061
H_{dom}^2	-0.00196	0.00023	-8.371
SC_1	0.48160	0.08709	5.53
SC_2	0.36118	0.04125	8.757
SC_4	-0.11580	0.05130	-2.257
SC_7	-0.17282	0.10945	-1.579
R^2	0.3529		
RMSE	6.3358		
Dep. Mean	-0.20807		
No. of Obs.	1502		
Variance correction terms:			
C_{ratio}: < 5 cm	1.26255		
C_{ratio}: 5–10 cm	1.15526		
C_{ratio}: 10–15 cm	1.11487		
C_{ratio}: 15–20 cm	1.05096		
C_{ratio}: 20–25 cm	1.03475		
C_{ratio}: 25–30 cm	1.05407		
C_{ratio}: 30–35 cm	1.17978		
C_{ratio}: > 35 cm	1.37698		

Table 52. Model for bias. Tree basal area growth model for pubescent birch (*Betula pubescens*) on mineral soils.

Independent variable: $\ln(\text{Bias}) = \ln(i_g + 1) - \ln(\hat{i}_g + 1)$ (Model 77)

Variable	Coefficient	Std. error	T
Intercept	0.27428	0.24753	1.499
H_{dom}	0.07849	0.00584	13.447
H_{dom}^2	-0.00120	0.00017	-7.001
TS/1000	-2.67933	0.51359	-5.217
$(TS/1000)^2$	1.15406	0.26848	4.299
LAKE	0.45273	0.11199	4.043
SC_1	0.43534	0.07394	5.887
SC_2	0.11509	0.02622	4.39
SC_5	-0.40626	0.08258	-4.92
SC_7	-0.15671	0.10945	-1.432
SC_8	0.10357	0.04767	2.172
R^2	0.2348		
RMSE	8.24656		
Dep. Mean	-0.23158		
No. of Obs.	3934		
Variance correction terms:			
C_{ratio}: < 5 cm	1.15147		
C_{ratio}: 5–10 cm	1.22573		
C_{ratio}: 10–15 cm	1.13414		
C_{ratio}: 15–20 cm	0.97380		
C_{ratio}: 20–25 cm	0.94264		
C_{ratio}: > 25 cm	1.07059		

Table 53. Model for bias. Tree basal area growth model for other deciduous tree species on mineral soils.

Independent variable: $\ln(\text{Bias}) = \ln(i_g + 1) - \ln(\hat{i}_g + 1)$ (Model 78)

Variable	Coefficient	Std. error	T
Intercept	0.53674	0.17338	3.588
H_{dom}	0.03468	0.00123	28.159
TS/1000	-2.38949	0.38113	-6.269
SC_1	1.02036	0.20140	5.066
SC_2	0.35737	0.04312	8.289
SC_4	0.07627	0.02304	3.31
SC_5	-0.04673	0.02630	-1.777
SC_7	-0.39517	0.08765	-4.508
SC_8	-0.20600	0.09857	-2.09
sp_5	0.29180	0.03325	8.775
sp_6	0.20954	0.02811	7.455
sp_7	0.01914	0.10393	0.184
sp_8, sp_9	0.37152	0.03509	10.586
R^2	0.0894		
RMSE	9.70212		
Dep. Mean	-0.12098		
No. of Obs. [1]	5923		
Variance correction terms:			
C_{ratio}: < 5 cm	1.11386		
C_{ratio}: 5–10 cm	1.1767849		
C_{ratio}: 10–20 cm	1.1360847		
C_{ratio}: 20–30 cm	1.1068616		
C_{ratio}: > 30 cm	1.3798528		

[1] Including the number of pubescent birch trees.

Table 54. Model for bias. Tree basal area growth model for Scots pine on peatlands.

Independent variable: $\ln(\text{Bias}) = \ln(\text{ig} + 1) - \ln(\hat{\text{i}}\text{g} + 1)$ (Model 79)

Variable	Coefficient	Std. error	T
Intercept	-3.89138	0.54014	-7.026
TS/1000	5.76914	0.99383	5.805
$(TS/1000)^2$	-2.40611	0.46272	-5.2
ALT	0.00293	0.00022	13.262
SEA	0.82861	0.14877	5.57
SC_1	-0.29352	0.12219	-2.402
SC_4	-0.26141	0.02237	-11.683
SC_5	-0.24866	0.02487	-9.997
SC_6	-0.39550	0.07558	-5.233
SCRUB	-0.32354	0.03092	-10.466
UNDRAINED	-0.27118	0.02919	-9.292
R^2	0.1524		
RMSE	6.81053		
Dep. Mean	-0.40325		
No. of Obs.	5533		
Variance correction terms:			
C_{ratio}: < 5 cm	1.24647		
C_{ratio}: 5–10 cm	1.11459		
C_{ratio}: 10–20 cm	1.06898		
C_{ratio}: > 20 cm	1.04918		

Table 55. Model for bias. Tree basal area growth model for Norway spruce on peatlands.

Independent variable: $\ln(\text{Bias}) = \ln(\text{ig} + 1) - \ln(\hat{\text{i}}\text{g} + 1)$ (Model 80)

Variable	Coefficient	Std. error	T
Intercept	-0.04965	0.18675	-0.047
ln(d)	0.29286	0.01791	16.355
$\ln(H_{dom})$	-0.62972	0.04073	-15.461
TS/1000	0.70113	0.14256	4.918
ALT	0.00170	0.00030	5.628
LAKE	0.32627	0.16136	2.022
SC_1	0.65389	0.13201	4.954
SC_2	0.28405	0.03164	8.978
SC_4	0.10779	0.03360	3.208
SC_5	-0.20786	0.08159	-2.548
R^2	0.2083		
RMSE	6.18213		
Dep. Mean	-0.20302		
No. of Obs.	2573		
Variance correction terms:			
C_{ratio}	1.15823		

Table 56. Model for bias. Tree basal area growth model for pubescent birch (*Betula pubescens*) on peatlands.

Independent variable: $\ln(\text{Bias}) = \ln(i_g + 1) - \ln(\hat{i}_g + 1)$ (Model 81)

Variable	Coefficient	Std. error	T
Intercept	-1.49202	0.16674	-8.523
TS/1000	1.11213	0.13546	8.21
ALT	0.00228	0.00026	8.775
SC_1	0.18397	0.09433	1.95
SC_2	0.09348	0.02995	3.121
SCRUB	-0.28639	0.06892	-4.155
UNDRAINED	-0.34648	0.04365	-7.937
R^2	0.0815		
RMSE	8.27769		
Dep. Mean	-0.03846		
No. of Obs.	2757		
Variance correction terms:			
C_{ratio}: < 5 cm	1.15435		
C_{ratio}: 5–10 cm	1.05338		
C_{ratio}: 10–20 cm	1.11601		
C_{ratio}: > 20 cm	1.35653		

Table 57. Model for bias. Tree basal area growth model for other broadleaved tree species on peatlands.

Independent variable: $\ln(\text{Bias}) = \ln(i_g + 1) - \ln(\hat{i}_g + 1)$ (Model 82)

Variable	Coefficient	Std. error	T
Intercept	-2.67024	0.71325	-3.647
TS/1000	3.39029	1.30970	2.589
$(TS/1000)^2$	-1.08965	0.60833	-1.791
ALT	0.00231	0.00025	9.106
SC_2	0.09608	0.02846	3.376
SCRUB	-0.25790	0.06608	-3.903
UNDRAINED	-0.34513	0.04079	-8.461
sp_3	0.47066	0.08516	5.527
sp_5	0.45852	0.10971	4.179
sp_6	-0.13055	0.06347	-2.057
sp_7	-0.19422	0.15068	-1.289
sp_8, sp_9	0.40588	0.09290	4.369
R^2	0.1012		
RMSE	8.31671		
Dep. Mean	-0.02186		
No. of Obs.[1]	3089		
Variance correction terms:			
C_{ratio}: < 5 cm	1.16468		
C_{ratio}: 5–10 cm	1.05695		
C_{ratio}: 10–20 cm	1.10804		
C_{ratio}: > 20 cm	1.34524		

[1] Including the number of pubescent birch trees.

Table 58. Model for bias. Tree height model for Scots pine on peatlands.

Independent variable: $\ln(\text{Bias}) = \ln(h) - \ln(\hat{h})$ (Model 83)

Variable	Coefficient	Std. error	T
Intercept	-0.08262	0.13913	-0.457
TS/1000	0.70792	0.25532	2.773
$(TS/1000)^2$	-0.45964	0.11890	-3.866
ALT	-0.00043	0.00006	-7.526
SEA	-0.47783	0.03861	-12.375
SC_2	-0.02611	0.01028	-2.539
SC_3	-0.01712	0.00623	-2.75
SC_5	0.02730	0.00554	4.931
SC_6	-0.04660	0.01993	-2.338
SCRUB	-0.02487	0.00799	-3.111
UNDRAINED	0.04334	0.00757	5.728
R^2	0.0955		
RMSE	1.73577		
Dep. Mean	0.08540		
No. of Obs.	5452		
Variance correction terms:			
C_{ratio}	1.00458		

Table 59. Model for bias. Tree height model for Norway spruce on peatlands.

Independent variable: $\ln(\text{Bias}) = \ln(h) - \ln(\hat{h})$ (Model 84)

Variable	Coefficient	Std. error	T
Intercept	-0.25968	0.18271	-1.365
d_{30} 1)	0.00375	0.00149	2.511
d_{30}^2 1)	-0.00031	0.00005	-5.946
TS/1000	0.81172	0.33157	2.448
$(TS/1000)^2$	-0.37828	0.15071	-2.51
ALT	-0.00044	0.00007	-6.187
LAKE	0.16576	0.03945	4.202
SC_4	-0.02569	0.00781	-3.29
SC_5	-0.05291	0.01949	-2.715
SCRUB	0.03949	0.02375	1.663
R^2	0.0987		
RMSE	1.47978		
Dep. Mean	0.11284		
No. of Obs.	2579		
Variance correction terms:			
C_{ratio}	1.0067457		

1) $d_{30} = d$, if $d \leq 30$ cm
$d_{30} = 30$, if $d > 30$ cm

Table 60. Model for bias. Tree height model for pubescent birch (*Betula pubescens*) on peatlands.

Independent variable: $\ln(\text{Bias}) = \ln(h) - \ln(\hat{h})$ (Model 85)

Variable	Coefficient	Std. error	T
Intercept	0.29346	0.03855	8.173
d_{20} 1)	-0.07106	0.00284	-25.025
d_{20}^2 1)	0.00251	0.00016	16.113
TS/1000	0.12696	0.03494	3.634
SC_1	-0.07549	0.02893	-2.61
SC_2	0.02106	0.01008	2.089
SC_4	-0.03481	0.00928	-3.752
SC_5	-0.18407	0.01911	-9.63
SCRUB	-0.07961	0.02199	-3.62
UNDRAINED	0.06948	0.01332	5.216
R^2	0.3573		
RMSE	2.53316		
Dep. Mean	0.12513		
No. of Obs.	2732		
Variance correction terms:			
C_{ratio}	1.0041588		

1) d_{20} = d, if d ≤ 20 cm
d_{20} = 20, if d > 20 cm

Table 61. Model for bias. Tree height model for other broadleaved tree species on peatlands.

Independent variable: $\ln(\text{Bias}) = \ln(h) - \ln(\hat{h})$ (Model 86)

Variable	Coefficient	Std. error	T
Intercept	-0.12688	0.21571	-0.588
d_{20} 1)	-0.07132	0.00278	-25.672
d_{20}^2 1)	0.00246	0.00015	16.301
TS/1000	0.97358	0.40639	2.396
$(TS/1000)^2$	-0.40511	0.19054	-2.126
LAKE	0.11083	0.05019	2.208
SC_2	0.02745	0.00961	2.858
SC_4	-0.03001	0.00927	-3.238
SC_5	-0.16052	0.01888	-8.502
SCRUB	-0.11331	0.02145	-5.283
UNDRAINED	0.03865	0.01280	3.02
sp_3	0.08913	0.02696	3.306
sp_5	0.08222	0.03739	2.199
sp_6	-0.11070	0.02010	-5.509
sp_7	-0.31710	0.04729	-6.705
sp_8, sp_9	0.07686	0.02930	2.623
R^2	0.3579		
RMSE	2.60640		
Dep. Mean	0.12508		
No. of Obs.	3055 2)		
Variance correction terms:			
C_{ratio}	1.00384		

1) d_{20} = d, if d ≤ 20 cm
d_{20} = 20, if d > 20 cm

2) Including the number of pubescent birch trees.

Table 62. Model for bias. Tree crown ratio model for Scots pine.

Independent variable: Bias = cr – $\hat{cr}$ (Model 87)

Variable	Coefficient	Std. error	T
Intercept	-0.40141	0.02958	-13.225
TS/1000	-0.79080	0.06091	-12.983
$(TS/1000)^2$	0.47168	0.02944	16.02
ALT	0.00022	0.00002	9.317
SEA	0.06588	0.01104	5.967
LAKE	0.06236	0.01019	6.121
H_{dom}	0.02304	0.00067	34.623
H_{dom}^2	-0.00040	0.00002	-20.603
SI_{Sp}	0.06649	0.00273	24.311
$(SI_{Sp})^2$	-0.00191	0.00009	-21.97
BA	-0.00967	0.00026	-37.345
BA^2	0.00013	0.000004	27.135
SC_2	0.01594	0.00452	3.529
SC_6	0.06116	0.02846	2.149
SC_8	0.09373	0.01491	6.288
R^2	0.2868		
RMSE	1.13233		
Dep. Mean	0.03124		
No. of Obs.	17324		

Table 63. Model for bias. Tree crown ratio model for Norway spruce.

Independent variable: Bias = cr – $\hat{cr}$ (Model 88)

Variable	Coefficient	Std. error	T
Intercept	0.05697	0.03494	1.819
TS/1000	-0.45311	0.06713	-6.75
$(TS/1000)^2$	0.26348	0.03203	8.225
SEA	0.02065	0.00914	2.259
LAKE	0.05110	0.01082	4.723
$BA\%_b$	0.07898	0.00487	16.227
H_{dom}	0.01377	0.00070	19.598
H_{dom}^2	-0.00010	0.00002	-5.888
ln(BA)	-0.01333	0.00165	-8.087
h	-0.00358	0.00017	-20.502
SC_1, SC_2	-0.00866	0.00238	-3.645
SC_4	0.05810	0.00340	17.103
SC_5	0.10011	0.02522	3.97
SC_7	0.07718	0.01081	7.142
SC_8	0.09683	0.02820	3.434
SCRUB	-0.10671	0.02106	-5.066
R^2	0.2381		
RMSE	1.07195		
Dep. Mean	0.05486		
No. of Obs.	14738		

Table 64. Model for bias. Tree crown ratio model for silver birch (*Betula pendula*).

Independent variable: Bias = $cr - \hat{c}r$ (Model 89)

Variable	Coefficient	Std. error	T
Intercept	-0.21277	0.02254	-8.347
ALT	-0.00067	0.00007	-8.929
LAKE	0.17392	0.03297	5.275
SEA	-0.1008	0.03005	-3.356
H_{dom}	0.01476	0.00233	6.327
H_{dom}^2	-0.00034	0.00006	-5.459
BA	0.00503	0.00038	13.187
SC_1	0.04756	0.01890	2.517
SC_2	0.05121	0.00921	5.557
SC_4	0.05415	0.01209	4.48
SCRUB	-0.09836	0.04455	-2.208
R^2	0.3811		
RMSE	1.36948		
Dep. Mean	-0.01794		
No. of Obs.	1440		

Table 65. Model for bias. Tree crown ratio model for pubescent birch (*Betula pubescens*).

Independent variable: Bias = $cr - \hat{c}r$ (Model 90)

Variable	Coefficient	Std. error	T
Intercept	-0.34492	0.07787	-4.289
TS/1000	-0.37472	0.14445	-2.594
$(TS/1000)^2$	0.27911	0.07275	3.836
ALT	0.00012	0.00005	2.601
LAKE	0.11740	0.03101	3.786
H_{dom}	0.01000	0.00171	5.825
H_{dom}^2	-0.00012	0.00005	-2.433
$BA\%_b$	0.04680	0.00986	4.748
BA	-0.00222	0.00087	-2.549
BA^2	0.00014	0.00002	7.83
h	0.03358	0.00200	16.753
h^2	-0.00138	0.00009	-14.871
SCRUB	-0.11774	0.01271	-9.264
R^2	0.3930		
RMSE	2.15374		
Dep. Mean	-0.12145		
No. of Obs.	3781		

Table 66. Model for bias. Tree crown ratio model for other broadleaved tree species.

Independent variable: Bias = $cr - \hat{cr}$ (Model 91)

Variable	Coefficient	Std. error	T
Intercept	-0.39508	0.07686	-4.886
TS/1000	-0.21996	0.13962	-1.575
$(TS/1000)^2$	0.20236	0.06884	2.939
ALT	0.00010	0.00005	2.065
LAKE	0.05426	0.02621	2.07
H_{dom}	0.01376	0.00155	8.901
H_{dom}^2	-0.0002	0.00004	-4.559
$BA\%_b$	0.01907	0.00920	2.073
BA	-0.00359	0.00073	-4.906
BA^2	0.00014	0.00001	10.362
h	0.02664	0.00187	14.232
h^2	-0.00101	0.00009	-11.416
SCRUB	-0.08463	0.01356	-6.24
sp_5	-0.04507	0.00926	-4.87
sp_6	-0.04709	0.00799	-5.891
sp_7	-0.10120	0.02858	-3.54
sp_8, sp_9	0.05698	0.01024	5.566
R^2	0.3059		
RMSE	2.51209		
Dep. Mean	-0.10851		
No. of Obs. [1)]	5745		

[1)] Including the number of pubescent birch trees.

6 Growth response to fertilization

6.1 Tree basal area growth response

Growth response to forest fertilization is predicted as relative increase in tree basal area and height growth.

Prediction of growth response on mineral soils is based on the model of Kukkola and Saramäki (1983). Their model predicts the relative growth response in stand volume growth. When the stand-level model was applied in MELA-System, the following simplifying assumptions were made:

1. relative growth response is similar for all trees within a stand
2. relative response in tree basal is equal to that in volume growth
3. in practical forestry the magnitude of growth response is 70 % of the response obtained with models of Kukkola and Saramäki based on measurements from the designed experiments.
4. the duration of fertilization response is assumed to be seven years on mineral soils.

Relative growth responses on mineral soils referring to the temperature sum (TS) equal to 1 250 d.d. are given in the following table by tree species and site fertility classes:

Tree species	Site fertility class SC1	SC2	SC3	SC4	SC5	SC6
Scots pine	–	–	23	35	53	–
Norway spruce and deciduous trees	13	17	32	39	53	–

The growth response is assumed to change with temperature sum according to the following formula:

$$\Delta ba_r = \Delta ba_r(ref) \cdot ((TS+1250)/1250)\ ,$$

where

Δba_r = relative basal area growth response, %

$\Delta ba_r(ref)$ = relative basal area growth response with temperature sum equal to 1250,%

On peatlands, the prediction of growth response to fertilization is based on the extensive inventory data (Keltikangas et al. 1986), in which the treatment history of sample plots was known. For fertilized sample plots of these data, growth response was estimated as the difference between measured and predicted basal area growths. Predicted growth of sample plots was obtained with the regression model based on the unfertilized sample plot data.

It is assumed that the duration of the response on peatlands is ten years. In the following table, relative growth responses on peatlands are presented by tree species and by site fertility classes:

Main site group	Site fertility class SC1	SC2	SC3	SC4	SC5	SC6
Spruce or birch dominated sites (K-sites)	22	22	14	19	19	19
Pine dominated (R-sites) and treeless sites	13	17	32	20	27	27

When the fertilization response model is applied, it is assumed that both on mineral soils and on peatlands fertilizer doses are equal to those commonly applied in practical forest fertilizations.

6.2 Tree height growth response

Prediction method for relative growth response in tree basal area is also applied in predicting the fertilization response in tree height growth. However, in height growth, the response is restricted so that maximum relative response is 20 %.

7 Concluding remarks

7.1 The properties of modelling data

Models are always simplifications and therefore susceptible to inaccuracies and biases. The reliability of an individual regression model can easily be presented in quantitative terms, e.g. in terms of confidence intervals. The simulation of stand development over a long period of time requires simultaneous and recursive application of separate model components, i.e. regression models. Therefore, the reliability of the result obtained with a whole simulation system is quite complicated, if not impossible, to present in exact measures. The accuracy and the biasness of the simulation result is affected by the interaction of model components, model errors, errors in the measurement data, and the degree of propagation or compensation of these errors during the long-term simulations, just to name few sources of uncertainty.

The methods of variance propagation (e.g. Mowrer 1990) and Monte-Carlo simulation (e.g. Gertner 1987 and Kangas 1997) have been used to describe the uncertainty caused by the above mentioned reasons. Both methods assume, that the covariance structure of the separate regression models and the covariance structure between the models used in the simulation system, as well as the temporal covariances are known. Normally, the complicated covariance structure has been simplified when reliability of simulation systems are studied because of the lack of complete data sets.

These aspects have not been addressed in this document mainly because it was impossible to find data to describe the whole covariance structure of the simulation system. Nevertheless, some major aspects concerning the applicability and reliability of the models, presented in this document, are listed below.

Most of the data applied in model development consisted of inventory growth plots (INKA, TINKA and SINKA) that formed a sub-sample of data collected in 6th, 7th and 8th Finnish National Forest Inventories. These data were the regarded to be the most extensive repeatedly measured data that were available and suitable for model development. Into the data of INKA, SINKA and TINKA were accepted only healthy stands that were in satisfactory silvicultural condition. Plots were established only in single-storied stands, in which the proportion of dominant tree species was over 50 % in stand volume.

Data were collected during the 1976 and 1991 on mineral soils, and 1984–1994 on peatlands. Therefore they are representatives of the well-managed Finnish forest during the period of late 70's to early 90's, and they represent the prevailing forest management of that time period. However, forest management practices have significantly changed since those years.

Because the modelling data was not representative for all Finnish forest, the models were calibrated with representative data of 8th National Forest Inventory. In most of the calibration models, only parameters affecting on the growth level of different geographical or site strata were used. This resulted in the models that are marginally unbiased in these strata, but the stand dynamics is still based on the modelling data with better stand description.

The properties of modelling data certainly affect the behaviour and the reliability of models. This should be kept in mind, when applying the models, especially if models are applied in the situations where stand properties noticeably differ from those of the modelling data. Although, much emphasis were put in model development to ensure logical model behaviour even when applied to conditions that are outside the variation of modelling data, no empirical evidence can be provided to support the predictions in those cases.

7.2 Modelling approach and model structure

The models were constructed to be directly applicable in forest management planning tools. The input and output of the models, i.e. the description of site stand and tree, were restricted to those measures that are simple enough to be measured or assessed in practical forest inventories. The description of the growing stock include measurements of tree dimensions, i.e. tree diameters and heights, and density of stands. These kinds of variables referring to absolute or relative tree sizes, and the density of trees per basal area unit are especially suitable for describing the dynamics of closed stands, in which the stand dynamics is largely controlled by direct competition between trees. Due to the structure and applied stand description, models are at their best in predicting the development of stands with complete crown closure.

In young stands, other growth factors than stand density affect to stand dynamics, such as micro-topography, soil properties, site variation and competition of other plants. Unfortunately, these factors are often too time consuming and difficult to be measured in extensive inventories, and are therefore poorly documented in measurement data and poorly represented in growth models. As a consequence, model structure is significantly less suitable for the description of the dynamics of young stand with incomplete crown closure. Thus, in young stands models reflect quite directly to the properties of empirical modelling data. Their capability for extrapolation in unusual stand conditions is poor in young stands. This restriction related to model structure restricts the applicability of the models in comparing silvicultural methods in young stands.

In model building, special attention was paid to the ability to predict the responses to the silvicultural practices, of which thinnings are the most important. Thinning response is included in the growth models. However, the applicability of models is restricted to thinnings from below. Only very few stands thinned from above, if any, were included in the modelling data. If models are applied to stands thinned from above, the magnitude of predicted growth response is not based on any empirical evidence.

The effect of species mixture on the growth of trees is taken into account in the growth models. The tests based on empirical data from mixed stands have showed the satisfactory model behaviour, when applied in simulating the development of even-aged conifer stands with varying birch mixture (Hynynen 1998). The structure of the models results in logical behaviour also in two-storied mixed stands, but these predictions have not yet tested against any empirical data.

Models are basically developed only for the four most common tree species of Finland, i.e. Scots pine, Norway spruce, silver birch, and pubescent birch. The development of other deciduous tree species can be predicted with the calibrated growth model of pubescent birch. In the calibration, the growth model of pubescent birch was adjusted to result in unbiased growth level of aspen, grey alder, common alder or other deciduous trees measured in NFI8 sample plots. Most of these deciduous sample trees in NFI data grow in mixed species stands. It is not recommended to apply the models to pure and well-managed stands of aspen, common alder or grey alder.

7.3 Applying the models to stands with irregular structure

Biodiversity aspects are commonly taken into account in today's forest management. It has a great impact on the structure of forests. Mixed stands and broadleaved tree species are favoured, retention trees are left in regeneration areas, and compartments are delineated according to landscape. The above mentioned silvicultural practices increase the irregularity of stand structure. Increase in the number of tree species, uneven spacing of trees within a stand, more irregular size distribution of trees, and uneven shape of stand compartments serve as examples of the sources of irregularity.

Due to restrictions in the modelling data, the reliability of the simulation models presented in this document decreases with the increase of irregularity of within-stand structure (Figure 21). Therefore, cautiousness is needed in interpreting the simulation results of the stands with uneven structure. One of the most actual and challenging tasks for further growth and yield modelling is to expand the applicability of models towards more diverse growing conditions.

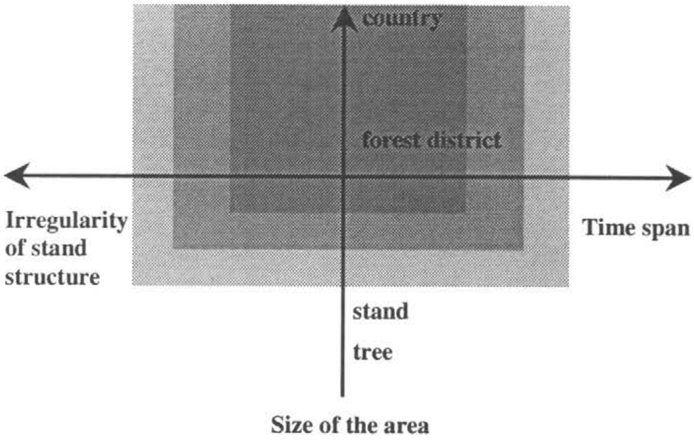


Figure 21. Schematic figure about the applicability of models used in forest management planning. The darker is the background the more reliable is the model behaviour.

References

Burkhart, H. E. 1992. Tree and stand models in forest inventory. Proceedings of Ilvessalo Symposium on national forest inventories. (IUFRO S4.02). Finnish Forest Research Institute. Research Papers 444: 164–170.

Gertner, G. 1987. Approximating presicion in simulation projections: an efficient alternative to Monte Carlo methods. Forest Science 33: 230–239.

Cajander, A. K. 1909. Über Waldtypen. Acta Forestalia Fennica 1: 1–175. [In German].

Gustavsen, H. G., Roiko-Jokela, P. & Varmola, M. 1988. Kivennäismaiden talousmetsien pysyvät (INKA ja TINKA) kokeet. Suunnitelmat, mittausmenetelmät ja aineistojen rakenteet. Metsäntutkimuslaitoksen tiedonantoja 292. 212 p. [In Finnish].

Haapala, P. 1983. Luonnonpoistuman ennustaminen puun kuolemistodennäköisyysmallilla. Metsäntutkimuslaitoksen puuntuotoksen tutkimussuunta. Stencil. 33 p. [In Finnish].

Henttonen, H. 1990. Kuusen rinnankorkeusläpimitan kasvun vaihtelu Etelä-Suomessa. Summary: Variation in the diameter growth of Norway spruce in southern Finland. (Dissertation). Helsingin yliopiston metsänarvioimistieteen laitoksen tiedonantoja 25. 88 p.

— 2000. Growth variation. In: Mälkönen, E. (ed.). Forest condition in a changing environment – the Finnish case. Kluwer Academic Publishers. Forestry Sciences 65: 25–32.

Hökkä, H., Alenius, V. & Salminen, H. 2000. Predicting the need for ditch network maintenance in drained peatland sites in Finland. Kunnostusojitustarpeen ennustaminen ojitusalueilla. Suo – Mires and Peat 51(1): 1–10.

Huikari, O. 1952. Suotyypin määritys maa- ja metsätaloudellista käyttöarvoa silmällä pitäen. Summary: On the determination of mire types, especially considering their drainage value for agriculture and forestry. Silva Fennica 75. 22 p.

— 1974. Site quality estimation on forest land. In: Proceedings of International Symposium on Forest Drainage, 2nd – 6th September 1974. Jyväskylä – Oulu, FInland. p. 15–24.

Hynynen, J. 1993. Self-thinning models for even-aged stands of Pinus sylvestris, Picea abies and Betula pendula. Scandinavian Journal of Forest Research 8(3): 326–336.

— 1998. Mitä käyttäjän tulisi tietää MELAn kasvumalleista. Julkaisussa: Nuutinen, T. & Mäkkeli, P. (toim.). MELA98 ja tietojärjestelmälaajennukset. MELA-käyttäjäpäivät 7.5.1998 Helsingissä. Metsäntutkimuslaitoksen tedonantoja 713: 18–29. [In Finnish].

Kangas,A. 1997. On the prediction bias and variance of long-term growth predictions. Forest Ecology and Management 96: 207–216.

Keltikangas, M., Laine, J., Puttonen, P. and Seppälä, K. 1986. Vuosina 1930–1978 metsäojitetut suot: ojitusalueiden inventoinnin tuloksia. Summary: Peatlands drained for forestry 1930–1978: Results from surveys of drained areas. Acta Forestlia Fennica 91. 54 p.

Kukkola, M. & Saramäki, J. 1983. Growth response in repeatedly fertilized pine and spruce stands on mineral soils. Communicationes Instituti Forestalis Fenniae 114. 55 p.

Kuusela, K. & Salminen S. 1969. The 5th National Forest Inventory in Finland. Communicationes Instituti Forestalis Fenniae 69(4): 1–72.

Laasasenaho, J. 1975. Runkopuun saannon riippuvuus kannon korkeudesta ja latvan katkaisuläpimitasta. Summary: Dependence of the amount of harvestable timber upon the stump height and the top-logging diameter. Folia Forestalia.233. 20 p.

— 1982. Taper curve and volume functions for pine, spruce and birch. Communicationes Instituti Forestalis Fenniae 108: 1–74.

Lappi, J. 1997. A longitudinal analysis of height/diameter curves. Forest Science 43(4): 555–570.

— & Bailey, R. L. 1988. A height prediction model with random stand and tree parameters: an alternative to traditional site index methods. Forest Science 34: 907–927.

Meteorological yearbooks of Finland 1972–1974. Finnish Meteorological Institute.

Mielikäinen, K. & Gustavsen, H. G. 1992. The empirical basis for tree and stand modelling in Finland. In: Nyyssönen, A., Poso, S. & Rautala, J. (eds.). Proceedings of Ilvessalo Symposium on National Forest Inventories, Finland 17–21 August 1992. Metsäntutkimuslaitoksen tiedonantoja 444: 179–184.

Mowrer, H. T. 1990. Estimating components of propagated variance in growth simulation model projections. Canadian Journal of Forest Research 21(3): 379–386.

Niemistö, P. 1997. Ensiharvennuksen ajankohdan ja voimakkuuden vaikutus istutetun rauduskoivikon kasvuun ja tuotokseen. Metsätieteen aikakauskirja – Folia Forestalia 4/ 1997: 439–454. [In Finnish].

Ojansuu, R. & Henttonen, H. 1983. Kuukauden keskilämpötilan, lämpösumman ja sademäärän paikallisten arvojen johtaminen Ilmatieteen laitoksen mittaustiedoista. Summary: Estimation of the local values of monthly mean temperature, effective temperature sum and precipitation sum from the measurements made by the Finnish Meteorological Office. Silva Fennica 17(2): 143–160.

— , Hynynen, J., Koivunen, J. & Luoma, P. 1991. Luonnonprosessit metsälaskelmassa (MELA) – Metsä 2000-versio. Metsäntutkimuslaitoksen tiedonantoja 385. 59 p. [In Finnish].

Päivinen, R., Nousiainen, M. & Korhonen, K.T. 1992. Puutunnusten mittaamisen luotettavuus. Summary: Accuracy of certain tree measurements. Folia Forestalia 787. 18 s.

Penttilä, T. & Honkanen, M. 1986. Suometsien pysyvien kasvukoealojen (SINKA) maastotyöohjeet. Metsäntutkimuslaitoksen tiedonantoja 226. 98 s. [In Finnish].

Prosser, R., Rashbash, J. & Goldstein, H. 1991. ML3 Software for Three-level Analysis. Users' Guide for V.2. Institute of Education, University of London. 142 p.

Raulo, J. & Leikola, M. 1974. Studies on the annual height growth of trees. Communicationes Instituti Forestalis Fenniae 81(2): 1–19.

Reineke, L.H. 1933. Perfecting a stand-density index for even-aged forests. Journal of Agricultural Research 46: 627–638.

SAS Institute Inc. 1989. SAS/STAT User's Guide, Version 6, Fourth Edition, Volume 2 Gary, NC. 846 p.

Siitonen, M., Härkönen, K., Hirvelä, H., Jämsä,J., Kilpeläinen, H., Salminen, O. & Teuri, M. 1996. MELA Handbook 1996 Edition. The Finnish Forest Research Institute. Research Papers 622. 452 p.

Valtakunnan metsien inventoinnin (VMI7) kenttätyön ohjeet. 1977. Metsäntutkimuslaitos, Metsänarvioimisen tutkimusosasto. 59 p. [In Finnish].

Varmola, M. 1993. Viljelymänniköiden alkukehitystä kuvaava metsikkömalli. Summary: A stand model for early development of Scots pine cultures. Folia Forestalia 813. 43 p.

Tomppo, E., Henttonen, H. & Tuomainen, T. 2001. Valtakunnan metsien 8. inventoinnin menetelmä ja tulokset metsäkeskuksittain Pohjois-Suomessa 1992–94 sekä tulokset Etelä-Suomessa 1986–1992 ja koko maassa 1986–1994. Metsätieteen aikakauskirja 1B/2001: 99–248. [In Finnish].

Tonteri, T., Hotanen, J-P. & Kuusipalo, J. 1990. The Finnish forest site type approach: ordination and classification studies of mesic forest sites in southern Finland. Vegetatio 87: 85–98.

Total of 37 references

Model restrictions in Mela-System

In order to avoid illogical predictions in cases when input of the model is outside the limits of modelling data, some restrictions are used for input variables.

1 Restrictions to the of input variables of the tree basal area growth model

1.1 Tree diameter

The following minimum and maximum values for tree diameter used as input variables in tree basal area growth model are applied in Mela-System. If the actual value of tree diameter is outside the following limits, then its value is set to the limit as the input of the model.

Site/Tree species	Minimum diameter (cm)	Maximum diameter (cm)
Mineral soils		
Scots pine	1.0	29.0
Norway spruce	1.1	41.0
Silver birch	1.1	40.0
Other deciduous tree species	1.1	40.0
Peatlands		
Scots pine		60.0
Deciduous tree species		45.0

1.2 Stand dominant height

If stand dominant height is less than 4 meters on mineral soils, then the value of H_{dom} equal to 4 m is applied in tree basal area growth model.

2 Restrictions to predicted tree basal area growth on mineral soils

2.1 Minimum growth of small trees

The lower limit is set to basal area growth of small trees with height under 5 meters. Predicted growth is restricted to be greater or equal to this limit, which is obtained in the following manner:

If predicted basal area growth of a small tree is less than 15 cm^2, then the predicted growth is replaced by the new value (ig_{small}):

$ig_{small} = -3.0 + 0.015*TS$,

where TS = temperature sum.

2.2 Growth prediction of trees growing on low productive mineral soil sites with annual average yield is less than 0.1 m^3 (WASTE)

If land use class is WASTE, then growth is 50 % of growth on site with land use class is SCRUB. First, growth is predicted assuming that land use class is SCRUB, and then the predicted growth is multiplied with 0.5.

3 Restrictions to predicted tree basal area growth on drained peatlands

3.1 Minimum growth of small trees

The lower limit is set to basal area growth of small trees with diameter under 5 cm. Predicted growth is restricted to be greater or equal to this limit, which varies according to tree species as follows:

- Scots pine and Norway spruce: $ig_{min} \geq 6$ cm^2
- deciduous tree species: $ig_{min} \geq 4$ cm^2.

3.2. The effect of forest fertilizations on peatlands

Data from permanent sample plots of 8th National Forest Inventory were used as modelling data of growth models for peatlands. The considerable proportion of drained peatlands has been fertilized during the growth period of the modelling data. However, NFI data do not include any documentation about the possible fertilizations. Thus, the measured growths of NFI sample plots include the effect of fertilization. This fertilization effect included in growth predictions is taken into account with the help of the growth coefficients presented in the following table. The coefficients are based on statistics of forest fertilization areas on different sites, and on the results of the growth response after fertilizations. In Mela-System, the final growth prediction is obtained by multiplying the predicted growth with these coefficients.

Tree species: site class	Southern and Central Finland: Forest districts 0-15	Northern Finland: Forest districts 15-
Scots pine:	Coefficient	
K-Sites	0.9852	0.9852
R-Sites I, II	0.881	0.930
R-Sites III, IV	0.910	0.9434
R-Sites V, VI	0.971	0.971
Norway spruce: all site classes	0.9852	0.995
Deciduous tree species: all site classes	0.978	0.978

4 Restrictions to predicted tree basal area growth on undrained peatlands

4.1 Site specific restrictions

The number of sample plots on undrained peatlands was so few in the modelling data that separate models were not constructed for those sites. To predict growth for undrained peatlands, correction coefficients for models 35–37 were estimated based on the undrained peatlands in the calibration data of NFI8. To ensure that the level of the predicted growth is consistent with the empirical knowledge on the growth level on undrained peatlands, the following additional coefficients are applied to multiply the predicted tree basal area growth obtained with the models 36 (Scots pine), 36 (deciduous trees) and 37 (Norway spruce) (Tables 28–30).

Further, undrained spruce swamps (K-sites in Table 25) are always classified as SCRUB (low productive land with annual yield between 0.1 and 1 $m^3 ha^{-1}$) or forest land.

Main site group and peatland site type		Land use class	
	Forest land (F)	SCRUB (S)	WASTE (W)
K-sites:		Coefficient	
1: Lhk (F), VLK/KoLK (S)	1.0	0.7	
2: Rhk (F), RhSK (S)	1.0	0.7	
3: MK KgK (F), VSK (S)	0.7	0.7	
4: PK (F), PsK (S)	0.7	0.7	
P-sites and N-sites			
1: VLR (S), RLR, VL, RiL (W)	0.5	0.5	0.4
2: RhSR (F,S), RhSN, RhRiN (W)	0.6	0.5	0.4
3: KR (F), VSR (S), VSN (W)	0.6	0.5	0.4
4: KgR (F), PsR, LkR, TSR, VkR (S), LkN (W)	0.6	0.5	0.4
5: IR (F), TR (S)	0.6	0.5	0.4
6: RaR, KeR, RaN (W)	0.4	0.4	0.4

4.2 Maximum growth of large trees

The maximum allowable tree basal area growth for trees over 25 cm in diameter is for

- for conifers: $ig_{max} = 6.0$
- for deciduous trees: $ig_{max} = 4.0$.

4.3 Undrained peatlands with land use classes SCRUB and WASTE

If land use class is SCRUB, and tree diameter is between 10 and 15 cm, then the final tree basal area growth estimate (ig_{final}) is obtained as follows:

- for conifers: $ig_{final} = 6.0 + (((15.0 - d)/5.0)*(ig_{pred}-6.0))$,
  where ig_{pred} = growth predicted with models 35 (pine) and 37 (spruce)
- for deciduous trees: $ig_{final} = 4.0 + (((15.0 - d)/5.0)*(ig_{pred}-4.0))$,
  where ig_{pred} = growth predicted with models 36.

If land use class is SCRUB, and tree diameter is over15 cm, then the maximum allowable tree basal area growth (ig_{max}) is for

- for conifers: $ig_{max} = 6.0$
- for deciduous trees: $ig_{max} = 4.0$.

The above-mentioned restrictions are in force also when land use class of undrained peatland is WASTE, and site type class is equal to VI (cf. Table 25).

5 Restrictions to the calibration effect

The effect of tree basal area growth calibration is restricted in the following manner:

- If calibrated growth is less than 50 % of the growth prediction before calibration, then calibrated growth prediction is set to 50 % of the predicted growth before calibration
- If calibrated growth is more than 150 % of the growth prediction before calibration, then calibrated growth prediction is set to 150 % of the predicted growth before calibration
- Calibration is not in force, if tree diameter is less than 2 cm.

ISBN 951-40-1815-X
ISSN 0358-4283
Hakapaino Oy 2002