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Growth Models for Young Stands

Development and evaluation of growth models for commercial forests in Sweden

Kenneth Nyström

SWEDISH UNIVERSITY OF AGRICULTURAL SCIENCES

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Abstract

In long-term forest management planning systems, growth simulators are important. Through growth simulation the consequences of different silvicultural regimes can be evaluated, and suitable management schedules be chosen. This thesis deals with different aspects on growth of trees in young stands, i.e. stands between 0.5 and 8 metres height. The overall aim is to improve the accuracy of growth simulation in young stands in Sweden.

The thesis comprises five papers, dealing with three main topics: (i) site productivity, (ii) evaluation of predictive models for basal area and height increment of single trees, and (iii) uncertainty in growth predictions.

In the first study, 91 Norway spruce (*Picea abies,* (L.) Karst.) plantations in northern Sweden were investigated. Site index was estimated using current Swedish practices, and the expected yield was estimated based on the site index assessments. The study showed that there is a bias in the Swedish system for site index classification, and that this bias may lead to severe underestimates (about 35 %) of the yield capacity of Norway spruce stands in the area.

In the second study, based on Scots pine (*Pinus sylvestris*, L.) plots, the stability of site index estimates between stands established at different points of times was analysed. The study did not reveal any major trend in estimated site indices in stands on similar sites, established at different points of time. However, there was a significant difference in site index between stands established before and after 1940. A conclusion was that these differences were due to differences in stand establishment and silvicultural practices.

Two studies have been conducted, where new models for predicting basal area and height increment of single trees in young stands are presented. In some of these models, tree age was not included as a predictor variable. Although an accurately determined age of a young tree generally contributes to the accuracy of the growth forecast, the uncertainty in age determination makes the contribution of age as a predictor variable doubtful. Common for all models evaluated was that site productivity was modelled indirectly through the incorporation of temperature sum and variables describing site conditions, such as vegetation type and soil moisture.

In one of the studies, the uncertainty of yield forecasts was modelled by specifically accounting for the random components of growth. Through Monte-Carlo simulation, distributions of yield estimates rather than point estimates were predicted. Single-tree growth models were derived using a mixed model regression approach. An example is given regarding how the estimated distributions can be used in a Bayesian approach to forest management planning, whereby the precision of the yield estimates will influence what decisions should optimally be carried out.

Keywords: growth modelling, height and basal area increment, site productivity, uncertainty of predictions, young stands.

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Contents

Appendix

Papers I - V

This thesis is based on the following papers, referred to by the corresponding Roman numerals in the text:

I. Elfving, B. and Nyström, K. 1996. Yield Capacity of Planted *Picea abies* in Northern Sweden. *Scandinavian Journal of Forest Research 11: 38-49.*

II. Elfving, B. and Nyström, K. 1996. Stability of site index in Scots pine plantations over year of planting in the period 1900-1977. EFI, Research Report No. 5, page 71-77. *In:* Growth Trends of European Forests. H. Spiecker, K. Mielikäinen, M. Köhl and J.P. Skovsgaard (Eds.). Springer-Verlag Berlin Heidelberg 1996. ISBN 3-540-61460-5.

III. Nyström, K. and Kexi, M. 1997. Individual tree basal area growth models for young stands of Norway spruce in Sweden. *Forest Ecology and Management 97: 173-185.*

IV. Nyström, K. and Ståhl, G. 2001. Forecasting probability distributions of forest yield, allowing for a Bayesian approach to management planning. *Silva Fennica* (in press).

V. Nyström, K. 2001. Models for Predicting Single Tree Height Increment in Young Stands in Sweden. Manuscript.

Papers I, II, III, and IV are reproduced with the kind permission of the publishers.

Introduction

Forests are long-lived dynamic biological systems that are continuously changing due to biotic and abiotic conditions. It is often necessary to project these changes in order to obtain relevant information for sound decision-making. Forest management decisions are made based on information about both current and future resource conditions. Inventories made at one instant in time provide information on current state as well as input data for further analysis of potential future states. Growth and yield models are tools for capturing and describing the essential elements of stand dynamics in a relatively small set of mathematical equations. The growth simulators, or growth models, usually employ a set of functions to describe the stand development over time, i.e., stand establishment, growth, and mortality, under various conditions and actions (e.g., Vanclay 1994, Peng 2000). The main uses of growth models include inventory updating, evaluation of silvicultural options, and management planning (e.g., Burkhart 1990). In Sweden today, the most important use of growth models is within long-term forest management planning systems.

In Sweden, about 35 percent of the productive forest area consists of stands younger than 30 years (Anon. 2000). Clear-cutting has, since the 1950s, become the dominating harvesting and regeneration practice. At present (1995) about 200 000 hectares, slightly less than 1% of the forest area, are regenerated annually in Sweden (Nilsson and Gustafsson 1999). Of this area, approximately 55 percent is regenerated artificially by planting or sowing, 40 percent by natural regeneration using seed trees, while 5 percent of the area is left without any treatment.

In forest management planning, it is essential that accurate predictions of regeneration success and development of young stands can be made. Results of operational regeneration in terms of stand density, species mixture and height evenness vary considerably depending on regeneration practices and site conditions (c.f., Tiren 1950, Ackzell et al. 1994, Jonsson 1999).

At present, the HUGIN-system (Lundström and Söderberg 1996) and the Forest Management Planning Package (Jonsson et al. 1993) are the two major long-term forest management planning systems used at national and company levels in Sweden, respectively. The growth simulator for young stands in these systems was developed during a period when the management of the commercial forests in Sweden aimed at producing even monocultures (Dahlin et al. 1997, Anon. 1998).

The work with growth and yield modelling is a process of constantly meeting new challenges. New knowledge, and continuously changing conditions, environmental as well as managerial, requires new or improved models. Thus, there is a need to increase the knowledge and improve the tools for growth and yield forecasts, applicable in long-term forest management systems in Sweden.

Some of the most important issues to address are (i) environmental changes leading to changed site productivity, and potential bias in the site index classification system, (ii) changed forestry practices, requiring modifications of existing growth simulators, and (iii) explicit modelling of the error terms in the growth and yield forecasts, making it possible to evaluate the accuracy of predicted forest states.

Site productivity

A basic assumption for many growth simulators is that future growth conditions will remain similar to those of the past, and thus yield prediction becomes a projection of past patterns of growth (cf., Kimmins 1990). The potential productivity of a site has often been regarded as given by nature and stable in a long-term perspective. However, environmental changes in the last decades, such as increasing global atmospheric CO_2-levels and atmospheric deposition of nitrogen, are likely to have an effect on forest ecosystems and result in site-related growth trends. According to Spiecker et al. (1996), a trend is a long-term change of a mean level, and growth trends are indicated by long-term site related deviations from expected growth. To determine possible growth trends, a reference growth describing the expected growth is needed. A reference is valid only when it represents the site and stand conditions as well as the management regime of the investigated forest for the given reference period.

The growth simulators used in the HUGIN-system, are based on site index according to the Swedish site-quality system (Hägglund and Lundmark 1977, 1981, Hägglund 1979). In inhomogeneous stands and on sites without trees, site index is assessed using functions based on site factors such as ground vegetation, location, elevation, slope, soil texture, soil moisture, and soil depth. However, one major problem with the Swedish site-quality system is that site index curves based on height development, on average indicate higher site indices in young stands than the corresponding estimates based on site factors (e.g., Tegnhammar 1992, Elfving and Nyström 1996).

Estimating site productivity, defined as maximum mean annual increment, including all stem volume produced during the rotation in a fully stocked and even-aged stand, is a major issue in forest growth and yield studies. Reliable estimates of site productivity are essential for accurate predictions of timber yield and meaningful simulation studies (Vanclay 1992a, Elfving and Nyström 1996). Site index estimates according to height-age curves for dominant trees have been commonly used to account for site related variation in increment models, but the use of such curves is restricted to certain conditions concerning the top height trees and the surrounding stand. Thus, new expressions for site productivity in growth models need to be developed.

Changed forestry practices

In the new Swedish forest policy, the environmental objectives are set to be of equal importance as those of timber production (Skogsstyrelsen 1994). This means that the requirements on silvicultural practises have changed, and thus the structure of forests will change as well. The result is that the young stands will be more heterogeneous than they used to be. In turn, this puts requirement of higher flexibility of growth and yield models for the regeneration phase as well as the rest of the rotation period. Effects of the changed forestry practices with increased demand on environmental considerations in order to promote the biological diversity, among other things involve that:

- The amount of natural regeneration increases. The proportion of natural regeneration has increased from about 15% during the 1980's to almost half of the regenerated area 1993-1994. After this peak, however, the proportion has decreased to about 40% (Nilsson and Gustavsson 1999).
- Changed strategies in silviculture, involving regeneration methods better adapted to the site conditions. This might lead to increased amounts of edge zones between patches with different regeneration. Since the beginning of the 1980s the proportion of regeneration areas smaller then 2 hectares (ha) has increased from 19% in 1984 to 25% in 1996. The big regeneration areas, i.e. areas larger than 20 ha, have decreased from 34% to 27% during the same period of time (Anon. 1999).
- Nature conservation trees from the old stands are retained at the regeneration cuttings to increase biodiversity and increase the variation in the new stand. Another trend is a reduced use of pre-regeneration cleaning in the establishment of the new stand as well as changed instructions for cleaning, where a more varied tree species composition and height variation is allowed compared to earlier practices (Nilsson and Söderberg 1999)

These changes in forestry practices will most likely lead to an increased proportion of stands that are more heterogeneous with respect to height-, diameter-, age- and species distribution, compared to stands that were established during 1950-1980. Consequently, the development of tools to estimate growth and yield in different kinds of stand structures has become a topic of interest.

Growth and yield models

Growth refers to the increase in size, typically of an individual tree or of all trees within a stand, over a specified time period. Yield refers to the final size of the tree or stand attribute of interest (e.g. volume or basal area). In a growth model, increment is commonly expressed as a function of tree, stand and site factors. The number of factors used to model the increment varies. In most practical cases, only a limited set of factors affecting growth is generally available, thereby limiting the scope of how growth models can be constructed. Growth and yield models may consist of a single equation or a set of interrelated sub-models, which together comprise a simulation system.

A distinction is generally made between mechanistic process models and empirical growth models (e.g., Peng 2000). With the former kind of models, the factors that cause growth are modelled explicitly, while in the empirical models any indirect connections between growth and measurable quantities of trees, stands, and sites are utilised. With the empirical models, the purpose is generally to derive models that provide high accuracy in practical forecast applications. This thesis deals entirely with this category of models.

Growth and yield models have been classified according to the level of detail in the state description, i.e. on the basis of the primary growth unit and on the spatial considerations in the model (e.g. Munro 1974, Burkhart 1990, Vanclay 1994, Peng 2000). Traditionally, growth models are classified as stand or single tree models. Stand-level models use (and predict) aggregated values of stand parameters such as basal area, mean diameter, and volume per hectare, stems per hectare, top height, etc. Stand models are usually simple and robust, and require relatively little information to simulate stand growth and development (Peng 2000). To obtain a higher degree of resolution when this type of models is used, a projected state can be distributed on, e.g., different diameter classes using some empirical distribution function (e.g., Baily and Dell 1973, Pettersson 1992, Lindsay et al. 1996). A specific kind of growth models is the stage-based matrix models, wherein the probabilities of trees or stands to transit between different states are modelled (e.g., Solomon et al. 1986, Pukkala and Kolström 1988).

Model choice depends on the purpose of a study, the stand conditions, and the availability of relevant data. In regular, pure even-aged stands, density and hence competition can be evaluated on a stand level basis in terms of stem volume, basal area, number of stems, etc. In heterogeneous stands, on the other hand, single tree models have a potential to better capture the differences in growth conditions between different parts of a stand (e.g., Söderberg 1986, Wykoff 1990, Monserud and Sterba 1996).

Growth modelling for young stands

In most growth simulators for management planning, it is necessary to simulate the regeneration success and the early development of the established seedlings before the actual growth modelling can start. Models for predicting the regeneration status after clear cutting have been developed by, e.g., Elfving and Hägglund (1975), Alder (1979), and Belcher et al. (1982). Elfving (1977, 1992) estimated the regeneration success in terms of the expected stocking at 12 years total age. To do this, regression functions depending on regeneration method and site conditions were developed.

To account for the random variability in regenerations, a common approach is to use hierarchical stochastic simulation to predict the regeneration success (e.g., Ferguson et al. 1986, Schweiger and Sterba 1997).

Once the regeneration success is estimated, tree or stand characteristics must be assigned before the growth modelling can start. In the case of Elfving (1977, 1992) sample plots with tree data from a specific survey of young stands were assigned to target stands, based on the estimated regeneration success.

With data from already established young stands, or with assigned data following the estimation of regeneration success, the development of young stands is the next step within long-term forecasts. Within the Swedish HUGIN system (Bengtsson 1981, Hägglund 1981), the development of young trees is modelled through height-age relationship curves for main crop trees, developed by Elfving (1982). The height development of an individual tree on a plot is derived from functions based on the height development of the main crop trees, the social position of the specific tree, and stand density. Nyström (2000) developed new functions using height increment as dependent variable, based on the principles of potential growth of main crop trees and a modifier function for single tree increment. Variables such as diameter, age, and volume of the trees are modelled using static relationships between these features and height (Nyström and Söderberg 1987, Näslund 1940,1947, Andersson 1954).

Models for predicting height and diameter development in young Norway spruce stands in southern Sweden were developed by Nyström and Gemmel (1988), with the specific purpose of predicting the development of supplementary planted trees within gaps in regenerations. Näslund (1986) developed a partly stochastic model for predicting damage and mortality during the early development.

Although a stand has been established, recruitment of small trees to the stand continues. Thus it is necessary to model the in-growth of new trees to make accurate forecasts. Usually, this is done by estimating the number of trees that will pass a certain diameter or height threshold value during a certain period of time. Models of this kind have been developed by, e.g., Moser (1972), Ek and Monserud (1974), Vanclay (1992b), and Shifley et al. (1993).

When the stand has reached a specific threshold value of diameter and height, generally there is a shift from growth models for young stands to growth models for established stands (e.g., Söderberg 1986). In the Swedish HUGIN system, this shift takes place at approximately 8 metres height.

Uncertainty in growth predictions

Since the 1980s, a new field within growth and yield research has emerged. This field relates to techniques for explicit modelling of the random elements of growth, and using the estimated variance and covariance components not only for improving the point estimates of future forest states, but also for predicting the accuracy of the yield estimates.

In traditional growth models for individual trees, the unexplained variation normally is about 40-50% of the expected value of the predicted increment. This error component is, however, not uncorrelated between trees and between successive growth periods, an assumption that is made, consciously or unconsciously, when the functions are applied in a traditional way. Several studies have shown that systematic errors occur if the random errors are not considered (e.g., Gertner 1991, Kangas 1996, 1997) and that the course of development in multi-layered stands will be erroneously predicted (e.g., Stage and Wykoff 1993). Early studies in this field were conducted in Sweden within the HUGIN-project (Holm 1980).

It is often valuable to have explicit measures of the uncertainty in predictions. Using the above-mentioned techniques, the accuracy can be expressed in terms of distributions of forecast values, and management decisions can be made considering the uncertainty of the data (e.g., Ståhl et al. 1994).

The technique to explicitly model the random errors also has the advantage that the model parameters can be more effectively estimated by considering the correlation in data (e.g., trees from the same plot, or successive increment data from the same tree). This has been shown by e.g. Lappi (1986), Gregoire (1987), and Gregoire et al. (1995).

Objectives

The main objective of this thesis was to develop predictive models for single tree growth in young stands, applicable in long-term forest management planning systems in Sweden. The species concerned in the thesis were Scots pine (*Pinus sylvestris*, L.), Norway spruce (*Picea abies* (L.) Karst.) and birch spp. (*Betula pendula* Roth. and *Betula pubescens* Ehrh.).

The specific objectives of the papers (I-V) were:

I. To investigate existing tools for site classification with new data, and to improve the estimates of spruce productivity in northern Sweden.

II. To investigate if environmental changes have affected site productivity.

III. To compare the predictive capability of functions based on unbiased site index estimates with functions using merely site and location variables as indicators of site quality, and to develop models for prediction of basal area increment for individual trees in young Norway spruce stands.

IV. To develop and evaluate a technique for the prediction of probability distributions of forest yield, rather than point estimates, based on growth models for single trees.

V. To develop single tree height increment models for young stands, that are better adapted to current silvicultural practices than the previous ones.

Material and Methods

Material

The results of the analyses in this thesis (Papers I-V) are based mainly on data obtained from the HUGIN- young stand survey (Elfving 1982). In the analysis of the site index estimations (I-II) also data from operational and experimental plantations have been used.

The HUGIN-young stand survey

In the period 1976-1979, permanent plots were established in 799 young stands, with a mean height about 3 m, distributed all over Sweden (Fig. 1). The stands were selected by stratified random sampling among objects inventoried earlier, 1960-1968, in regular regeneration surveys carried out by the Swedish National Board of Forestry. Treatment history records were documented for these regeneration areas.

The selection of objects from these regeneration areas to the HUGIN young stand survey aimed at achieving a good representation of regenerations by method of establishment, geographical area, site fertility, stand age (years after regeneration), and stocking.

The selected stands were established after clear cutting mainly between 1950-1970. Approximately 40% were naturally regenerated, 10% sowed, and 50% planted by Norway spruce and Scots Pine (Fig. 1).

In each stand, five circular sample plots of 100 m^2 size were randomly laid out. Each plot was marked and the position of every tree mapped.

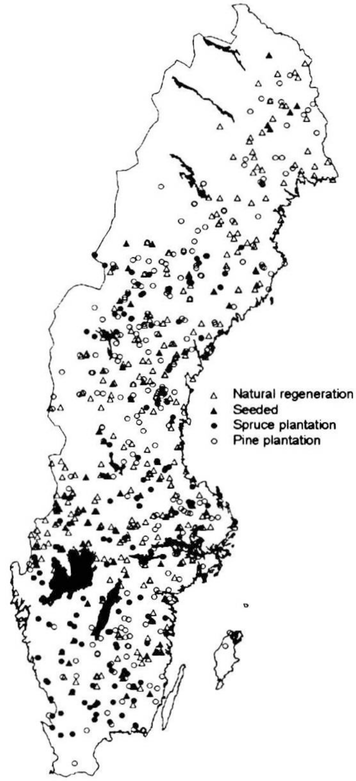

Figure 1. Geographical locations of stands in the HUGIN young stand survey, by method of stand establishment.

Total height and diameter at breast height (1.3 m) were measured, and damage registered. Diameter was measured by callipering. The height was measured with a telescopic pole, with the display unit at breast height.

Damages were classified according to damaging agent, position in the tree, and severity with respect to expected future growth. On dense plots a dimension limit was established and trees below the limit were assessed within the section 1-2 m from the plot centre, only.

A sub-set of trees was selected at random from the tree list on each plot. On these sample trees, age at breast height (1.3 m) was generally determined from whorl count or, occasionally, ring count on an increment core. The social position of a tree was subjectively classified as main crop tree, subsidiary tree, or standard. Main crop trees were selected, approximately 16 regularly distributed in a fully stocked plot, mainly among vigorous dominant and co-dominant trees.

Data describing site characteristics were recorded according to the Swedish site quality system (Hägglund and Lundmark 1981). Each plot was described in terms of the site factors soil type, soil texture, depth of the soil layer, soil moisture type, soil water flow class, slope, and exposition. The vegetation in the field and bottom layers was assessed as vegetation type.

After five years, in the period 1981-84, the plots were revisited. It was registered whether the trees remained or had been removed by pre-commercial thinning. On remaining trees, height, diameter and damage were assessed as earlier.

Operational and experimental plantations

For the study on spruce productivity (Paper I) 91 operational and experimental plantations in the age interval 27-46 years were sampled. The stands were located between latitudes 62-65 °N and altitudes 130-620 m.a.s.l., and they were among the oldest spruce plantations existing in the area.

For the site index study on pine (Paper II) both data from the HUGIN-young stand survey and from experiments in plantations and sowings established with varying objectives were used. The experiments comprised 197 stands in whole Sweden established on mesic sites in different years during the period 1886-1977. Plot size varied between 0.1-0.5 ha. Data from the last measurement were used, generally performed in the period 1977-1990.

Methods

Regression analysis (e.g., Draper and Smith 1981) has been the dominating method used for the analyses and for the derivation of growth functions within this thesis. In studies I-III, standard multiple regression techniques were applied, while in the other studies mixed linear (IV) and nonlinear (V) regression (e.g., Searle 1971, Littell et al. 1996) was applied.

Applying mixed models, the random components of growth could be explicitly treated, while with traditional models, all residual variation is contained within one single residual term. The term "mixed" is due to the fact that the mixed regression model contains both fixed parameters and random parameters.

In study IV, random stand and plot-within-stand parameters were included in the model. In study V, a random plot parameter was included. By doing this, the parameters of the growth functions were estimated with higher precision than would otherwise had been the case, since the dependencies in data were treated correctly. With traditional regression, this is generally complicated. Moreover, by separating the random variation on different terms it was possible to make separate estimates of variance components. These components were used as a basis for Monte-Carlo simulations, whereby probability distributions of future yield were predicted (paper IV). To make the simulations, the covariance of the random terms between different tree species had to be estimated. A method was developed whereby the covariances could be estimated based on the model assumptions made.

Results

Reliability of existing tools for site classification (Paper I)

The first study (Paper I) focuses on the reliability of existing tools for site classification, and on the yield capacity of Norway spruce plantations in central northern Sweden.

On average, the difference between SIH (classification according to height curves) and SIS (classification according to site factors), using the Swedish site quality system (Hägglund and Lundmark 1981), was found to be 4.6 m. Higher values were obtained when SIH was used (Fig. 2a). The difference was larger on poor sites than on rich sites. No differences in mean values of SIH were found in data from two different points of time, separated by 10 years (1979 and 1989).

Tegnhammar (1992) suggested a modification of the Swedish system for site index estimation. Using Tegnhammar's modified functions, the relationship between SIH and SIS turned out to be much better (Fig. 2b). On average for all plots, the difference between SIH and SIS was not significantly different from 0 in this case.

Existing growth models (Ekö 1985, Söderberg 1986) were applied to stand data to predict future growth. The mean annual increments were, on average, 20% lower when site index was assessed as SIS as compared to when it was assessed as SIH. The bias implies that the potential yield of planted spruce in northern Sweden might be underestimated by 35%. (i.e. according to the existing site index system a difference of 4.6 m in site index results in 35 % difference in potential yield.)

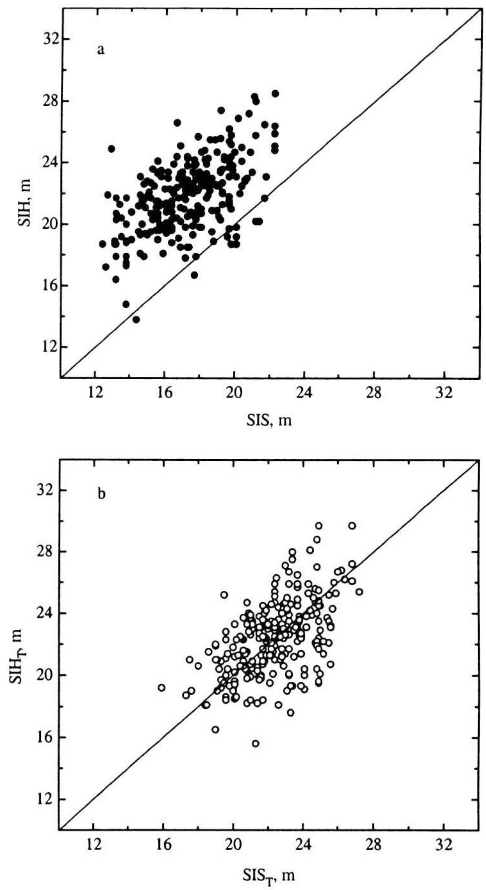

Figure 2. Pair-wise comparisons of different site index estimates. (a) The relationship between estimates of SIH and SIS (●). (b) The relationship between SIH_T and SIS_T estimates (○), where the index T denotes estimation using functions by Tegnhammar (1992).

Has site productivity changed? (Paper II)

This study aimed at detecting long-term site productivity changes, by analysing site index changes during the last century. To discern changes in site productivity from impacts of changes in silvicultural management regimes (cf., Spiecker et al. 1996), the height development of dominant trees was used as an indicator. This parameter is assumed to be less affected by management than other growth parameters (Assmann 1961).

Site index was assessed using the height curve systems of Hägglund (1974), SIH, and Elfving and Kiviste (1997), SIEK. Changes in site index over time were analysed using multiple regression analysis with point of time for stand establishment as one of the independent variables.

For pine plantations from the HUGIN survey of young stands (dataset 1), no significant trend in site index over year of stand establishment was found (Fig. 3).

In the second data set - the permanent sample plots - an annual increase of site index in the range of 0.01-0.02 m $year^{-1}$ (SIH, SIEK) was found for stands established between 1900 and 1970 (Fig. 4.). However, the main difference seemed to be that stands established before 1940 had lower site index than those established after 1940.

In conclusion, plantations established after 1940 indicated 0.8 m higher site index than older plantations.

Besides this sharp increase no significant trend could be detected. The sudden increase was thought to be an effect of changed silvicultural practices.

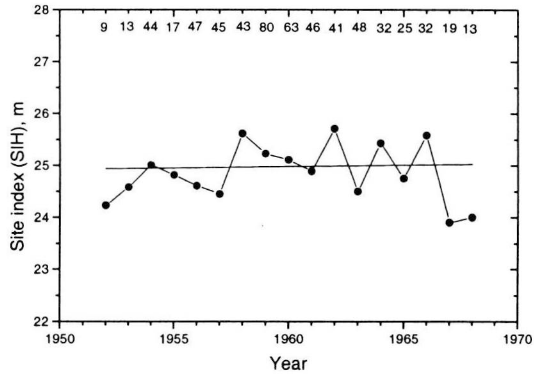

Figure. 3. General trend over time (—) and residuals (--•--) in site index (SIH) for different years of stand establishment (Function F1 in paper II). The number of plots in different years is indicated below the upper frame in the figure.

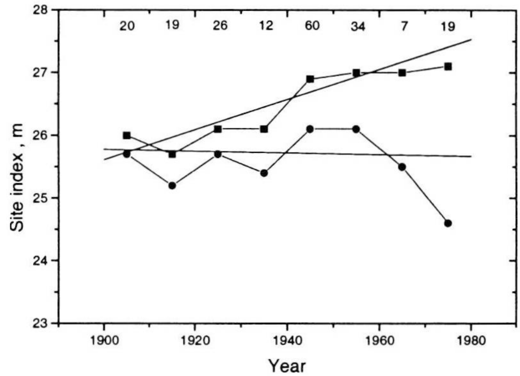

Figure. 4. General trend over time (—) and residuals (-•- SIH, -▪- SIEK) in site index for different years of stand establishment (Function F2, F3 in paper II). The number of plots in different years is indicated below the upper frame in the figure.

Expressions for site productivity in growth models (Paper III)

The main objective of Paper III was to compare different approaches to include site fertility in growth models. Single tree basal area increment models were developed with different approaches; the goodness of the different approaches was evaluated by means of studying goodness-of-fit statistics from the regression analyses. The data used consisted of 146 Norway spruce plantations including 595 survey plots, selected from the HUGIN survey of young stands. The choice of Norway spruce for this study was mainly due to the availability of unbiased functions for site index estimation, of spruce, developed by Tegnhammar (1992).

An important finding in this study was that there are no apparent differences in fit statistics between regression functions for basal area growth prediction, when site index is included directly as an independent variable and when it is indirectly modelled using different site factors as independent variables. Distance dependent models were slightly better than distance independent models. The adjusted coefficient of determination (R_{adj}^2) increased from 0.77 to 0.79 in models with tree age and from 0.74 to 0.76 in models without tree age, respectively. Inclusion of tree age in the models increased the precision only slightly; the explained variation increased with approximately 3%.

With tree age in the models, the importance of including site variables decreased considerably. The effect of site index on the basal area increment was about 35% higher in the models without tree age than in those including tree age. The inclusion of a distance dependent competition index had an opposite impact to that of age; the effect of the site variables on the basal area increment increased in the distance dependent models.

New models for growth in young stands (Papers III-V)

The models developed within these studies predict basal area (Papers III-IV) or height increment (Paper V) from commonly used tree and stand variables, which makes it possible to use them in the long-term forest management planning systems currently in use in Sweden. Common for most models was that site quality was incorporated through temperature sum, defined as the summation of all daily mean temperature values exceeding the threshold temperature +5°C (Odin et al. 1983), and site factors such as vegetation type and soil moisture, rather than site index directly. One major reason for this is the problems with the Swedish system for site index estimation, as shown by Tegnhammar (1992). Common for the models also is that they have been derived using a mixed models approach (c.f., Searle, 1971) to account for dependencies in data.

Other important features of the new functions are:

- Independent variables are incorporated that makes the functions sensitive to edge effects and overstory trees in regenerations (Paper V). These features are important for the growth functions to work correctly in regeneration that have been the result of increased concern for biodiversity during the last decades.

- The growth functions are independent of age (Papers III and V), although the precision of the functions was shown to decrease slightly when age was left out. However, in practical applications age cannot be precisely determined for all trees due to the cost associated with such assessments.
- The functions do not require a judgement on what trees should be considered as main-crop trees. This feature makes the application of the functions more objective.

Prediction of probability distributions of forest yield (Paper IV)

In Paper IV, as well as in other studies in this thesis, mixed model regression analysis was applied for developing growth functions in young stands. By applying this method, the parameter estimates received higher precision due to a correct treatment of the dependencies in data. Moreover, estimates of variance components associated with different parts of the random error term were estimated. Provided the different random error terms follow some known probability distribution, growth forecasts can be made to predict probability distributions of future yield rather than point estimates.

The major objective of Paper IV was to outline and evaluate a procedure for making predictions of yield distributions following growth function estimation with a mixed models regression approach. Dependencies in data were due to measurements of several trees on several plots within the same stands. Thus, the random error component (at the tree level) was specified to consist of three terms, corresponding to a random stand effect, a random plot effect (within stand), and residual variation at the tree level. In general, the size of the variance components of the stand and plot effects were about 25% of the size of the variance of the residual term. Relatively high (>0.5) correlations between the random terms were found at the stand level between conifers and birch, and at the plot level between pine and spruce.

Through Monte-Carlo simulation, probability distributions of stand-level forest yield were estimated. In Fig. 5., the predicted distributions are shown, as well as the real yield outcomes (10-year projection period) in stands from the HUGIN survey of young stands. The results supported the hypothesis that probability distribution yield estimates can be constructed in the proposed way.

The method is sensitive to the number of simulations made in a specific stand. In Fig. 6., the relative standard error for the proportion observations falling in the median basal area class is shown, for different numbers of simulations. In this case, the basal area classes were 0.1 m^2ha^{-1} wide.

As an illustration of the kind of results that are obtained with this method, it is shown in Fig. 7., how the predicted within-stand probability distributions tend to be wider the longer the projection period is. The width of the distribution provides an estimate of the precision of the predicted yield.

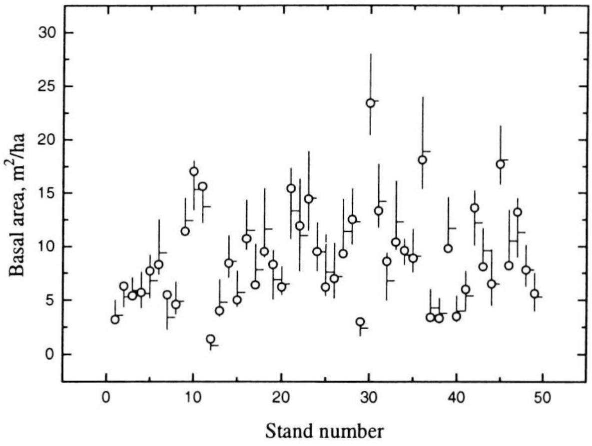

Figure 5. Observed (o) basal area within the predicted basal area distribution, given by the 5th, 50th, and 95th percentiles.

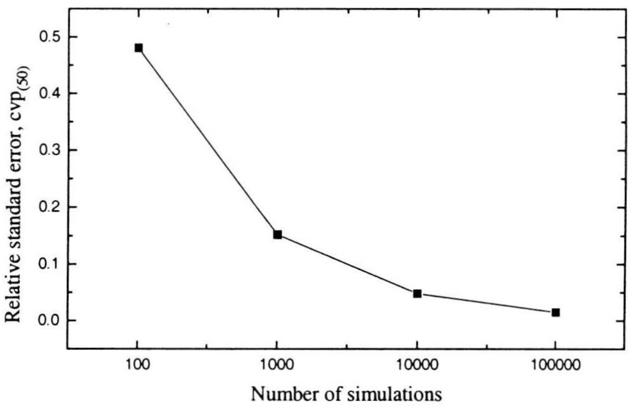

Figure 6. Relative standard error after different numbers of simulations, for the proportion of observations falling in the basal area class corresponding to the median, $cvp_{(50)}$, of the true distribution.

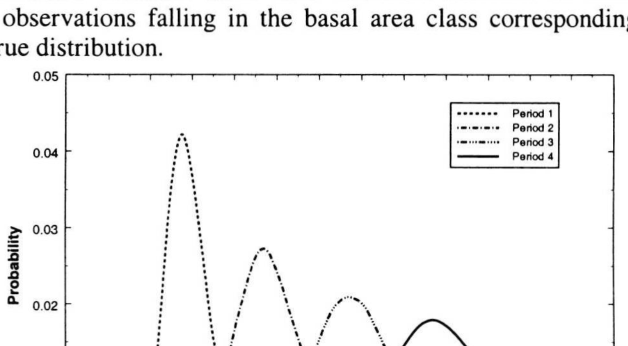

Figure 7. An example of a 20 years projection (four periods) of within-stand basal area probability distributions. The initial basal was area 6.4 m^2/ha

Discussion and Conclusions

The overall aim of the thesis was to develop and evaluate new predictive models for single tree growth in young stands, applicable in long-term forest management planning systems in Sweden. In the thesis, this aim has been broken down on three separate topics, which will be discussed below. The topics are site productivity, development of new growth models, and uncertainty in growth predictions.

Site Productivity

The studies on site productivity (Papers I and II) formed parts in a study of growth trends in European forests (Spiecker et al. 1996). Most studies in that project indicated an increasing growth level in recent decades, although no single reason could be distinguished. Increasing atmospheric CO_2-level, nitrogen deposition, as well as changed land use and silvicultural methods, were proposed as causes for the trend.

In the Swedish case, the large difference between SIH and SIS (4.6 m) found in the study of northern spruce plantations (Paper I) was interpreted mainly as a silvicultural effect. The site factor based functions, used to estimate SIS, were developed from data acquired in naturally regenerated and generally selectively logged spruce forests, where the top height trees often were recruited from liberated advance growth. The early development of these trees was probably hampered, indicating lower site indices. The top height development of plantations could be expected to follow the site index curves. This was confirmed, in paper I, by the study of plots measured both in 1979 and 1989. SIH did not change significantly during this period. Also, the study in Paper II on SIH in pine plantations established in different decades, indicated that top height development in plantations really follows the site index curves.

The difference between methods for estimating site productivity causes confusion. Tegnhammar (1992) constructed a correction system for estimation of site index in spruce stands, in which stand age was included. He argued that the level of the site index value is of less importance, while it is the ranking of sites according to productivity that matters. However, as Leary (1985), cited by Vanclay (1992a), stated: "what began as an interim solution (site index) to a difficult problem (a direct measurement of site fertility) should not now be called the solution to the original problem". The correlation between height development and stem volume growth is strong but not perfect (cf.., Assmann 1961, Hasenauer et al. 1994). It seems better to directly include primary site variables in growth functions, rather than using the indirect measure site index. This philosophy was used in Papers III-V.

New growth models

The inclusion of site variables directly in the growth models is a common practice in the case of uneven-aged stands. Single tree growth simulators for irregular stands without the use of site index and age as predictors, have previously been developed and implemented in, e.g., the Stand Prognosis Model (Stage 1973). Site factors like habitat type, geographic location, elevation, slope, and aspect have been directly incorporated into the prediction equations by Wykoff and Monserud (1988), Wykoff (1990), and Monserud and Sterba (1996). The present growth models (Papers III-V) used a similar approach to incorporate the site fertility. Site effects were characterised by temperature sum (Odin et al. 1983), vegetation type and site properties mainly describing soil moisture content (Hägglund and Lundmark 1981).

The strong relationships between temperature sum and productivity have been demonstrated by, e.g., Morén and Perttu (1994), and Fries et al. (1998). The temperature sum is principally calculated from the variables latitude and altitude. By replacing the latter static variables by temperature sum, it might to some extent be possible to analyse the potential effects of a changing climate (cf., Fries et al. 1998).

The idea behind including vegetation type is that the soil nutrient regime often is correlated with the presence or absence of certain indicator species or vegetation associations (e.g., Cajander 1926, Ellenberg 1988, Wilson et al. 2001). However, the field layer vegetation is by no means stable over the rotation period of a stand; it depends to some extent on the stand density, causing a shift of vegetation association from young to old stands. Tegnhammar (1992) compared the distribution of vegetation types within different stand age classes using data from the Swedish NFI, collected 1983-1987. One finding was that in young stands the dominating vegetation type was thin grass (mainly *Deschampsia flexuosa*), while in older stands the V*accinium myrtillus*-type dominated. Thus, in the presented models the vegetation association "Medium", included both the above vegetation types. In the original site index system by Hägglund and Lundmark (1981), the two vegetation types generally lead to roughly the same site index values.

Although the simple description of site fertility used in the models may have some shortcomings, residual analyses indicated that developed models were well adapted to a wide range of site conditions.

One objective for this thesis was to develop growth models that explicitly can account for the effects of the "new" silviculture, i.e. retained trees in the regeneration. From this perspective, the data used are not perfect. Investigated stands were mainly established in the 1950s and the 1960s. The silvicultural practises of that time were different from today's practices. Some of the methods used today e.g. planting of containerised seedlings and broadleaves, are not represented. The methods of site preparation and the genetic constitution of the planting stock also have changed.

However, although the material has some limitations, it does include saplings (young trees) growing close to standards and close to stand boundaries. In the new height increment functions for single trees (Paper 5) the effects of standards were included by a variable describing the density of the standards on the plots. The effect of standards outside the plot, or close to boundaries of an old stand was significant only for Scots pine. The standards generally consisted of seed trees of Scots pine, they were not left to promote biodiversity. Thus, the data give weak support for effects on the regeneration of nature conservation trees other than pine.

A simple simulation revealed that the mean height development was reduced about 18 % during a 10 year period (6-16 total age) in a Scots pine plantation with standards compared to estimated height without standards. However, the long-term consequences on the production have not been analysed.

A negative influence of seed trees and shelter trees on height development for pine and spruce seedlings has earlier been shown by e.g. Hagner (1962). It is recommended based on field trials (Kubin 1998), that seed trees should be removed within 4 years to not reduce the height increment of the growing regeneration. Niemistö (1998) shows plant establishment and height development of plants on different distances from seed trees of Scots pine. The number of plants was about 30-40 % lower close to the seed trees compared to 10 metres from seed trees. The height increment was reduced up to a distance of 15 metres from a seed tree.

An important additional shortcoming of the material is that it only describes the development of the regeneration after clear cuts. Growth functions for regeneration in shelter-wood forestry (e.g., Koistinen and Valkonen 1993, Örlander and Karlsson 2000), and similar types, are still lacking. One finding in these above referred studies was that the initial tree size of the advance growth is important for the future development. The height position of a tree, i.e. the height of a subject tree compared with other trees on a plot, is determined quite early in the development of a stand (cf. Elfving, 1975, Nilsson and Albrektson 1994) and usually remains rather stable (e.g. Ruha et al. 1997).

Initial size, i.e. height and basal area, are the most important predictor variable in the growth models evaluated in this thesis. When age was included as an independent variable in the growth models, the effects of most site variables decreased. The reason is that the combination of age and tree size reflects the earlier growth rate and thus indirectly the site conditions and competitive status of the tree. The correlation is high over short periods but will probability fade away in a longer perspective. Thus the exclusion of tree age is justified in functions for long term predictions. Also, the uncertainty (or high costs of) in age determination in a practical application makes the contribution of age as a predictor variable doubtful.

The effect on growth of climatic variation between single years was not taken into account in the growth models. The relatively long increment period (five years), and the wide temporal range of the study material (obtained between the 5-year periods 1976-1981, 1977-1982, 1978-1983, and 1979-1984) were supposed to smooth the annual variation in weather. Residual analyses did not indicate any significant trends over annual ring indices (Jonsson and Stener, 1986).

To sum up the functions developed are judged to fit the purpose to give realistic estimates of growth in young stands under various stand and site conditions following clear cut as practised in today's forestry.

Uncertantity in growth predictions

All growth predictions are uncertain. Traditionally, this uncertainty has seldom been acknowledged. Rather, the forecasts have been carried out in terms of point estimates of forest yield, ignoring the large errors potentially present in such predictions.

In this thesis, it is advocated that probability distributions of yield rather than point estimates be predicted. A straightforward Monte-Carlo approach for deriving this kind of estimates is derived (paper IV) and evaluated. An advantage with this approach is that the uncertainty in predicted states can immediately be determined from the width of the predicted distribution. Moreover, predictions of this kind can be very useful in Bayesian decision support systems.

Correct derivation of variance components, to be used as a basis for the simulations, turned out to be problematic. One major problem is the measurement errors that are almost always present in data of the kind used to derive growth functions. Provided that these measurement errors do not show any systematic trends, they pose little or no problem in traditional (point estimate related) growth models. However, when yield forecasts are made as in Paper IV, it becomes very important to separate between "pure" random errors and measurement errors. If the latter errors are included in the variance components, the resulting error terms used in the simulations will be too large. Not only will this lead to too wide predicted distributions, but it might also lead to biased forecasts due to non-linearities in the growth functions (cf., Gertner 1991).

Provided functions of this kind are properly derived and applied, they have a potential to better capture the natural variation in future states. With a traditional approach, only the mean levels will be described, and it may also be the case that predictions of this kind are biased (e.g., Kangas 1997).

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