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INFORMATION SYSTEM OF DENDROMETRIC MODELS AND DATA A TOOL FOR MODELING OF FOREST GROWTH

TAKSEERMUDELITE JA ANDMESTIKE INFOSÜSTEEM PUISTU KASVUKÄIGU MODELLEERIMISEKS

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CONTENTS

LIST OF ORIGINAL PUBLICATIONS 6
ABBREVIATIONS 8
1. INTRODUCTION 9
2. REVIEW OF LITERATURE 13
  2.1. Types of growth models 13
  2.2. Empirical data and outlier detection 14
  2.3. Modeling stand level growth 15
  2.4. Growth models in Estonia 16
  2.5. Research needs 18
3. AIMS OF THE STUDY 19
4. MATERIAL AND METHODS 20
  4.1. Forest Modeling Information System 20
    4.1.1. Forest growth and yield tables 20
    4.1.2. Forest research plots 21
  4.2. Modeling stand level growth 24
    4.2.1. Estimating potential density 24
    4.2.2. Forest growth models 25
    4.2.3. Stand growth simulation combinations 28
  4.3. Modeling single tree survival 30
5. RESULTS 34
  5.1. Forest Modeling Information System 34
    5.1.1. Concept of the Forest Modeling Information System 34
    5.1.2. The database of forest growth and yield tables 34
    5.1.3. The database of forest research plots 37
    5.1.4. The database of empirical dendrometric formulas 38
  5.2. Forest growth models based on ForMIS 40
    5.2.1. Estimating potential density 40
    5.2.2. Stand level growth models 41
    5.2.3. Comparing different combinations of model components 42
  5.2.4. Single tree survival models 44
6. DISCUSSION 46
7. CONCLUSIONS 50
REFERENCES 53
SUMMARY IN ESTONIAN 63
ACKNOWLEDGEMENTS 66
PUBLICATIONS 69
CURRICULUM VITAE 142
ELULOOKIRJELDUS 144
LIST OF PUBLICATIONS 145

LIST OF ORIGINAL PUBLICATIONS

The thesis is based on the following papers; in the text references to them are given in Roman numerals. The papers are reproduced by the kind permission of the publishers.

I Hordo, M., Kiviste, A., **Sims, A.** 2006. The network of permanent sample plots for forest growth in Estonia. *DVFFA – Sektion Ertragskunde, Jahrestagung* 2006. 115-121.

II **Sims, A.**, Hordo, M., Kangur, A., Kiviste, A., Jõgiste, K., Gadow, K.v. 2009. Tracking disturbances induced changes in stand development on irregular measurement intervals in the Järvselja forest experiments. *Baltic Forestry*. 15 (2): 00-00. [accepted]

III **Sims, A.** 2005. Takseermudelite andmebaasi loomisest. [The database of forest management models.] *Metsanduslikud Uurimused (Forestry Studies)*, 43: 124-131. [In Estonian with English summary].

IV Kangur, A., **Sims, A.**, Jõgiste, K., Kiviste, A., Korjus, H., Gadow, K.v. 2007. Comparative modeling of stand development in Scots pine dominated forests in Estonia. *Forest Ecology and Management*. 250: 109-118.

V **Sims, A.**, Kiviste, A., Hordo, M., Laarmann, D., Gadow, K.v. 2009. Estimating Tree Survival: a Study based on the Estonian Forest Research Plots Network. *Annales Botanici Fennici*. 46: 336-352.

The contributions from the authors to the papers are as follows:

	Paper				
	I	II	III	IV	V
Original idea and structure of paper	MH	KA, AK, **AS**	**AS**	AK, **AS**	KA, **AS**
Data, methods and study design	**All**	AK, **AS**, KA	**AS**	AK, **AS**	**All**
Data collection	**All**	AK, AS, KA, MH	**AS**	AK, **AS**, KA	**All**
Data analysis	**All**	AS, AK	**AS**	**All**	KA, **AS**
Preparation of manuscript	**All**	**All**	**AS**	**All**	**All**

AK – Ahto Kangur, **AS – Allan Sims**, HK – Henn Korjus,
KA – Andres Kiviste, MH – Maris Hordo, All – all authors of the paper.

ABBREVIATIONS

ENFRP	The Estonian forest research plots network
JLTFE	Järvselja long-term forest experiments
OSMFEP	Forest experimental plots on abandoned oil-shale mining areas
FNRRP	Forest naturalness restoration research plots
ForMIS	Forest Modeling Information System
HNLS	Calculated tree height
HNLSr	Calculated relative tree height
H1	Mean height of upper tree storey
D	Tree diameter
Dr	Tree relative diameter
D1	Quadratic mean diameter of upper tree storey
BAL	Basal area of larger trees
BALr	Relative basal area of larger trees
HEG5	Competition index by Hegyi (1974) calculated within 5 m radius
HEGH	Competition index by Hegyi (1974) calculated within radius of 40% of the stand mean height
TTJ	Relative sparseness based on Tjurin (Krigul, 1969)
SpDr	Relative tree diameter of spruce
TS	Tree species

1. INTRODUCTION

Growth and yield studies have a long history in forestry. With a history of over 250 years, yield tables for pure stands are the oldest models (e.g., Paulsen, 1795; Cotta, 1821) in forestry science and forest management (Porte and Bartelink, 2002). In the early 1850s, Central European foresters used graphical methods to model the growth and production of forests (Peng, 2000). Growth and yield tables, based on chronosequences of stands throughout entire rotations, were the main growth models until the middle of the 20th century; therefore, those were constructed for important tree species in Europe (Skovskaard and Vanclay, 2008).

Forest modeling is based on empirical data, on which hypotheses are verified and mathematical models are created; therefore, forest research as a discipline based an empirical data involves the development, calibration and validation of models (Nilson, 1992). According to recent forest literature reviews (Pretzsch et al., 2002; Hasenauer, 2006; Skovsgaard and Vanclay, 2008), traditional growth and yield tables and equations approximating them have been replaced with more sophisticated stand growth simulators during recent decades.

Models are being used for understanding and describing forest "behavior" in the past and present but more often for predictions of the future (Vanclay, 1994). Knowledge of forest development is used in forest management planning in the form of forest and management models. The availability of such knowledge is necessary for decision making; therefore, the need for the electronic archiving and sharing of forest models seems to be clear (Rennolls et al., 2002). The use of information and computer technology is rapidly increasing and, therefore, opportunities have increased in the analysis, storage and dissemination of information throughout the world. Thus, information systems are and will be significant tools in practical forestry.

The initial idea to create a database of empirical dendrometric formulas was presented in Estonia by Nilson (1992) and the first prototype of the database was built (Nilson, 2000). In 2000, a software application was designed for public use with a graphical user interface (Sims, 2001) for managing empirical formulas. The next step was a web-based public database, where description of models was made available on a website

(Sims, 2004). Only a few other databases which share empirical formulas are available for public use. For example, the University of Kassel has created the Register of Ecological Models, which is a meta-database for existing mathematical models in ecology and environmental sciences (Benz et al., 2001), and the University of Greenwich has created the Register of Forest Models (Rennolls et al., 2002).

The Institut Européen de la Forêt Cultivée (IEFC) in France has compiled the Register of models for forest, where a model has wider meaning: a model can be an empirical formula or even a growth simulator. The register was chosen by COST Action FP0603 "Forest Models for Research and Decision Support in Sustainable Forest Management" (COST, 2009) as a system for sharing forest models.

A wide range of forest models has been developed in the last decades, during which concerted efforts have been made in forest modeling. However, many of them describe narrow problem areas, having more practical output or legislative significance, and have been created for practical use without properly published documentation. Later it is difficult to determine in which circumstances the model is useful, especially how valid a decision based on such models can be. Additionally, there are a number of models for which no documentation exists at all (Benz and Knorrenschild, 1997).

Forest growth and yield tables are valuable data at the stand level; therefore, those are collected by many researchers. In 1997 at the European Forest Institute many tables, mainly from Western Europe, were collected by Gert-Jan Nabuurs and Mart-Jan Schelhaas, and based on those tables the public database "European Yield Tables" at the Joint Research Centre (http://afoludata.jrc.it/DS_Free/YT_intro.cfm) is now available. In Estonia, most of the this work is done by Professor Artur Nilson, who has collected and analyzed growth and yield tables and models for tree species growing in Estonia. His database has been further developed, and additional tables for different tree species from Western Europe have been appended by the author of the current study.

As growth and yield models are mainly developed on the basis of existing empirical data, the most appropriate modeling technique is selected by the level of detail of the available data and the level of resolution (Burkhard, 2003). The data needed for improvement and calibration of growth models can be obtained by continuous observation on permanent sample plots (also known as longitudinal studies) or by establishing chronosequences with temporary plots distributed over a wide range of forest site conditions, densities and ages (also known as cross-sectional studies). A compromise may be achieved with a system of interval plots (also known as a short-time series: a series which covers a short time). Since the measurement interval represents a period of undisturbed growth, it is possible to measure change rates as in a longitudinal study and at the same time cover a wide range of initial conditions as in a cross-sectional study (Glenn-Lewin and van der Maarel, 1992; Gadow and Hui, 1999).

Information technology has developed quite rapidly and it allows analysis and modeling of more data, faster than previously; therefore, forestry study has moved from stand level analysis to single tree level analysis (Hasenhauer, 2006). For analyzing and modeling forests in Estonia at the single tree level, the Estonian Forest Research Plots Network (ENFRP) began in the middle of 1990s (Kiviste et al., 2003; Kiviste and Hordo, 2003). When using empirical data, it is necessary to collect and digitize it, but with every step there is a chance for mistakes, and so errors accumulate. Therefore, an information system for managing data, including outlier detection and data validation, is a valuable tool. In order to manage the database and increase the quality of the sample plots data, a data quality assurance system has been developed (Hordo, 2004; Hordo et al., 2006).

To obtain a better overview of forest experiments and data in different countries, the Northern European Database of Long-Term Forest Experiments (NOLTFOX, http://noltfox.metla.fi) has been set up, containing general information about forest experiments in Northern Europe and the Baltic countries. In 2001, the first version of NOLTFOX was launched for public use.

Box and Draper (1987) stated that "all models are wrong, but some of them are useful." This means that models must be validated before using them. Forest research involves the development, calibration and validation of models; however, effective model evaluation is not a single, simple procedure, but comprises several interrelated steps that cannot be separated from each other or from the purpose and process of model construction (Vanclay and Skovsgaard, 1997). Several statistical tests, as well as visualization, may be useful, both with data used for model calibration and with data used for independent evaluation of the model, though the validity of conclusions depends on the validity of assumptions and the application in question. These principles should be kept in mind throughout model construction and evaluation (Vanclay and Skovsgaard, 1997).

2. REVIEW OF LITERATURE

2.1. Types of growth models

Empirical models (Vanclay, 1994) (also called *statistical models* (Matala et al., 2003), *biometric models* (Pretzsch et al., 2008)) are developed aiming to predict growth and yield using statistical techniques, and calibrated for comprehensive data sets (Vanclay, 1994). Empirical forest growth models can be used directly for decision-making at the stand level. They are adequate for describing growth within a wide range of silvicultural practices and site conditions. Relatively simple data input requirements and accuracy in predicting growth have made them the principal yield models of forest management. However, this approach ignores potential changes in environment, genetics, site and silvicultural treatments that might occur from rotation to rotation (Bailey and Martin, 1996), since there is no link to underlying causes of productivity. Moreover, productivity is based on dominant/mean height rather than the capacity of the site to produce biomass (timber) and store carbon in an ecosystem.

Process-based models (Vanclay, 1994; Constable and Friend, 2000; Mäkelä et al., 2000) (also called *mechanistic models* (Vanclay, 1994; Constable and Friend, 2000; Mäkelä et al., 2000; Monserud, 2003)) are developed to model growth processes and fundamentals of productivity. They are mathematical representations of biological systems that incorporate our understanding of physiological and ecological mechanisms into predictive algorithms. They take into account plant responses to site factors at the physiological level either if they are manipulated by humans directly, such as fertilization, or indirectly, such as atmospheric carbon dioxide concentrations. For example, the effect of change in atmospheric carbon dioxide concentrations is manifested through the process of photosynthesis, at the scale of individual leaves. This primary effect changes growth rates, alters investment in growth above and below ground, and affects nutrient acquisition and concentrations in tissues. It also alters water relations, competitive interactions, rates of decomposition and microbial populations, insect feeding habits, and energy, nutrient, and water flow through the forest ecosystem.

Hybrid models (Monserud, 2003; Pretzsch et al., 2008) are developed from the complementary merging of well understood processes and reliable tree/stand empiricism aiming to create a process model for the manager, overcoming the shortcomings of both approaches to some extent. The improvement of both process-based and empirical models will lead to better hybrid models. There is a combination of causal (at the process level, such as: carbon balance, water balance, soil carbon cycling, soil carbon cycling) and empirical (at the higher stand level the model is empirical) elements.

2.2. Empirical data and outlier detection

Forest growth models can be developed using data either from permanent sample plots observed over long time periods (Monserud and Sterba, 1996), from temporary sample plots complemented with increment cores (Wykoff, 1990) or from short-term interval plots which represent a compromise between the two, producing one growth rate for a large number of initial states within a reasonably short period of time (Gadow et al., 1998). Examples of forest experiments conducted over more than a century, providing an uninterrupted series of observations, are the extensive permanent networks maintained by a number of European forest research institutes (Hasenauer, 2006).

In many data analysis tasks a large number of variables are being recorded or sampled. One of the first steps towards obtaining a coherent analysis is the detection of outlaying observations. Hawkins (1980) defines an outlier as an observation that deviates so much from other observations as to arouse suspicion that it was generated by a different mechanism. Barnet and Lewis (1994) indicate that an outlying observation, or outlier, is one that appears to deviate markedly from other members of the sample in which it occurs, similarly, Johnson (1992) defines an outlier as an observation in a data set which appears to be inconsistent with the remainder of that set of data.

Although outliers are often considered as an error or noise, they may carry important information. Detected outliers are candidates for aberrant data that may otherwise adversely lead to model misspecification, biased parameter estimation and incorrect results. It is therefore important to identify them prior to modeling and analysis (Williams et al., 2002; Liu et al., 2004). Effective outlier detection is the key analysis of the quality improvement procedure (Heo et al., 2006).

2.3. Modeling stand level growth

The purpose of using a growth model is to make reasonable predictions about tree growth and stand development, which may be achieved in different ways and at varying levels of detail, depending on the data available about the trees and the growing site. There has been considerable debate (Söderberg, 1986; Nabuurs and Päivinen, 1996; Hynynen et al., 2002; Pretzsch et al., 2002; Hasenauer, 2006) about empirical modeling of stand growth and yield processes:

- Models based on stand variables have been used for more practical purposes.

- Single-tree modeling leads to greater flexibility in attempting to use details of spacing.

The most common variables to describe stand level growth are height, diameter, basal area, density and volume.

According to the literature, to predict stand height growth at any given age different authors have used current age and height together as predictors (Hägglund, 1973; Tappo, 1982; Nilson and Kiviste, 1983; Kuliesis, 1993; Kiviste, 1997; Karlsson, 2000; Kasesalu and Kiviste, 2001; Palahi et al., 2004) and organic layer thickness of soil (Kiviste, 1997).

Diameter growth may be predicted from current age (Kiviste, 1997; Kasesalu and Kiviste, 2001), current diameter (Kiviste, 1997; Kasesalu and Kiviste, 2001; Kangur et al., 2007), current height (Kuliesis, 1993), relative density (Kuliesis, 1993), site index (Kangur et al., 2007) and current basal area (Kangur et al., 2007).

Basal area growth may be predicted from current basal area (Ekö, 1985; Kangur et al., 2007), current number of trees (Ekö, 1985; Kangur et al., 2007), age (Ekö, 1985; Bisenieks, 1975), site index (Ekö, 1985; Kangur et al., 2007; Bisenieks, 1975) and current diameter (Kangur et al., 2007).

Stand density may be predicted from current density (Gadow, 2003), current height (Gadow, 2003; Kangur et al., 2007) and current diameter (Kuliesis, 1993; Kangur et al., 2007).

Volume growth may be predicted from current age and height together as predictors (Gustavsen, 1977; Tappo, 1982; Nilson and Kiviste, 1983; Kuliesis, 1993; Kiviste, 1997), current height (Tappo, 1982), site index (Tappo, 1982), current volume (Gustavsen, 1977; Tappo, 1982; Kuliesis, 1993; Kiviste, 1997) and organic layer thickness of soil (Kiviste, 1997).

2.4. Growth models in Estonia

A considerable number of growth and yield tables have been developed by many authors in Estonia:

- for Scots pine (*Pinus sylvestris* L.) - Reim (1930), Muiste (1959), Gräzin (Krigul, 1969), Kasesalu (1969), Kiviste (Tappo, 1982);

- for Norway spruce (*Picea abies* L.) - Gräzin (Krigul, 1969), Kiviste (Tappo, 1982);

- for Silver birch (*Betula pendula* Roth.) - Henno (1959; 1965), Kiviste (Tappo, 1982);

- for black alder (*Alnus glutinosa* L.) - Haller (1932).

As empirical models, several stand growth models (Tappo, 1982; Kiviste, 1999a; b; Nilson, 2005) and some single-tree models (Jõgiste, 1998) have also been developed for stand growth prediction in Estonia. Only few authors have developed process-based forest models (Kull and Kull, 1989; Oja and Arp, 1997) in Estonia.

The algebraic difference equations by Kiviste (1999a; b) are being employed as general growth and yield prediction functions in practical forest management planning in Estonia. These models were developed from the type of stand growth equations presented by Cieszewski and Bella (1989). The model parameters were estimated using the data of the state forest inventory in Estonia in 1984-1993 (Kiviste, 1995; 1997). The average height, quadratic mean diameter at breast height, and the volume of 423,919 stands were grouped by forest site type, dominant tree species, stand origin (naturally regenerated or cultivated), and stand age-class (using five-year intervals). This grouping produced a total of 171 age-series of height, diameter, and volume. Data from young stands (under 20 years for coniferous and hardwood, and 10 years for deciduous forests), over-mature stands and outliers were excluded before the calculation.

Stand mean height (H_{t2}) at the desired age (t_2) can be calculated from the initial age (t_1) and height (H_{t1}) as follows:

$$H_{t2} = \frac{H_{t1} + dH + rH}{2 + 4 \cdot \beta H \cdot (t2^{-a}) / (H_{t1} - dH + rH)}$$

where a and b are constants,

$$\beta H = b - 493 \cdot \ln(OHOR + 1)\,, \tag{1}$$

$$dH = \beta H / 50^{a} \text{ and}$$

$$rH = \sqrt{(H_{t1} - dH)^{2} + 4 \cdot \beta H \cdot H_{t1} / t1^{a}}\ .$$

The stand quadratic mean diameter (D_{t2}) at the desired age (t_2) can be calculated as follows:

$$D_{t2} = \frac{D_{t1} + dD + rD}{2 + 4 \cdot \beta H \cdot (t2^{-a}) / (D_{t1} - dD + rD)}$$

where a and b are constants,

$$\beta D = b - 306 \cdot \ln(OHOR + 1)\,, \tag{2}$$

$$dD = \beta D / 50^{a} \text{ and}$$

$$rD = \sqrt{(D_{t1} - dD)^{2} + 4 \cdot \beta D \cdot D_{t1} / t1^{a}}\ .$$

The stand volume (V_{t2}) at the desired age (t_2) can be calculated as follows:

$$V_{t2} = \frac{V_{t1} + dV + rV}{2 + 4 \cdot \beta H \cdot (t2^{-a}) / (V_{t1} - dV + rV)}$$

where a and b are constants,

$$\beta V = b - 54348 \cdot \ln(OHOR + 1)\,, \tag{3}$$

$$dV = \beta V / 50^{a} \text{ and}$$

$$rV = \sqrt{(V_{t1} - dV)^{2} + 4 \cdot \beta V \cdot V_{t1} / t1^{a}}\ .$$

Kiviste's difference models (Eqs. 1, 2, 3) were developed from stands in which both natural and anthropogenic disturbances were included. The presumed maximum stand age in these models was fitted with the optimal rotation period of the dominant tree species.

2.5. Research needs

The existing growth and yield tables and growth equation systems in Estonia have been mainly developed for general growth and yield prediction for practical forestry at the stand level.

Neighboring countries have developed single tree growth models and Estonia has established the ENFRP for studying forest growth; therefore, it is necessary to concentrate study more at the single tree level growth modeling. At the Estonian State Forest Management Centre, a computer-based decision support system is being developed. Both adequate forest stand descriptions and stand growth and structure models are needed for the effective use of the system (Kiviste and Hordo, 2003).

COST Action FP0603 has stated (COST, 2009): *The main objective of the Action is to promote the developing of methodologies to improve forest models to support the sustainable management of forests. The Action will enhance the quality and consistency of forest growth models to simulate the responses of forests to alternative managerial and climate scenarios.* Estonia is a participant in the action; therefore, it is necessary to follow the action's aim and contribute in growth modeling for alternative managerial and climate scenarios.

3. AIMS OF THE STUDY

This doctoral thesis continues and extends the research I started with my M.Sc. study (Sims, 2003) and deals with developing a web-based tool for modeling forest growth and yield as well as systematization of empirical forest equations, advances in data management, collection of growth and yield tables and modeling forest growth at the stand level and individual tree survival.

The specific aims of the thesis are:

- To develop an information system for knowledge management and storage of empirical forestry data; implement data verification, validation and outlier detection for assessing and improving the quality of empirical forestry data (I).

- To study long-term sample plots with irregular intervals of measurements for compensating and completing missing data (II).

- To develop a method for systematizing dendrometric formulas and implementing it in web-based application (III).

- To develop growth models and compare simulation scenarios in Scots pine dominated forests in Estonia (IV).

- To analyze on the Estonian Forest Research Plots Network data the tree and stand levels variables affecting the tree survival probability in Estonian forests (V).

4. MATERIAL AND METHODS

4.1. Forest Modeling Information System

The aim of the Forest Modeling Information System (ForMIS) is to systematize and structure existing information that we have for modeling and predicting forest growth and yield in the Baltic Sea region.

The information system contains four different modules:

- forest growth and yield tables,
- forest experiment and sample plots data,
- forest equations,
- empirical dendrometric formulas.

4.1.1. Forest growth and yield tables

The term *yield* is used in forestry with a number of qualifiers, e.g., annual, intermediate, final, sustained, and financial (Brack and Word, 1997), and each of these has a special meaning in forest management. A yield table is mainly a tool for long term planning. It is a type of growth table with expected productivity/volumetric yield for a given age, site or crop quality and sometimes other indices, such as density. Yield tables usually refer only to even-aged stands and are summaries of expected yields tabulated by stand age, site index, etc. (Vanclay, 1994).

Data to prepare growth and yield tables may be obtained mainly from: permanent sample plots, temporary sample plots, and stem analysis. Permanent sample plot information is by far the most satisfactory on which to base yield tables. There are three main types of yield tables: normal, empirical and variable density:

- *Normal Yield Table* (Avery and Burkhard, 1983; Vanclay, 1994; Brack and Word, 1997) - a normal yield table is based on two independent variables, age and site, and applies to fully stocked stands. It depicts relationships between volume/unit areas together with other stand parameters and the independent variables. Since only two independent variables are involved, normal yield tables are conveniently constructed by graphical means. The density variable is held constant by attempting to select sample plots of a certain fixed density assessed as full stocking. Yields were generally tabulated by age and site index, but could also be presented as alignment charts (e.g., Reineke, 1927).

- *Empirical Yield Table* (Avery and Burkhard, 1983; Brack and Word, 1997) - in contrast to normal yield tables, empirical yield tables are based on average rather than fully stocked stands. This simplifies the selection of stands for sampling. The resulting yield tables describe stand characteristics for the average stand density encountered during the collection of field data.

- *Variable Density Yield Table* (Avery and Burkhard, 1983; Brack and Word, 1997) - the limitations listed above for normal and empirical yield tables led to the development of techniques for compiling tables with three independent variables, stand density being included as the third variable (hence the term variable density yield tables). Basal area/unit area, mean diameter or stand density indices are used to define the density classes. Such yield tables are particularly useful for abnormal stands, e.g., abnormal due to early establishment problems, insect and fungal attack, drought, fire, fluctuating demands for produce, etc.

4.1.2. Forest research plots

The history of empirical forest research in Estonia can be traced back to 19th century. The establishment of well-designed and documented field experiments for forest research purposes began after the establishment of the Järvselja Forestry Training and Research Centre (Figure 1) in 1921 (Mathiesen and Riisberg, 1932).

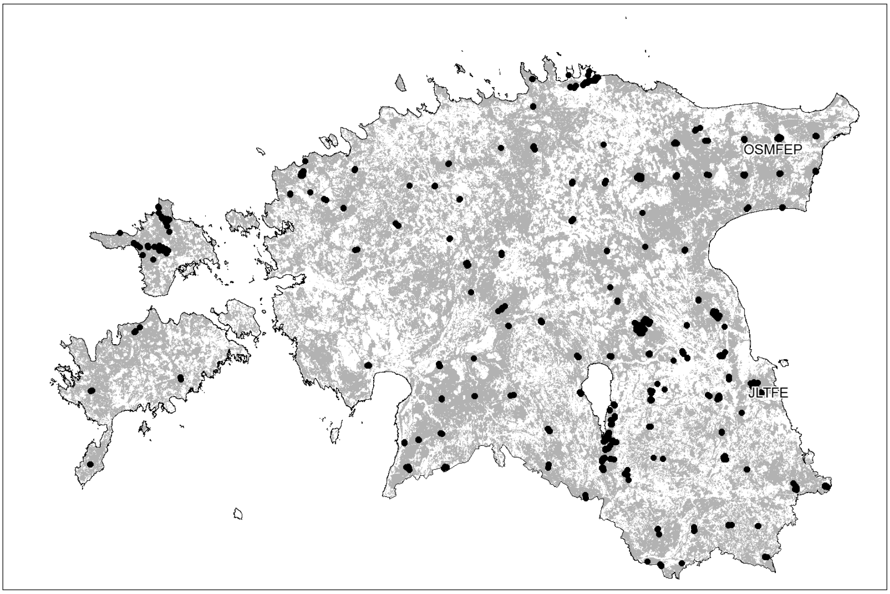

Figure 1. Location of forest research and experiments plots on forest map (grey area is forests, Peterson (2003)). The dots are the locations of the ENFRP and the FNRRP plots; locations of the OSMFEP and the JLTFE have labels.

Among the early long-term forest experimental series in Järvselja are growth and yield experiments initiated by Andres Mathiesen (Kasesalu, 2003) and thinning experiments initiated by August Karu and Lembit Muiste (Tullus and Reisner, 1998). Long-term forest growth and yield monitoring plots were established during the period 1922 to 1935. The rectangular experimental plots were relatively small covering between 400 and 600 m^2. The small plot size was compensated with a high number of replicates in the same stand. The experimental sites were selected such that all forest sites and dominant tree species in the Järvselja region were represented. The basic stand parameters were measured and trees on the plots were numbered.

Irregular measurement intervals are common in long-term measurement series on forest research plots in Estonia. They often occur when previously abandoned field plots are "revived", i.e., re-measured after long periods during which no observations were made. Thus, modeling annual tree growth and survival based on data with irregular measurement intervals requires specific methods within such "measurement gaps", as demonstrated by Nord-Larsen (2006).

Forest growth on the abandoned opencast oil shale mining areas (OSMFEP) has been studied on permanent sample plots established in 1970s-1980s under supervision by Elmar Kaar. Study area is located in Northeast Estonia (Figure 1). Sample plots are rectangular with a size from 500 to 2200 m^2. Diameter of all trees was measured in centimetres with a calliper at 1.3 m height from the ground level and the height was measured on sample trees in decimetres with a vertex. 12-20% of trees were randomly sampled for height measurements. Large trees had bigger probability to be sampled than smaller trees. Height of not sampled trees has been calculated from height-diameter relationship on plot. First measurements on sample plots have been done at stand age of 10-20 years. All plots have been re-measured with interval 5-10 years, each plot has been measured 3-5 times.

An Estonian forest research plots network (ENFRP) for modeling stand variables and construction of stand growth simulators, which require individual tree growth measurement series, was established in 1995 (Kiviste and Hordo, 2003). The spatial distribution of the plots is presented in Figure 1. The ENFRP covers the main forest types and the age ranges of typical commercial forests in Estonia; re-measurements on the permanent plots have been carried out at five-year intervals since 1995. Generally, the permanent forest growth plots are of circular shape, established with radii of 15, 20, 25 or 30 meters. The plot size depends on the forest age and density, such that, as a rule, in every plot there are at least 100 trees of the upper tree storey. In each plot, the polar-coordinates, the diameter at breast height, and defects were assessed for each tree. The tree height and height to crown base were measured for every fifth tree and also on dominant and rare tree species. The height to the first dry branch of old coniferous trees was also assessed.

Routine inspection of forest plot measurement data for outliers is necessary, because it provided information about the causes and consequences of measurement errors. For the detection of outliers, several statistical methods were applied (Hordo, 2004). Empirical distributions of most tree variables by species and storey were analyzed using Grubb's test, Dixon's test and the 4-sigma region method. Multivariate methods (height curves, residual diagnostics, and logistic regression) were used for detecting outliers in the interaction of several variables.

4.2. Modeling stand level growth

4.2.1. Estimating potential density

Gadow and Hui (1993) compared different methods for estimating the potential density of unthinned stands of *Cunninghamia lanceolata* from the southern region of China, including the approaches used by Goulding (1972), Sterba (1975) and Clutter and Jones (1980).

Such sophisticated estimation techniques are not needed in cases where long-term experiments had reached the limiting density. No live trees had been removed in the plots during the period 1926 to 1932 and again during the last 49 years (only the very smallest were harvested preemptively, i.e. assuming that they would die anyway). In this study, potential densities are analyzed on two unthinned experiment plots: M046_11_01 (pure pine stand) and M274_04_02 (pine/birch stand).

The relationship between the average tree size (increasing over time) and the number of live trees per unit area (declining over time) may be described by means of a so-called limiting line. A convenient model for this limiting relationship was used by Reineke (1933):

$$\mathrm{N} = a \cdot D^{b} \tag{4}$$

where N is the maximum possible number of trees per hectare, D is the quadratic mean diameter, a and b are constants.

In the case of a regular spatial distribution of the trees within a forest, the average distance between the trees may be estimated by the square root of 10,000 (square meters in one hectare) divided by the number of trees per ha. Hart (1928) proposed calculating the average distance between the trees in a forest with N stems per ha as the square root of the growing space. Nilson (1973) thus defined stand sparsity or distance between regularly placed trees as follows:

$$\mathrm{L} = \sqrt{\frac{10000}{N}} \tag{5}$$

where N is the number of trees per hectare.

Nilson (1973) proposed to estimate the potential density using the relationship Eq. 5 and argues (Nilson, 2006) that the most simple and logical relation is expected between variables of the same dimension.

$$\mathrm{L} = a + b \cdot D \tag{6}$$

where L is the stand sparsity (Eq. 5), and D is the quadratic mean diameter of the trees in a stand; a and b are empirical parameters.

4.2.2. Forest growth models

For this study, Scots pine dominated plots were selected from the database. The stand was considered as pine dominated if the proportion of pine volume exceeded 50%. The five-year changes in stand height (H), quadratic mean diameter (D), density (N), basal area (G) and volume (V) are presented in Figure 2. The selected plots were pure pine stands (at least 93% of trees on selected plots being pines).

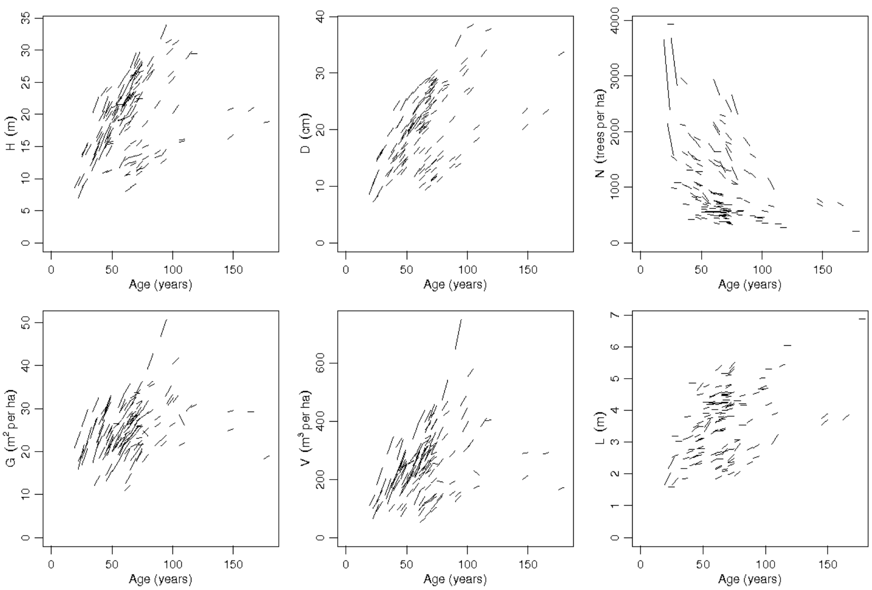

Figure 2. The five-year changes in pine stand height (H), quadratic mean diameter (D), density (N), basal area (G) and volume (V).

The predictor variables (quadratic mean diameter, stand density, basal area and sparsity) should be selected as closely as possible to the originally measured variables for reducing the error propagation, collinearity and variance inflation generated during derivation. The model forms should be selected according to the principles of model simplicity (i.e., parameter parsimony) (Burkhart, 2003) and biological realism (Gadow, 1996; Schmidt et al., 2006). The following equations were selected to describe the change in stand variables (growth and survival). The following model was used for stand basal area growth:

$$\Delta G_{t+5} = c_1 \cdot e^{(-c_2 \cdot D_t)} + c_3 \cdot H_{100} + c_4 \cdot G_t + \varepsilon \qquad (7)$$

where ΔG_{t+5} is the stand basal area increment in a five-year period, D_t is the stand quadratic mean diameter at the beginning of the five-year period, H_{100} is the site index (stand mean height at the age of 100 years), G_t is the stand basal area at the beginning of the five-year period, c_1, ..., c_4 are regression coefficients and ε is the error component. Stand basal area at the end of the five-year period (G_{t+5}) can be calculated as follows:

$$G_{t+5} = G_t + \Delta G_{t+5} \,. \qquad (8)$$

The following regression equation was applied to estimate the stand quadratic mean diameter increment ΔD_{t+5}:

$$\Delta D_{t+5} = c_1 + c_2 \cdot D_t + c_3 \cdot H_{100} + c_4 \cdot G_t + \varepsilon \qquad (9)$$

Stand quadratic mean diameter at the end of the five-year period (ΔD_{t+5}) can be calculated as follows:

$$D_{t+5} = D_t + \Delta D_{t+5} \qquad (10)$$

A classic approach to predicting stand density at the end of a five-year period is to estimate the proportion of survived trees (P_{t+5}) during the prediction interval (Vanclay, 1994). For this purpose, I used the logistic equation with logit-transformation:

$$P_{t+5} = \frac{e^{x}}{1+e^{x}} \tag{11}$$

with $x = c_1 + c_2 \cdot RD_t + c_3 \cdot D_t + c_4 \cdot H_{100} + \varepsilon$, where RD_t is the relative degree of stocking at age t. The number of trees per hectare at the end of the period (N_{t+5}) is calculated as follows:

$$N_{t+5} = N_t \cdot P_{t+5} \tag{12}$$

Following Nilson (1973), I fitted the separate tree distance based regression equation for estimating the development of variable L:

$$\Delta L_{t+5} = c_1 + c_2 \cdot D_t + c_3 \cdot H_{100} + c_4 \cdot G_t + \varepsilon \tag{13}$$

where ΔL_{t+5} is the five-year stand sparsity change. Stand sparsity at the end of the five-year period (L_{t+5}) can be calculated as follows:

$$L_{t+5} = L_t + \Delta L_{t+5} \tag{14}$$

The algebraic difference equation for predicting number of trees at given height published by Gurjanov et al. (2000) was used:

$$N_{t2} = 1000 \cdot \left[\left(\frac{N_{t1}}{1000} \right)^{c_1} + c_2 \cdot (H_{t2}^{c_3} - H_{t1}^{c_3}) \right]^{\frac{1}{c_1}} + \varepsilon \tag{15}$$

where N_{t1} is the number of trees per hectare at the beginning of the prediction period and N_{t2} is the number of trees per hectare at the end of the prediction period.

For describing basal area growth, the algebraic difference equation presented by Gadow and Hui (1999) was applied:

$$G_{t2} = G_{t1} \cdot N_{t2}^{(1 - c_1 \cdot H_{t2}^{c_2})} \cdot N_{t1}^{(c_1 \cdot H_{t1}^{c_2} - 1)} \cdot \left(\frac{H_{t2}}{H_{t1}} \right)^{c_3} + \varepsilon \tag{16}$$

where G_{t2} is the stand basal area at the end of the prediction period.

Correlation coefficient between observed and empirical values is high in case when values have wide range, where lowest and highest value can have even more than 100 times difference (e.g., stand density 100 or 10 000 trees per hectare). Thus, correlation coefficient is more descriptive calculating it between variables increments instead of the variables actual values.

4.2.3. Stand growth simulation combinations

The individual model components may be combined in many ways to predict the growth of stands as a whole. Six different simulation combinations were used to analyze model predictions of five important stand variables (height, quadratic mean diameter, stand density, basal area and volume) at the end of a five-year prediction period.

Stand quadratic mean diameter, basal area, stand density and sparsity have certain mathematical relationship; therefore, one variable can be calculated from others (Eqs. 17, 18, 19, and 20).

$$D = \sqrt{\frac{40000}{\pi} \cdot \frac{G}{N}} \tag{17}$$

$$G = \frac{\pi \cdot N \cdot D^2}{40000} \tag{18}$$

$$N = \frac{40000}{\pi} \cdot \frac{G}{D^2} \tag{19}$$

$$N = \left(\frac{100}{L} \right)^2 \tag{20}$$

$$G = \frac{V}{HF} \tag{21}$$

Table 1. The sequence of modeling steps and equations used in simulation combinations showing the sequence of calculation of projected variables with corresponding formula or formula reference of each simulation.

Combination	*Sequence of model components in the six simulation combinations*				
	1	2	3	4	5
D.G	H=Eq. 1	D=Eq. 10	G=Eq. 8	N=Eq. 19	V=Eq. 22
D.L	H=Eq. 1	D=Eq. 10	N=Eq. 20	G=Eq. 18	V=Eq. 22
D.N	H=Eq. 1	D=Eq. 10	N=Eq. 12	G=Eq. 18	V=Eq. 22
G.N	H=Eq. 1	G=Eq. 8	N=Eq. 12	D=Eq. 17	V=Eq. 22
Dif	H=Eq. 1	N=Eq. 15	G=Eq. 16	D=Eq. 17	V=Eq. 22
Est	H=Eq. 1	V=Eq. 3	D=Eq. 2	G=Eq. 21	N=Eq. 19

Table 1 shows the calculations of projected stand variables in these combinations. In simulation combinations, some stand variables were calculated using growth models (Eqs. 1, 2, 3, 8, 10, 12, 15, and 16) while other variables were calculated using static formulas (Eqs. 17 ... 22). The calculations of stand variables differ in simulation combinations in the use of different formulas or different calculation sequences. The simulations were carried out on the data on 142 intervals from the Estonian network of permanent growth and yield sample plots. Stand volume (Eq. 22), form height (Eq. 23) and relative degree of stocking (Eq. 24) in the simulations were calculated according to the Estonian forestry inventory practice.

$$V_t = HF_t \cdot G_t \tag{22}$$

$$HF_t = H_t \cdot (\text{-}0.0309 + \frac{2.5936}{H_t} + \text{-}0.0617 \cdot \sqrt{H_t} + 0.2107 \cdot \ln(H_t)) \tag{23}$$

$$RD_t = \frac{V_t}{-30.5946 + 16.6305 \cdot \mathrm{H_t} + 0.0254 \cdot \mathrm{H_t}^2} \tag{24}$$

The root mean square errors (RMSE) were calculated for each stand variables in all simulation combinations.

4.3. Modeling single tree survival

Figure 3 presents distributions of permanent sample plots analyzed in this study by forest site types, dominant species and stand development stages. Most plots are located in the nemoral and mesotrophic forest types. The site type 'others' includes alvar, transition bog, and fen forests. Pine stands are more represented than stands with other tree species. The alder forests include four black alder plots and five grey alder plots. Almost all groups by site type and by main species include stands of all development stages. Regarding stand age, it appears that the distribution of plots is quite balanced between the ages of 20 and 80 years (Figure 4). Four plots stocked with pine forests have an age of 150 years or more.

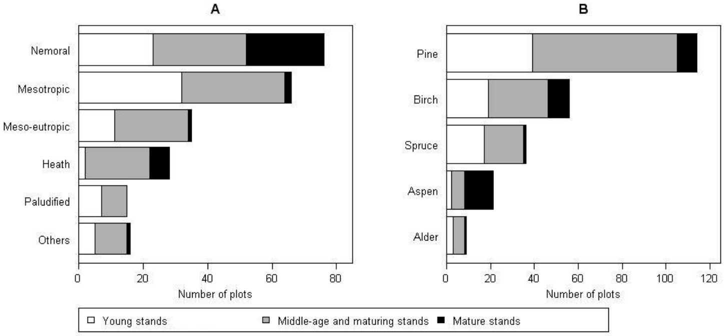

Figure 3. Distribution of plots by groups of (A) forest site types and (B) main tree species.

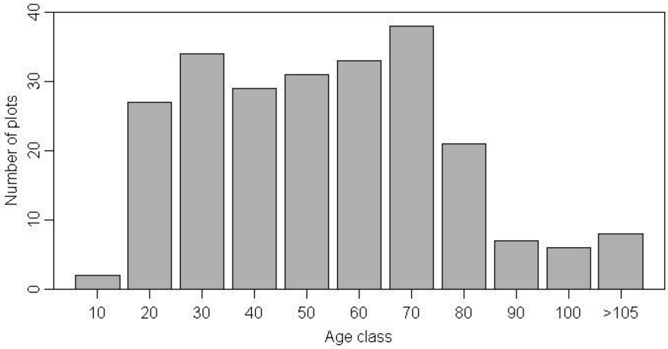

Figure 4. Distribution of plots by age classes

According to a conceptual model of forest stand development based on study of Estonian long-term permanent sample plots data (Kangur et al., 2005) stand dynamics can be divided into four different stages: stand initiation, stem exclusion, demographic transition and old multi-aged. These stages are characterized by different ecological processes. In this study I have data from after stand initiation stage, thus I determined the last three stand development stages according to dominant species and stand age, which is common practice in Estonian forest management.

In modeling tree survival, a variety of predictors have been considered. Hamilton (1986) classified the factors that affect tree survival into four groups: tree size, tree competition status in the stand, tree viability and stand density.

Relative tree diameter, relative tree height, basal area of larger trees, relative basal area of larger trees and Hegyi's (1974) competition indices were investigated as variables characterizing individual tree competitive status. Only Hegyi's competition indices require known tree positions, others are relatively easy to calculate them. The relative tree diameter is calculated as a ratio.

On the sample plot level, the investigated measurement variables of the first storey were stand age, stand density, stand basal area, quadratic mean diameter, mean height, stand volume, and relative density. To calculate the stem volume of each tree, the volume equation by Ozolins (2002) was used. Stand volume was calculated as the sum of the first storey tree stem volumes per hectare.

Simple linear functions are not suitable for modeling survival because they may give predictions of the survival probability outside the feasible range (0, 1). For modeling a variable that follows a binomial distribution, a logistic model may be used where the dependent variable is logit-transformed, as follows:

$$\mathrm{logit(P)} = \ln \frac{\mathrm{P}}{1-\mathrm{P}}$$

$$\text{where } P = \frac{e^z}{1+e^z}, \qquad (25)$$

$$z = c_0 + c_1 \cdot x_1 + c_2 \cdot x_2 + \ldots ,$$

c_0, c_1, c_2 are constants and x_1, x_2 are variables.

In the present analysis, more than 20 logistic models of tree survival and mortality were analyzed. Several authors have used Eq. 25 for different tree species, where every species has a specific set of coefficients (Hamilton, 1986; Eid and Tuhus, 2001; Monserud and Sterba, 1999; Vanclay, 1991; Hynynen et al., 2002). Factors influencing mortality may be regarded on both the single tree and stand level.

A term multilevel models is used for models for data with hierarchical structure (Faraway, 2006), e.g., for prediction of individual tree variables are used data at the stand level and tree level; thus, repeated measures, longitudinal and multilevel data consist of several observations taken on the same individual or group. This induces a correlation structure in the error component; however, mixed effect models allow the modeling of such data (Faraway, 2006).

Tree survival probability P was modeled with the mixed model (Hynynen et al., 2002):

$$\text{logit}\left(\text{P}_{\text{ij}}\right) = \beta_{0\text{j}} + \beta_1 \cdot X_{1ij} + \beta_2 \cdot X_{2ij} + \ldots.\beta_m \cdot X_{mj} + \beta_{m+1} \cdot X_{m+1j} + \ldots \qquad (26)$$

where P_{ij} is the tree survival probability;

logit() is the logit-transformation (Eq. 25);
β_{0j} is the random intercept ($\beta_{0j} = \beta_0 + u_j$: $u_j \sim N(0, \sigma_u^2)$);
i is tree number;
j is plot number;
X_{1ij}, X_{2ij} are tree level variables;
X_{mj}, X_{m+1j} are stand level variables;
β_0, β_1, β_2, ..., β_m, β_{m+1}, are model parameters

In logistic regression analysis, the deviance (also called log likelihood statistic) is used to characterize goodness of fit, calculated by logarithmic likelihood. The likelihood ratio test helps us estimate the influence of new arguments added into the model. The likelihood ratio follows a chi-square distribution where p is the number of parameters, which allows estimation of the statistical significance of added arguments (Dobson, 2002). To select the best subset of variables, the score statistic was calculated for every single tree variable for ranking single tree influence on survival using

PROC LOGISTIC (Freund and Littell, 2000) in SAS. The score statistic is asymptotically equivalent to the likelihood ratio test statistic but avoids the need to compute maximum-likelihood estimates (Schaid et al., 2002).

In the case of a traditional linear regression analysis (with the assumption of a normal distribution of residuals) to characterize the goodness of fit of a model, the root mean square error or coefficient of determination (R^2) is used (Dobson, 2002). By analogy with R^2 for ordinary regression, the generalized R^2 (Eq. 27) was used which represents the proportional improvement in the log-likelihood function due to the terms in the model of interest, compared to the minimal model (Dobson, 2002; Shtatland et al., 2002).

$$R^2 = 1 - \frac{\log L(M) - p - 1}{\log L(0) - 1} \tag{27}$$

where log*L*(M) is the maximized log-likelihood for the fitted model with the number of parameters p; log*L*(0) is the log-likelihood of the "null" model containing only the intercept term.

The SAS LOGISTIC procedure presents two different definitions of generalized coefficients of determination. One has been developed by Cox and Snell (1989, pp. 208-209), the other is an adjusted one by Nagelkerke (1991). In this study, the coefficient of determination defined by Eq. 27 was used because Shtatland et al. (2002) has shown that it has a number of important advantages over the coefficients of determination of Cox and Snell (1989) and Nagelkerke (1991).

For the logistic ANOVA the procedure GENMOD with SAS software (Littell et al., 2002) was used for analyzing the tree cohort influence. For multilevel analysis of tree and stand variable influences the generalized linear methods were used with SAS procedure GLIMMIX (Schabenberger, 2005) and function ***lmer*** in the R (Crawley, 2007). The SAS procedure GLIMMIX fits statistical models to data with correlations or non-constant variability and where the response is not necessarily normally distributed. The function ***lmer*** is used for fitting mixed-effects models in the R (package lme4). Both allow analyzing a response variable with a binomial distribution and logit-transformation. However, the SAS procedure GLIMMIX implements a restricted pseudo-likelihood (RPL) method, whereas a restricted maximum likelihood (RML) method is used in the R function ***lmer***.

5. RESULTS

5.1. Forest Modeling Information System

5.1.1. Concept of the Forest Modeling Information System

This web-based information system, combining empirical data and existing knowledge of forest development, enhances the use of forestry metadata and forest models manipulation and verification/validation procedures.

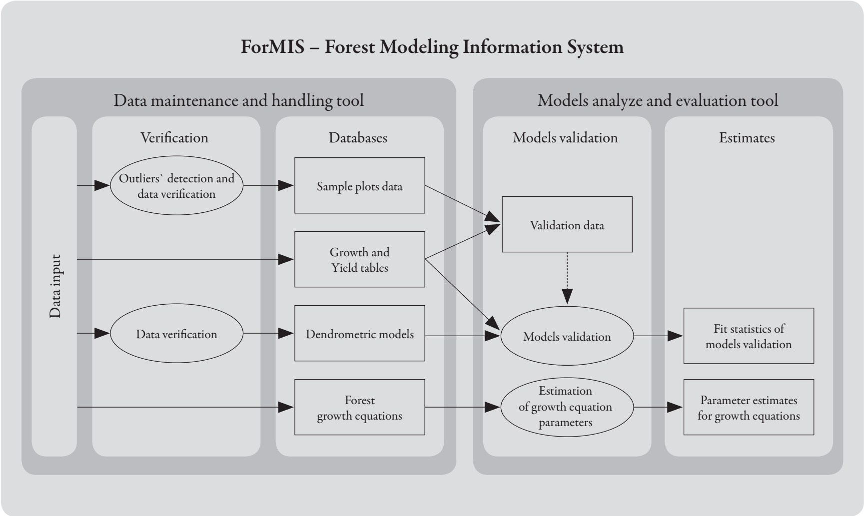

Figure 5. Schematic relation of data maintenance and management in ForMIS.

Figure 5 gives an overview of data management processes in the information system. In principle, the information system contains two parts - empirical data management and models evaluation. Data management includes data verification in data recording into the database, outlier detection after data recording and several standard procedures (e.g., stand level data calculation from tree data).

5.1.2. The database of forest growth and yield tables

Yield tables are tables in which one can find forest stand characteristics at the hectare scale at varying ages (Vanclay, 1994). Most of the tables are valid for monospecious, even-aged stands, and can be based on permanent sample plots in which the optimal management was carried out or on a set of sample plots which represent the regular management. They are usually assessed for different management regimes and site classes (Brack and Word, 1997). Although the research in this field is moving towards more dynamic modeling tools for forest management and mixed species forests, the information contained in these traditional tables is still very valuable (Vanclay, 1994).

All tables in the database of growth and yield tables (Table 2) are accessible at http://formis.emu.ee/gytables/, where growth and yield information is presented by sets of tables.

Table 2. Number of growth and yield tables in sets collected into ForMIS.

Country	*Number*		
	sets	*tables*	*records*
Austria	4	45	982
Belarus	14	56	914
Belgium	9	26	274
Bulgaria	4	17	266
Croatia	1	3	44
Czech Republic	7	53	1,363
Denmark	6	15	380
Estonia	15	71	919
Finland	11	37	619
France	2	9	114
Germany	25	92	3,428
Hungary	1	6	336
Latvia	11	59	1,057
Lithuania	15	106	1,799
Netherlands	2	11	314
Norway	1	4	126
Russian Federation	48	185	3,913
Slovakia	2	2	100
Spain	7	27	651
Sweden	15	98	2,330
Switzerland	1	7	255
Ukraine	31	154	2,141
United Kingdom	8	52	1,227
Total	**240**	**1,135**	**23,552**

The growth and yield tables may be presented in a tabular (Table 3) or a graphical form (Figure 6) or as regression equation relating yield to age, site and stand density. Regression equations are inserted into the database of empirical dendrometric formulas.

Table 3. An example of an growth and yield table in ForMIS (Scots pine table (no 34), H50 = 24.1 m, before thinning values (Tappo, 1982)).

Age	Height	Diameter	Basal area	Density	Volume	Sparsity
20	10.6	9.7	20.9	2,856	113	1.87
30	16.2	14.7	25.1	1,484	190	2.60
40	20.7	19.1	27.1	948	253	3.25
50	24.1	22.8	27.9	682	299	3.83
60	26.7	26.1	28.4	532	333	4.34
70	28.7	28.8	28.5	438	357	4.78
80	30.3	31.1	28.5	375	375	5.16
90	31.6	33.1	28.5	331	389	5.50
100	32.6	34.9	28.4	298	399	5.79
110	33.4	36.4	28.4	273	407	6.05
120	34.1	37.7	28.3	254	414	6.27

Height, diameter and basal area dynamics is presented also in a graph in ForMIS (Figure 6).

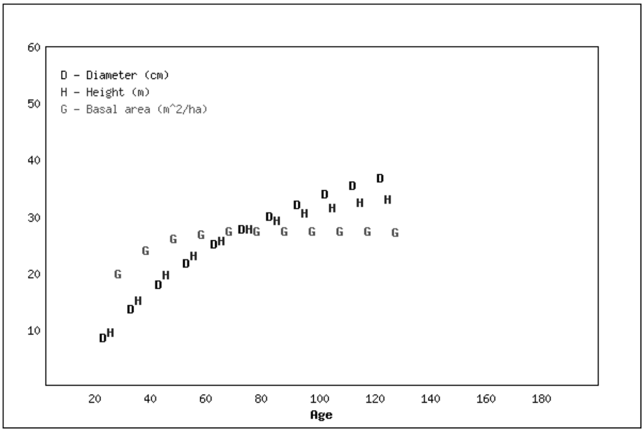

Figure 6. An example of a graph of development of height, diameter and basal area in ForMIS (Scots pine table (no 34), H50 = 24.1 m, before thinning values (Tappo, 1982)).

5.1.3. The database of forest research plots

Different types of permanent sample plots have been established across Estonia (Table 4). Table 4 shows number of measurements by different projects, where total of 3,497 plots and 514,308 tree measurements are made.

Table 4. Number of measured plots and trees by different forest research projects.

Project	*Plots*		*Trees*	
	number	*measurements*	*number*	*measurements*
ENFRP	708	1,615	113,340	240,538
FNRRP	50	150	7,304	19,163
JLTFE	209	1,377	38,437	193,851
OSMFRP	128	355		60,756
Total	**1,095**	**3,497**		**514,308**

Collected data has been used for the modeling of forest structure and for studies on forest growth analysis; for example, 1) diameter distribution models (Merenäkk, 2006), 2) diameter and height relationships (Kiviste et al., 2003), 3) competition indices (Raudsaar, 2003), 4) spatial structure of trees, 5) individual-trees and stand diameter and height growth models (IV), 6) survival (mortality) probability models (Kiviste et al., 2005; V), 7) permanent sample plots GIS (Lang et al., 2005), 8) measurement errors/ outliers study (Hordo, 2004; 2005), and 9) developing the information system for dendrometric formulas and data (Sims, 2003; 2004; Sims et al., 2006).

Tree-by-tree re-measured permanent sample plot data is needed to develop and improve forest growth models in Estonia. ForMIS was enhanced for detecting measurement errors and outliers in the ENFRP data. The program has been helpful for improving the ENFRP data; table 5 shows the number of data corrections by years. The program can be easily adapted to all types of forest sample plot data collected in different ways. Additional re-measurement data will give a chance to update the statistical criteria and models used in the program and make it more sensitive (Hordo, 2004).

Table 5. Number of corrected data by variables and year on the ENFRP

		Errors for all trees					*Errors on sample trees*		
Year	N_{all}	*Storey*	*Species*	d_1	d_2	N_{st}	h	h_{cr}	h_{db}
1995	**11,026**	247	39	2	3	**2,054**	5	3	0
1996	**10,526**	346	111	8	5	**2,013**	8	0	0
1997	**4,677**	42	53	3	3	**3,530**	7	5	0
1998	**8,213**	23	0	0	0	**1,181**	1	1	0
1999	**20,373**	821	154	11	12	**7,935**	15	7	2
2000	**19,525**	438	76	2	2	**6,350**	16	9	0
2001	**20,924**	825	155	26	27	**5,813**	469	12	0
2002	**20,324**	639	99	27	24	**5,660**	43	12	7
2003	**16,091**	186	21	24	18	**4,412**	29	6	0
2004	**22,222**	1,244	146	356	356	**7,500**	186	182	50
2005	**22,499**	792	1	19	14	**7,239**	29	19	1
2006	**22,984**	1,848	2	347	342	**5,703**	7	2	0
2007	**20,733**	0	0	1	1	**5,163**	9	3	0
2008	**20,421**	618	4	27	32	**4,172**	20	7	0
Total	**240,538**	**8,069**	**861**	**853**	**839**	**68,725**	**844**	**268**	**60**

Where N_{all} is all trees measured, N_{st} is the number of sample trees measured, d_1 and d_2 are tree diameters at breast height in different directions, h is sample trees height, h_{cr} is height of crown base, and h_{db} is height of first dead branch.

5.1.4. The database of empirical dendrometric formulas

An empirical dendrometric formula is a mathematical forest model created to calculate any tree or stand dendrometric variable based on another variables. Dendrometric variables are tree and stand dimensional (diameter, height, etc.) and site characteristic (site index, bonitet, etc.) variables.

The database contains formulas that are ready for use in practical forestry. Every formula in the database includes at least an equation, constants by tree species, and descriptions of every input and output variable. Additionally, the name of the author (if it is known), references, and a short description of the model are also presented in the database.

The database is meant for publishing forest modeling end products - empirical dendrometric formulas; thus, the users of the information system can be practical foresters using formulas in different forestry applications. However, the database is also useful for forest modelers, who require an overview of existing models; therefore, it is possible for model authors to enter their models into the database.

Models from Estonia (71), Finland (30), Germany (24), Latvia (23), Lithuania (19), Sweden (17), Belorussia (2), Russian Federation (2), Austria (1) and Norway (1), as of mid-2009 have been recorded in the database.

All formulas are available at http://formis.emu.ee/formod/. End-users can download all formulas as a user-defined function for programming in the Visual FoxPro, Visual Basic and Visual C# environments; or copy formulas for use in Excel, OpenOffice.org, Visual FoxPro and the statistical software R.

5.2. Forest growth models based on ForMIS

5.2.1. Estimating potential density

In this study, the potential density is analyzed using two approaches: the conventional limiting relationship (Eq. 4) and Nilson's stand sparsity (Eq. 6).

In both analyzed experiment plots no live trees had been removed in the plots during the period 1926 to 1932 and again during the last 49 years (only the very smallest were harvested pre-emptively, i.e. assuming that they would die anyway).

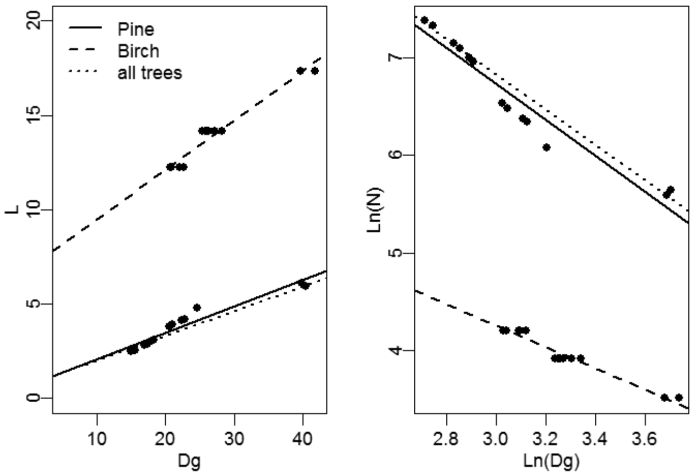

Figure 7. Nilson's Stand Sparsity ($L=a+b \cdot D$, left) and Reineke's Limiting Line ($Ln(N)= a+b \cdot Ln(D)$, right) fitted separately for birch and pine trees in the JLTFE plot M274_04_02.

Birch and pine are both light demanding species and their shade tolerance decreases rapidly after growing out of the seedling stage. At the beginning of the plot enumeration, the diameter distributions of the birch trees were dominant. This effect can be seen in the early quadratic mean diameter of pine and birch in the left graph of Figure 7. Later on, after reaching a diameter of more than 40 cm, the mean diameters of pine and birch trees are almost equal. This result is not (only) due to growth, but mainly due to the higher mortality of the pines in the lower ranges of the diameter distribution.

It is interesting to note the differences in the slopes and intercepts of the limiting relationships for pine and birch, given the specific relative proportions of tree numbers during the entire measurement period. In 1925, there were 67 birch and 1600 pine trees per ha. Thus four percent of the trees were birch and 96 percent pine. In 2004, ten percent of the trees were birch.

The slope parameter values of the Stand Sparsity line are indicative of the mortality rates for a given increase in D. The values in Figure 7 are 0.14 for pine and 0.26 for birch, and 0.13 for the whole population. The slope for pine slightly exceeds the slope for the whole stand. This implies a higher pine mortality rate per unit of D increase.

5.2.2. Stand level growth models

Forest growth model for Scots pine dominated stands was built up using interval measurement data. Sample plots with no management and large-scale natural disturbance within the studied interval were used. Table 6 shows the parameter estimates for the growth models developed and calibrated from the data on 142 intervals.

Table 6. Parameter estimates and fit statistics for growth models of Scots pine dominated stands based on interval measurements.

Model	*Parameter estimates*				*R*	*RMSE*
	c_1	c_2	c_3	c_4		
Basal area growth (Eq. 8)	12.0422	0.1712	0.1039	-0.0506	0.66	0.95
Diameter growth (Eq. 10)	1.1909	-0.0256	0.0403	-0.0198	0.59	0.34
Stand density (Eq. 12)	3.7012	-0.0210	-2.5612	0.0997	0.53	0.05
Stand sparsity (Eq. 14)	0.1103	-0.0033	-0.0004	0.0017	0.25	0.08

Model	*Parameter estimates*				*R*	*RMSE*
	c_1	c_2	c_3	c_4		
Gurjanov et al. stand density (Eq. 15)	-2.1023	0.0002	2.5313		0.36	0.06
Gadow and Hui basal area (Eq. 16)	0.8747	-0.0340	0.9732		0.64	1.13

R =correlation coefficient between observed Δy and predicted $\Delta \hat{y}$; RMSE =root mean square error

The fit statistics R and RMSE of these models are not comparable in the case of different dependent variables, whereas different equations for the same dependent variable are comparable (e.g., Eq. 8 with Eq. 16 for basal area prediction and Eq. 12 with Eq. 15 for stand density prediction). The fit statistics (R=0.66 and RMSE=0.95) of the basal area growth model (Eq. 8) for the five-year growth projection show better results than those for the basal area difference model (Eq. 16). Similarly, the fit statistics (R=0.53 and RMSE=0.05) of the proportion of survived trees model (Eq. 12) perform better than those of the survival difference model (Eq. 15).

5.2.3. Comparing different combinations of model components

The RMSE has been calculated for every stand variable in the simulations (Table 7). In all simulation combinations, the stand height was the first projected variable in the calculation sequence obtained by the same stand height model (Eq. 1) and where the same RMSE value (0.617 m) occurred. The set of RMSE values showed negligible difference for the first four simulation combinations in Table 7, where projected variables were calculated based on increment equations.

Table 7. RMSE values of projected vs. observed stand variables at the end of the five-year prediction period according to different simulation combinations

Simulation combination	*H*	*D*	*N*	*G*	*V*
D.G	0.617	0.336	98.232	0.952	21.252
D.L	0.617	0.336	105.634	0.935	21.107
D.N	0.617	0.336	99.434	0.986	21.138
G.N	0.617	0.340	99.434	0.952	21.252

Simulation combination	*H*	*D*	*N*	*G*	*V*
Dif	0.617	0.584	94.850	1.132	24.585
Est	0.617	0.395	160.204	1.695	24.194

The “Dif” simulation combination showed considerably higher RMSE values for quadratic mean diameter, basal area and volume calculations. It has a higher RMSE, because the stand density and height were predicted independently, and especially since the height model was calculated using a different data set. Both height and stem number already contain a prediction error. The results of the “Est” combination showed the highest RMSE values in stand basal area and density calculations. Both variables were calculated via volume and form height and were therefore dependent on the prediction error of the form height model. Figure 8 shows poorer performance between the observed and predicted basal area of the “Dif” and “Est” simulation combinations in comparison with other simulation combinations. However, stands with very large basal areas have the systematic underestimation in every simulation combination.

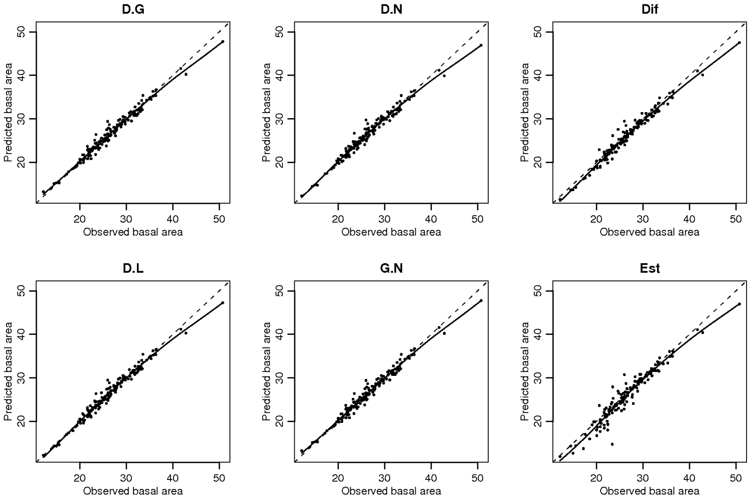

Figure 8. Observed vs. predicted basal area for various simulation combinations.

5.2.4. Single tree survival models

The selected variables were divided into three groups: vertical size variables (HNLS, HNLSr, H1, etc.), horizontal size variables (D, Dr, D1, etc.) and competition variables (BALr, BAL, HEG5, HEGH, etc.). Variables of relative size (relative diameter, relative height) could be handled as size group variables as well as competition group variables. However, in this study, relative size variables were handled as size group variables, because I assume that they indicate the amount of resources needed for tree survival.

For selecting variables into the multiple-model, an ordered list of score statistics was calculated for all variable combinations using the LOGISTIC procedure. However, not all variable combinations on top of the list of score statistics were biologically interpretable and with statistically significant parameter estimates.

Taking a great number of arguments into the model may be justified in the case of a random sample, such as a forest inventory, where all elements of population have the same probability to be part of the sample. Unfortunately, the selection of stands in the Estonian forest research plot network was not entirely random, which is also revealed in the distribution histograms in Figures 2 and 3. That is why the principle of developing as parsimonious model as possible (Burkhart, 2003) was followed in this study.

For multilevel logistic modeling with a random intercept (Eq. 26) I selected a tree level variable from each group, a stand level competition variable, and the tree species as regressors (HNLSr, Dr, BALr, TTJ, SpDr, and TS). The results of this multilevel logistic modeling on different data sets are presented in Table 8.

Table 8. Results of generalized linear mixed modeling with the function lmer (R) for Eq. 26.

Regressor	*All data*		*Young stands*		*Middle-aged and maturing stands*		*Mature and over mature stands*	
	Estimate	*St. Error*	*Estimate*	*St. Error*	*Estimate*	*St. Error*	*Estimate*	*St. Error*
Intercept	1.962	0.644	4.774	1.296	-0.777	0.727	8.993	2.369
HNLSr	5.333	0.302	4.867	0.878	4.850	0.639	3.596	1.069

Regressor	*All data*		*Young stands*		*Middle-aged and maturing stands*		*Mature and over mature stands*	
Dr			-1.034	0.955	1.821	0.411		
BALr	-1.649	0.242	-3.821	0.897			-2.236	0.805
TTJ	-2.876	0.607	-2.820	1.081	-2.413	0.800	-8.464	2.118
SpDr							-3.576	1.679
TS Aspen	-0.817	0.199	-0.676	0.388	-0.991	0.264	-1.189	0.533
TS Birch	0.171	0.148	0.423	0.295	0.104	0.191	-0.313	0.444
TS Spruce	0.411	0.170	0.703	0.270	0.385	0.243	1.645	1.715
TS B. Alder	-0.266	0.254	-0.653	0.364	1.036	0.526	-2.016	0.883
TS G. Alder	-2.065	0.192	-1.521	0.330	-2.654	0.258	-2.584	0.544
	Fit statistics							
logLik	-4856		-1692		-2752		-363.1	
Deviance	9712		3384		5505		726	
R^2	0.168		0.189		0.168		0.084	

All terms in the model have biological sound: tree survival is increasing with relative height (HNLSr) and decreasing with increasing competition (BALr and TTJ). Considering effect of different tree species, spruce survival was significantly higher and grey alder survival significantly lower than other tree species for all development stages. This can be explained by shade tolerance of spruce and short life of grey alder. Significance of spruce relative diameter for old stands indicates to relatively lower survival of bigger spruces because of wind- and fungi damages (Laarmann, 2007).

In the young, middle-age and maturing stand development stages the relative tree density affects tree survival in case of all tree species, but in mature and over-mature stages only relative diameter in case of spruce is significant. In younger development stages trees survive with larger relative diameter; on contrary in older stand development stages spruces with smaller relative diameter survive. Therefore, it is reasonable to divide stands into development stages when analyzing tree survival, because in the different stages different mechanisms have influence to the tree survival.

6. DISCUSSION

In essence, normal and empirical growth and yield tables have similar limitations. For example, it is difficult to determine the fully stocked stands, or representative, economically feasible stocked stands for compiling growth and yield tables. The stocking level is dynamic and varies in different stands, therefore is difficult to apply relative density correction for stands other than normal or average. The main limitations of normal and empirical tables listed by Brack and Word (1997) states that:

- no confidence limits are attached to trends;
- extrapolations are made outside and beyond sampled thinning regimes and ages;
- used volume functions are mostly two-dimensional and of regional application;
- volumes are computed for normal trees only and no account is taken of malformation and other such factors affecting recoverability;
- rarely is taken into account the pruned component of a stand.

In general growth and yield models used in decision support systems and forest management planning lack sensitivity in regards of the interactions of successional dynamics over various ages. They are stand development curves fitted to observed stand growth data describing the net production of a stand. The trend in forest management planning toward ecosystem-based forest management principles has created a need to apply more sophisticated decision support systems. More detailed modeling approaches, such as individual tree models using competition indices, hybrid and process based models, have already been developed and applied. One way of strengthening the traditional growth and yield modeling approach is to construct compatible tree and distribution models in addition to stand-level models (Richardson et al., 2006).

The natural decline of the number of surviving trees in an unthinned forest is usually characterized by intermittent brief spells of high mortality, followed by long periods of low mortality. The process is not a continuous one (Boardman, 1984; Gadow, 1987). Stochastic models have been used in some cases to mimic these processes. However, for the purpose of simulating alternative silvicultural regimes, it is generally assumed that natural mortality is a continuous process.

Populations of trees growing at high densities are subject to density-dependent mortality or *self-thinning*. For a given average tree size there is a limit to the number of trees per hectare that may co-exist in an even-aged stand. This limiting relationship is site- and species-specific, and the topic is highly relevant to research dealing with natural disturbances. Estimating the potential density of forest stands is a central element of forest modeling. It is also one of the most difficult problems to solve, mainly because data from untreated, fully-stocked stands, such as the previously abandoned plots in Järvselja, is very scarce.

Based on the analysis in this study, I'm convinced that Nilson's approach is very useful in estimating the maximum density in Estonian forests, for different stand and site types. The advantage of Nilson's stand sparsity, in contrast to the widely used Reineke's limiting line, is the fact that it allows such clear interpretations which are easy to understand.

Considering the high cost of maintaining a series of unthinned, densely-stocked stands, such data is usually not available, but it is needed for the mortality and *self-thinning* analysis. Most likely, it is possible to interpolate to the measurement gaps tree height and diameter data together with stand density. Dendrochronology (stem analysis with radial and height growth chronology) can assist in obtaining forest externalities, i.e., the data on forest management (thinnings) and natural disturbances (Metsaranta and Lieffers, 2009).

An important aspect of increment functions is that because the actual increment rates are estimated directly from the observed data the functions are based on a limited set of independent variables (Hasenauer, 2006), but this also restricts prediction of stand variables for a given time interval (usually five years, depending on the calibration data measuring interval). The prediction of stand development using algebraic difference models offers more flexibility in terms of prediction interval length.

Growth and survival can only predict if the interval is a period of undisturbed growth. However, to evaluate different management scenarios, we must be able to model disturbance events as well as growth. A basic assumption with interval plots is that the interval is a period of undisturbed growth. All models in this study, except Kiviste's difference equations (Kiviste, 1999a;

b), were developed or calibrated on the undisturbed interval plot data. The growth models include natural growth and natural single tree survival, but they do not include anthropogenic interference as can be expected in the case of commercial forests. These models therefore allow us to predict stand growth in commercial forests between harvest events in the long run.

The main advantage of the use of algebraic difference equations over the fixed-step increment equations is the ability to use flexible time steps. However, experience has shown that the projection intervals should not deviate too much from the time steps of the measurement data. An important constraint when using the algebraic difference equations is to avoid long-term predictions in one prediction sequence.

Algebraic difference equations are useful in predicting stand variables, which are not related to stocking density. Stand height growth is the most common stand variable, which does not depend on stand density and is usually predicted from current height and age. Quadratic mean diameter growth depends highly on stand density; therefore, it is recommendable to avoid long-term predictions in one sequence. Stand density, basal area and volume will develop in unmanaged forest up to maximum density and is followed then by the natural *self-thinning* phase or in a commercial forest until to thinning event. In general the development of these three variables over long period of time depends on the severity of stem exclusion – *self-thinning* is a long natural process with the peaks of high mortality rates (Gadow, 1987), comparably to the these mortality peaks also after the thinning events the growing space of remaining trees is much greater and is followed by growth rate increase. Therefore, those variables should be predicted following the maximum density line and a short-term iterative calculation is more suitable for this purposes.

Table 8 presents results of multilevel logistic modeling obtained with the R function **lmer**. SAS procedure GLIMMIX and the R function **lmer** methods included the same set of statistically significant variables and produced similar parameter estimates. These variables were divided into three groups: vertical size variables, horizontal size variables, and competition variables. Variables of relative size (relative diameter, relative height) can be determined as size group variables as well as competition group variables. In this study, relative size variables were handled as size group variables, because I assume that they indicate the amount of resources needed for tree survival.

Tree survives when the amount of available resources is higher than the amount of resources needed for tree survival. All terms in the survival model are biologically sound: tree survival (P) is increasing in accordance of tree relative height increase (following the availability of photosynthetically active light increase) and decreasing with the increasing competition status (amount of available resource decrease per individual tree). Considering the effect of different tree species, spruce survival was significantly higher (shade tolerant species) and grey alder (shortest lifetime) survival significantly lower than for other tree species in all development stages. However, according to a conceptual model of forest stand development (Kangur et al., 2005) and analysis in this study, it is reasonable to predict tree survival separately for different development stages. This is due the processes significantly varying influence in different development stages.

7. CONCLUSIONS

The thesis presents the information system ForMIS, its user applications, data and model requirements. The information system ForMIS for managing and storing empirical forestry data has been launched including data verification, validation and outlier detection of empirical forestry data. ForMIS contains four different modules: a database of sample plots, a database of growth and yield tables, a database of dendrometric formulas and a database of forest equations.

Sample plots module in ForMIS has user-friendly tools for data analysis and import. Currently the database comprises 514,308 trees from 3,497 plot measurements. This ForMIS module was enhanced with outlier detection and data verification procedures for detecting measurement errors and outliers in the ENFRP data. During the application period 1995-2008 corrections have been made to 10,622 values (diameter, species name and storey) from 240,538 single tree measurements and to 1,172 values (tree height, height of crown base and dead branches) from 68,725 sample tree measurements.

To the module of growth and yield tables have been collected a total of 240 sets of tables from 23 European countries, containing 1,135 growth and yield tables and 23,552 data rows.

A module of dendrometric formulas was included in ForMIS for systematizing and sharing empirical dendrometric formulas. The information system is expected to become a useful tool for modelers as well as to the models end-users. The module is with open access and new models can be continuously added into the system. End-users can download every formula as a user-defined function for programming in Visual FoxPro, Visual Basic and Visual C# environment; or can copy formulas for use in Excel, OpenOffice.org, Visual FoxPro and the statistical software R.

The natural dynamics of tree survival in an unthinned forest is usually characterized by sudden short periods of high mortality followed by long periods of low mortality. The process is not a continuous one (Boardman, 1984; Gadow, 1987). In this thesis, the irregular interval measurements on long-term experimental sample plots in Estonia present a problem for analyzing the occurrence of disturbances. Examples of abandoned forest experiments that have recently been restored are in Järvselja, and I proposed a method for evaluating previously unrecorded disturbances on a plot during certain gaps in measurements.

This study compares the results of stand simulation using fixed interval increment functions and algebraic difference functions with variable interval lengths. To compare the flexibility of two different types of empirical model in stand-level prediction, I tested the performance of:

a) increment equations developed in the current study on the basis of interval plot data,
b) algebraic difference equations calibrated on interval plot data and
c) algebraic difference equations developed on Estonian forest inventory data.

The model tests were carried out by comparing the projections of five stand variables (height, quadratic mean diameter, basal area, stand density, and volume) in different combinations. The results do confirm the assumption that using different model types for obtaining projected stand variables makes the projections differ, but not the assumption that considerable differences can be expected in projections when using different combinations of predictor variables in calculation sequences for obtaining projected variables. In this regard, the five-year projections of dependent stand variables with simulation combinations using increment equations showed negligible difference from each other, but considerable difference from difference equations.

Stand density development is one of the most important but complicated aspects of forest modeling. Algebraic difference models allow us to predict the average long-term stand development in accordance with a given initial state. The growth models developed in the current study predict growth by 5-year intervals and are therefore inconvenient for the end-user to apply. On the other hand, they are more flexible when taking the *self-thinning* limit into account. The stands on interval plots used for model parameterizations have not reached the *self-thinning* state yet and show a relatively high basal area and diameter growth. Improving the prediction capability of these models requires longer intervals of undisturbed development.

Tree survival was analyzed on a dataset that includes 31,097 trees from 236 research plots, measured twice during the period of 1995-2004. During the

5-year period between measurements, altogether 2,319 trees (or 7.5%) had died (dead standing, broken or fallen). Tree mortality is a key factor in the understanding of forest dynamics. The accuracy and relevance of a growth model depends on the accuracy of predicting tree survival. This study shows that from tree and stand level variables the statistically significant affect to the tree survival probability in most of Estonian forests have: relative tree height, relative diameter, relative basal area of larger trees, relative stand sparsity, spruce relative diameter, and tree species. All terms in the model have biological sound: tree survival is increasing with relative height and decreasing with increasing competition.

In the young, middle-age and maturing stand development stages the relative tree density affects tree survival in case of all tree species, but in mature and over-mature stages only relative diameter in case of spruce is significant. In younger development stages trees survive with larger relative diameter; on contrary in older stand development stages spruces with smaller relative diameter survive. Therefore, it is reasonable to divide stands into development stages when analyzing tree survival, because in the different stages different mechanisms have influence to the tree survival.

The first models for individual-tree growth and mortality prediction have already been developed in Estonia. Nonlinear models containing a limited number of parameters and “logical forms” could be preferred in growth studies. ForMIS enables efficient testing and calibrating of forest growth models from neighboring countries on Estonian permanent plot data.

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SUMMARY IN ESTONIAN

Takseermudelite ja andmestike infosüsteem puistu kasvukäigu modelleerimiseks

Empiiriliste metsanduslike andmete haldamiseks ja säilitamiseks on loodud takseermudelite ja andmestike infosüsteem (ForMIS), mis võimaldab ka andmesisestuse kontrolli ning erindite diagnostikat. ForMIS sisaldab nelja erinevat moodulit: proovitükkide andmebaas, kasvukäigutabelite andmebaas, dendromeetriliste mudelite andmebaas ja kasvufunktsioonide andmebaas. Kogu süsteemiga on võimalik tutvuda ForMIS kodulehel http://formis.emu.ee/, kus ta on avalikult kasutatav.

Hetkel on proovitükkide andmebaasi kantud 3 497 proovitüki mõõtmiselt kogutud 514 308 puu andmed. Andmesisestuse kontrolli ning erindite diagnostika protseduuride abil on andmestikust leitud ning parandatud suurel hulgal vigu. Ainuüksi kasvukäigu püsiproovitükkide võrgustiku 1995 kuni 2008 aasta mõõtmisandmetest (240 538 puu mõõtmist) on parandatud 10 622 väärtust (diameetrid, puuliik ja rinne) ning mudelpuude (68 725 puud) andmetest on parandatud 1 172 väärtust (kõrgus, elusa võra algus, kuiva oksa kõrgus).

Empiirilistest andmetest on kogutud infosüsteemi ka paljude autorite poolt erinevatel aegadel koostatud kasvukäigutabelid kogu Euroopast. Hetkel on andmebaasis 23 Euroopa riigist 240 tabelite komplekti, milles sisaldub 1 135 kasvukäigutabelit 23 552 andmereaga. Tabeli komplekt esitab erineva boniteediga ühe autori poolt ühele puuliigile loodud puistute kasvukäigutabelite kogumikku.

Dendromeetriliste mudelite andmebaas on loodud empiiriliste dendromeetriliste mudelite süstematiseerimiseks ning avalikuks kasutamiseks. Andmebaasis on peamiselt mudelid, mida kasutatakse praktilises metsamajanduses. Seetõttu on nende kasutajad nii metsanduslikud töötajad kui ka modelleerijad, kellele andmebaas annab ülevaate olemasolevatest mudelitest ning võimaldab ka avaldada oma tehtud uusi mudeleid. Andmebaasi suurus ei ole piiratud ning uute mudelite lisamine toimub pidevalt.

Dendromeetriliste mudelite andmebaasis hoitakse mudeleid süstematiseeritult, mis võimaldab lihtsalt mudeleid vormindada ning erinevate programmidega töötamiseks sobivale kujule teisendada. Dendromeetriliste mudelitega töötamise lihtsustamiseks on kasutajatel võimalus kopeerida mudel valemina või laadida alla kasutajafunktsioonina. Kopeerida on võimalik kas Visual FoxPro, Exceli või statistika programmis R töötamise jaoks, kasutajafunktsioonina on võimalik alla laadida kas Visual FoxPro, Visual Basic-u või Visual C# jaoks.

Käesoleva töö üheks osaks on puistu kasvu modelleerimine ning üksiku puu ellujäämistõenäosuse analüüsimine.

Puude arvu dünaamika majandamata puistus toimub üldiselt lainetena, kus mingi lühikese perioodi jooksul sureb suur hulk puid ning seejärel on pikk periood, kus puistu suremus on madal. Majandamata metsas suremuse analüüsiks on vaja pikema ajalisi mõõtmisi, kus pikka aega ei ole tehtud elusate puude raieid. Järvseljas rajati eelmise sajandi alguses hulk proovitükke, millel mõõtmised on olnud ebaregulaarsed. Suur hulk nendest proovitükkidest on hiljuti taastatud ning need on mõõtmisandmed on heaks materjaliks pikema ajaliste uuringute läbiviimiseks. Kuna mõningatel proovitükkidel on vahepeal mõõtmiste vahe olnud peaaegu 50 aastat, siis on enne analüüsi vajalik tuvastada võimalikud muutused ning majanduslikud tööd. Käesoleva uurimuse käigus analüüsiti Järvselja püsikatsealade andmeid leidmaks, kas antud proovitükid on oma arengus olnud pikka aega bioloogiliselt piirtihedad, mis näitab metsamajanduslike tööde puudumist. Piirtiheduse hindamiseks kasutati Nilsoni puistu piirtiheduse ja diameetri vahelist seost ning leiti, et töös analüüsitud proovitükid on kogu oma kasvu jooksul olnud piirtihedad.

Eestit katva kasvukäigu püsiproovitükkide andmetel analüüsiti puude ellujäämist ning seda mõjutavaid tegureid. Analüüsiks võeti 236 proovitükki, millel oli 31 097 puu mõõtmise andmed, mis olid kogutud aastatel 1995 kuni 2004. Kordusmõõtmised toimusid viie aastase intervalliga ning selle aja jooksul oli 2 319 puud surnud. Puude ellujäämisest arusaamine on puistu dünaamika oluline osa, kuna paljud kasvumudelite ennustused sõltuvad just puude ellujäämisest. Käesoleva uurimuse tulemused näitavad, millised puistu ja puu tunnused mõjutavad kõige enam puude ellujäämise tõenäosust Eesti metsades. Ellujäämist mõjutas puistu tunnustest kõige enam puistu täius ning puu tunnustest mõjutasid puu suhteline kõrgus, suhteline diameeter ning suhteline suuremate puude rinnaspindala.

Puistu tiheduse muutumine on üks olulisemaid, kuid keerulisemaid metsandusliku modelleerimise aspekte. Puistu kasvu modelleerimiseks võib kasutada erinevat tüüpi mudeleid, millest enamlevinud on regressiooni- ning diferentsmudelid. Diferentsmudelid võimaldavad ennustada erinevate tunnuste kasvu pikalt ette. Regressioonimudelitega saab ennustada mingi fikseeritud perioodi võrra ning pikema perioodi jaoks tuleb puistu kasvu arvutada korduvate tsüklitega. Käesoleva töö käigus töötati välja männikute kasvu prognoosimiseks regressioonimudelid, millega ennustatakse puistu diameetri, kõrguse, rinnaspindala, puude arvu ja tagavara kasvu viie aasta kaupa. Selliste mudelite eeliseks on kõikide tunnuste üheaegne kasvatamine lühikeste perioodide kaupa, mis võimaldab leida ka puistu piirtiheduse saavutamise ajahetke. Diferentsmudeliga pikema perioodi jaoks kasvu prognoosimisel on võimalik ületada puistu bioloogiline piirtihedus, mis selgelt viitab prognoosimudeli ebasobivusele.

Puistu kasvu simuleerimiseks kasutatakse nii kasvu kui ka staatilisi mudeleid, kus mõned takseertunnused kasvatatakse ning ülejäänud arvutatakse juba kasvatatud takseertunnuste alusel staatiliste mudelitega. Käesoleva töö üheks osaks on võrrelda kuut erinevat puistu kasvu simuleerimise kombinatsiooni. Kõikide kombinatsioonide korral arvutatakse puistu kõrgus kasvumudeliga. Kuna puude arv, keskmine diameeter ja rinnaspindala vahel on matemaatiline seos (rinnaspindala on puude arvu ja keskmise puu rinnaspindala korrutis), siis nendest tunnustest kaks kasvatatakse ning kolmas arvutatakse nende vahelise seose järgi. Tagavara arvutatakse kasvatatud kõrguse ja rinnaspindala järgi. Erinevaid töös loodud valemeid kombineerides saadi kokku kuus simulatsiooni skeemi. Analüüsi tulemusena leiti, et juhul kui mudelid on loodud sama andmestiku põhjal, siis olulist vahet ei ole, mis järjekorras on tunnused arvutatud ning milliseid puistutunnuseid kasvatatakse ning milliseid arvutatakse staatiliste mudelitega. Olulisemalt erinevaks osutusid skeemid, kus kasutati Kiviste diferentsmudeleid rinnaspindala ja tagavara prognoosimiseks, mis on ka täiesti ootuspärane, kuna need mudelid sisaldavad ka raieid kuid test andmestikus ning teistes kasvumudelites puudusid raied.

Esialgsed mudelid üksikpuu kasvu ning suremuse prognoosimiseks on Eestis juba koostatud. Edasisel metsa kasvu uurimisel ja mudelite loomisel tuleb eelistada mudeleid, mis on võimalikult väheste parameetritega ning oleksid bioloogiliselt tõlgendatavad ja vastavad protsessi loogikale, et võimaldada ka mudelite ekstrapoleerimist.

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I

PUBLICATIONS

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The network of permanent sample plots for forest growth in Estonia

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Abstract

Both adequate forest stand descriptions and stand growth and structure models are needed for effective and sustainable forest management. The key to successful timber management is a proper understanding of growth processes, and one of the objectives of forest modeling is to provide the tools that enable foresters to compare alternative silvicultural approaches. Models of forest structure and growth are currently being developed in Estonia.

Tree-wise re-measured permanent sample plot data are needed to create and maintain forest growth models for Estonia. A new network of permanent sample plots for monitoring the growth and yield of Estonian forests was established in 1995-2005. The network covers the main forest types and the current age distributions of commercial forests in Estonia. The radius of the circular plots ranges between 15 and 30 meters, such that each plot holds a minimum of 100 trees. The sample plots are re-measured at five-year intervals. The polar coordinates and the breast height diameters of all trees are measured. Additionally, the total height, the height to crown base and to the lowest dead branch of 20 percent selected sample trees are measured. Currently, the database of the Estonian network of permanent sample plots contains measurement data for 105 349 trees from 730 sample plots. Altogether 71 506 trees in 492 permanent sample plots have been re-measured once, and 12 841 trees in 97 plots were re-measured two times.

A hierarchical system of stand growth models which are compatible with, and based on, distance independent individual tree growth equations appears be most suitable for forest management in Estonia. Consequently, on the basis of re-measurement data, tree growth and mortality were analyzed, and preliminary models have been elaborated. For reliable forest growth modelling, however, data from 3-4 re-measurements (during the next 15-20 years) would be needed. Nevertheless, the currently available data can be used for modelling of forest structure and dynamics, and for pilot studies exploring different methods of data analysis.

The new network of permanent sample plots for monitoring the growth and yield of Estonian forests is being used by several scientists. It has already proven its worth as a good data source for testing and building models for sustainable forest management in Estonia.

Introduction

Models of forest stand growth and structure are the basis for planning forest management activities like cutting, thinning, regeneration etc. Both adequate forest stand descriptions and stand growth and structure models are needed for effective and sustainable forest management. The key to successful timber management is a proper understanding of growth processes, and one of the objectives of forest modeling is to provide the tools that enable foresters to compare alternative silvicultural approaches (GADOW AND HUI 1999). Models of forest structure and growth are currently being developed in Estonia. At the Estonian State Forest Management Centre, a computer based decision support system is being developed. Unfortunately, forest models used in the system should be improved (NILSON 1999).

According to forestry literature from last decades (HÄGGLUND 1981, SÖDENBERG 1986, NABUURS AND PÄIVINEN 1996, HYNYNEN ET AL. 2002, PRETZCH ET AL. 2002), traditional growth and yield tables and equations approximating them are being replaced with more sophisticated stand growth simulators. The stand growth simulators based on individual tree growth models used in the Finnish MELA (HYNYNEN ET AL. 2002), the Swedish HUGIN (HÄGGLUND 1981), the Austrian PrognAus (LEDERMANN 2006) and MOSES (HASENAUER ET AL. 2006), the German BWINPro (NAGEL AND SCHMIDT 2006) and SILVA (PRETZSCH ET AL. 2006) would be acceptable types of growth model in a computer-based decision support system. However, much effort is required to establish and maintain long-term observations on permanent forest growth plots. According to results form Finland (HYNUNEN ET AL. 2002), data from at least 3-4 plot re-measurements (over 15-20 years) is required for reliable forest growth modelling. This period should be long enough to smooth out annual climate fluctuations.

Since today, in Estonia has been established several data sources, what has been used for forest growth and yield modelling: temporary plot data, stem analysis data, traditional forest inventory data, permanent research plot data, national Forest Inventory (NFI) data and new network of forest growth permanent plots (KIVISTE 1999). A growth model enables reasonable predictions to be made about tree growth and stand development. This purpose may be achieved in different ways, depending on the priorities of the user (GADOW 1996). For establishing the network of permanent sample plots, the Finnish permanent sample plot system INKA (Inventory growth plots), TINKA (Young forest inventory growth plots) and SINKA (Inventory growth plots on peatlands) (HYNYNEN 2001) were used. According the methodology, these were regarded as the most representative material available for modelling purposes.

A growth model is a synthesis of dynamic inventory data indicating growth and change in the forest. These data may be obtained from permanent plots. Permanent plots established to provide data for growth modelling should be designed to satisfy this primary need, and should not be compromised in order to satisfy secondary needs. They to not need to provide resource inventory data efficiently, as alternative sampling procedures can fulfill that need (VANCLAY 1994). The disadvantages are, at first that it takes years to get representative data set (problems with financing, disturbances on plots, changes in methodology and field-teams) and secondly additional time cost to determine the location of sample plots.

An all-Estonian network of permanent forest growth plots has been designed after a similar Finnish system (GUSTAVSEN ET AL. 1988) to provide empirical data for the models. The measurements of permanent sample plots with tree coordinates were started by U. Peterson in 1995. By now, 730 permanent sample plots have been measured. This paper presents the methods used on and the status in 2005 of the network of permanent sample plots.

Method

Growth modellers need data to develop models, to test models, and to use models, and each of these tree activities may require data of a different nature. One of the main principles in collecting data for growth modelling is to sample the full range of site and stand conditions, so that model predictions may be interpolated rather than extrapolated (at least in the sense of stand conditions etc) (VANCLAY 1994).

A method for establishing a network of permanent forest growth plots was developed at the Department of Forest Management of the Estonian Agricultural University. The following principles were used for designing the network of permanent forest growth plots (KIVISTE AND HORDO 2002, 2003).

- A long series of re-measured permanent plots would provide the best data for the modelling of forest stand growth.
- All basic forest types and age and density classes should be represented throughout Estonia.
- The plots should be randomly placed.
- In addition to measurements of trees, tree coordinates on the plots should be determined in order to find the same trees at the next re-measuring and to enable the construction of both distance-independent and distance-dependent models.
- Forest growth plots should be large enough to clearly characterize stand regularities.
- The network of permanent sample plots should be connected as much as possible with the European forest-monitoring program ICP FOREST I, with the network of National Forest Inventory and with previous research areas for the effective and multiple use of the measurement data.

The method of establishing permanent forest growth plots is mainly based on the experience of the Finnish Forest Research Institute (GUSTAVSEN ET AL. 1988). Some recommendations were taken into consideration from Curtis (1983). The codes of species, site types, faults and measurement units were taken from the Estonian NFI instructions (STATISTILISE ... 1999). The following procedures characterize the method.

- The compartments for plots were selected before the beginning of fieldwork according to the desired plot distribution (Table 1). For the placement of plot regions, the grid of the European forest-monitoring program ICP FOREST I (KAROLES ET AL. 2000) was used. Also, the grid of the Estonian National Forest Inventory was used to position plot centres. To save on transport costs, 2 or 3 pairs of surveyors worked together establishing several plots in the same plot region.
- All trees were measured on circular plots with a radius of 15, 20, 25 or 30 meters (Figure 1) to get at least 100 first-storey trees. Smaller trees (second-storey and under-storey trees) were measured in an inner circle with a radius of 8 (the outer circle 15 m) or 10 (the outer circle more than 15 m) meters.
- Measurements on plots were carried out by pairs of researchers. The recorder at the plot centre measured the azimuth and the measurer measured the distance from the plot centre, the breast height diameter in two directions and the faults of each tree. The measured trees were marked with a coloured spot at a height of 1.3 meters. Every fifth tree, dominant trees, trees of rare species and trees in the inner circle were measured as sample trees. For sample trees, the total height, the crown height and the height of dead branches were also measured. Crown height was defined as the height of the lowest live contiguous whorl. In addition to living trees, the coordinates and diameters of standing dead trees and fresh stumps were measured.
- The main instruments for tree measurements were a compass, a calliper and a hypsometer “Forester Vertex”.
- The age of stand components was determined by counting tree rings from cores extracted from sample trees. The thickness of the soil organic layer was measured in several locations on the plot.
- A metal or plastic stick was used to mark the plot centre. In addition, a couple of trees near the plot centre were marked with a coloured circle for easier location in 5 years’ time. The geographical coordinates of plot centres were determined using a GPS device. The plots and their neighbouring objects (roads, ditches, rocks, etc.) were mapped.

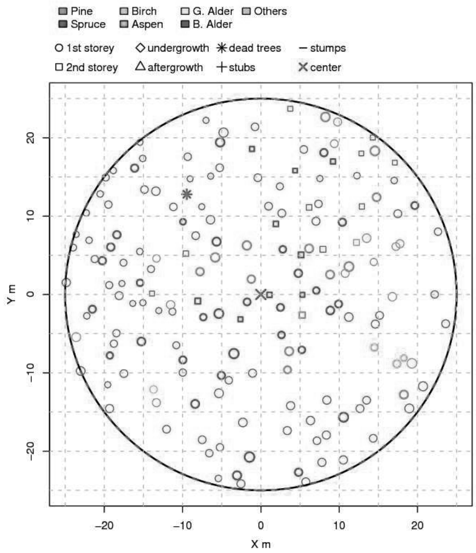

Figure 1: Map of trees: MA-*Pinus sylvestris*, KU-*Picea abies*, KS-*Betula pendula*, HB-*Populus tremula*, LV-*Alnus incana*, LM-*Alnus glutinosa*, JT-other tree species. Label of the layers: º 1st storey, ▫ 2nd storey, ▵ aftergrowth, ◊ undergroth, ∗ dead trees, + stubs, - stumps

The network of permanent sample plots

In Estonia, the first permanent forest growth plots, with tree coordinates, were established by Urmas Peterson in the Pikknurme and Aakre forest districts (Central Estonia) in 1995-1996. In 1997-1998, plots of the same type were established in the Sagadi forest district (North Estonia) and in several areas of south Estonia. During those years, various instruments and methods were tried. As a result, an optimal fieldwork technique was developed. In 1999, a network of permanent forest growth plots to cover the whole of Estonia was designed. From 1999 to 2005, about 100 permanent sample plots were established each year. Figure 2 show that the plots cover most of Estonia.

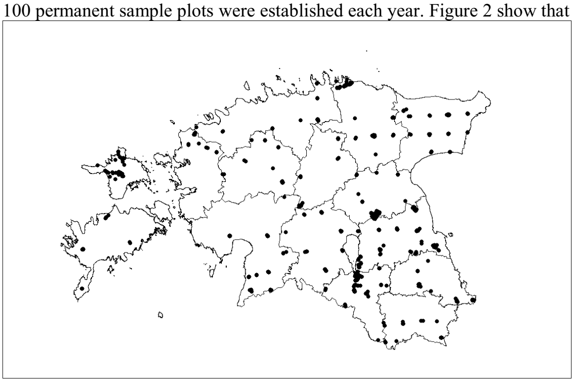

Figure 2: The network of permanent forest growth plots in Estonia established in 1995-2005. Each circle on the map represents a group of plots

Figure 2 shows heterogeneous placement of groups of plots. Most plots are placed according to the regular grid of the European forest-monitoring program ICP FOREST I. The frequent groups of plots in north and central Estonia also indicate previously established research areas.

Table 1: Distribution of permanent sample plots by the main forest site types

Forest site type	*Planned plots*	*Established plots*
Alvar	13	8
Heath	8	47
Mesotrophic	159	292
Meso-euthrophic	99	135
Nemoral	81	127
Herb-rich mixed	111	58
Dwarf-shrub-sphagnum	12	8
Grass fen	17	7
Bog moss	24	13
Full drained swamp	49	35
Total	*573*	*730*

The sample plots are re-measured at five-year intervals. At present, 730 permanent sample plots are established, 492 of which are already re-measured once and 97 plots two times (Figure 3). Figure 4 show that most of permanent sample plots are established in pine stands. Pine (*Pinus sylvestris*), spruce (*Picea abies*) and birch (*Betula pendula*) are most common and economically important tree species in Estonia.

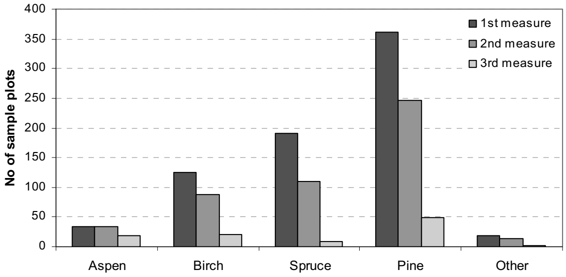

Figure 3: Distribution of permanent sample plots by dominant tree species and measurements

Total of 101 374 live trees are recorded at the first measurement, 33 058 of those are sample trees. At the second measure total of 61 361 live trees are recorded, 21 278 of those are sample trees and at the third measure total of 10 224 live trees are recorded, 3 465 of those are sample tree. Total of 189 696 measurement records, including dead trees, are at the current database. At present, Figure 4 show that most common tree species (pine, spruce and birch) in all age classes are represented almost more or less.

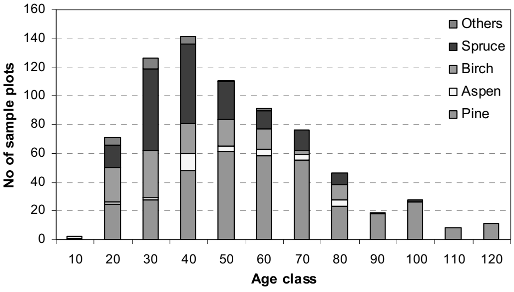

Figure 4: Distribution of permanent sample plots by age classes and dominant species

Data anaysis

The network of permanent sample plots data analysis purpose is to develop, to test stand growth models based on individual tree growth and mortality equations for sustainable forest management in Estonia. At the moment there is a drawback, for reliable forest growth modeling, data from 3-4 re-measurements (during 15-20 years) would be needed. Nevertheless, collected data can be used for modelling of forest structure and for pilot studies in growth data analysis, for example 1) diameter distribution models, 2) diameter and height relationships (KIVISTE ET AL. 2003), 3) crown models, 4) competition indices, 5) spatial structure of trees, 6) individual-trees and stand diameter and height growth models, 7) survival (mortality) probability models (KIVISTE ET AL. 2005), 8) permanent sample plots GIS (Geographical Information System) (LANG ET AL. 2006), and 9) measurement errors / outliers study (HORDO 2004; HORDO 2005; HORDO ET AL. 2005); 10) developing information system for forest management models and datasets (SIMS 2003, SIMS 2004, SIMS ET AL. 2005).

Routine inspection of forest plot measurement data for outliers was necessary because it provided information about the causes and consequences of measurement errors. For the detection of outliers, several statistical methods were tested. Empirical distributions of most tree variables by species and storey were analyzed using Grubb's test, Dixon's test and the 4-sigma region method. Multivariate methods (height curves, residual diagnostics, logistic regression) were used for detecting outliers in the interaction of several variables. A Visual FoxPro program was elaborated for detecting measurement errors and outliers in the forest sample plot data. The program can be easily adapted for all types of forest sample plot data collected in different ways. Additional re-measurement data will give a chance to update the statistical criteria and models used in the program and make it more sensitive (HORDO 2004).

Scientific activity as a whole is somehow related to creating, applying or checking models. In a forestry information system it is now possible to use information on forestry in the form of models. The aim of the database of forest management models is to standardize the form of forest management models and to simplify working with them in application software. The database contains 12 tables. There are tables for formulas, constants, authors, papers, variables, etc. The application allows the testing of models. There are two different ways to test, one where a user can give some values to arguments and the results are drawn as a chart, and another where the results are calculated based on test data. The first one can be used with all models. It is the initial test to see if model constants and arguments are entered correctly. The second type of test is where results are calculated into a table using the test data. The database currently includes 181 forest measurement models from 10 countries. The database is web-based and freely available at http://www.eau.ee/~mbaas/ (SIMS ET AL. 2005).

At present, model for survival (mortality) probability were developed. Tree survival (mortality) probability depending on tree and stand variables have studied. For modeling of tree survival probability, a logistic model using the logit-transformation was applied. Tree relative height had the utmost effect to tree survival probability. However, different factors were included into the logistic model for stands at different development stages: tree height, stand height and site index for young and pole stands; tree relative height, relative basal area of larger trees and stand density for middle-aged and maturing stands; tree relative height and stand density for mature and overmature stands. Acquired results improve our understanding about tree and stand dynamics in Estonian forests. The models can be used as preliminary sub-components for elaboration of the individual tree based stand growth simulator (KIVISTE ET AL. 2005).

The study of individual tree growth models has started. Diameter growth was calculated from basal area increment. Several age-dependent growth models were studied. The expected growth for a given five-year period under average conditions was predicted using individual tree models developed by Clutter and Jones (FORSS ET AL. 1996). This age-dependent growth models has been used with good success, it involves a function which estimates the change in relative tree size. And the beauty of using relative basal area model lies in the fact that stand-based projection and individual tree-based projection can be made compatible. The method has been used successfully in even-aged forest with various tree species (GADOW 1996) and on the permanent sample plot data in Estonia.

Conclusions

Tree-wise re-measured permanent sample plot data are needed to create and maintain forest growth models for Estonia. A new network of permanent sample plots for monitoring the growth and yield of Estonian forests was established in 1995-2005. The network covers the main forest types and the current age distributions of commercial forests in Estonia. Data from repeatedly measured long-term growth and yield permanent sample plots provide enough variation in growth factors (e.g. stand densities) in order to study the growth patterns of stands and trees growing in different conditions. The plot size is large enough for modelling stand dynamics, and data are geographically quite representative.

Currently, the database of the Estonian network of permanent sample plots contains measurement data for 105 349 trees from 730 sample plots. Altogether 71 506 trees in 492 permanent sample plots have been re-measured once, and 12 841 trees in 97 plots were re-measured two times.

Network of forest growth plots is a good data-generator for testing and building models for sustainable forest management in Estonia. First models for individual-tree growth and mortality have developed. Nonlinear models with models with limited number of parameters and 'logical forms' could be preferred in growth studies. Additional forest growth models of neighboring countries should be tested on Estonian permanent data.

A database of forest management models is under construction for including varieties of different forest models in Estonia and neighboring countries (http://www.eau.ee/~mbaas/). The information system is expected to become a useful tool for modelers as well as end-users of models. As the number of models in the system is not limited, new models can continually be added into the system (SIMS 2005).

The new network of permanent sample plots for monitoring the growth and yield of Estonian forests is being used by several scientists. It has already proven its worth as a good data source for testing and building models for sustainable forest management in Estonia.

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Tracking Disturbance-induced Changes in Stand Development at Irregular Measurement Intervals in the Järvselja Forest Experiments

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Abstract

Long-term sample plots have been used to study pathways of succession, and its mechanisms and causes. These observations are relevant not only to communities protected from human interference, but also to managed forests, where the objective is to explain response patterns following specific harvesting operations. The establishment and maintenance of a series of permanent plots requires a firm commitment beyond short-term economic fluctuations and political changes; nevertheless, such long-term experiments may be abandoned prematurely because of a lack of funding or changing policies. One aspect which has received little attention in the past is the "revival" of previously abandoned field plots. This paper analyses data from the Järvselja long-term forest experimental field plots which were abandoned in 1959 and "revived" in 1995 and 2004. This study distinguishes between two kinds of disturbance: natural and anthropogenic. The impacts of both kinds of disturbance are evaluated in terms of weight (quantity of biomass) and type (relative size of outgoing trees). Finally, the study evaluates density-dependent mortality or *self-thinning* using Reineke's limiting line and Nilson's stand sparsity. Our analysis found Nilson's approach better suited for interpreting the limiting relationship in mixed forests and for estimating maximum density for different stand and site types; therefore, this topic will be pursued in future studies based on the extensive database of the Estonian Forest Research Plots Network.

Key words: long-term forest experiments, measurement gap, Reineke's limiting line, Nilson's stand sparsity

Introduction

Sustainable management of forest resources is based on empirical research. The aim of the early field experiments was to measure timber yields at different stages of forest development (Schwappach 1890). Some of these experiments have been re-measured for over a century, even during times of war, providing valuable information on long-term developments. It is often postulated that permanent plots are required in studies of long-term vegetation dynamics (Bakker *et al*. 1996), which is an especially valid assumption in forest ecosystems with long-living tree communities.

Berry *et al*. (1998) state that “quick fixes” and “one-time efforts” are not very helpful in ecosystems research. They argue that piecemeal efforts do not provide the required information about long-term response. They provide arguments in favor of a continuous, long-term observational infrastructure supported by long-term policies, budgets and research perspectives.

The establishment and maintenance of a series of permanent plots requires a firm commitment beyond short-term economic fluctuations and political changes. Nevertheless, it may happen that experiments which were originally designed for long periods of time are prematurely abandoned because of a lack of funding or changing policies.

Today, forest science is based mostly on empirical data, which should be measured systematically. In Estonia, the Network of Estonian Forest Research Plots (Figure 1) was gradually formed during the past 20 years upon the initiative of several Estonian scientists. This network comprises several different long-term forest monitoring, research and experiment series: a) long-term growth and yield study plots in Järvselja (Kangur *et al*. 2005), b) thinning experiments in Järvselja (Tullus and Reisner 1998), c) a series of long-term afforestation plots on abandoned oil-shale quarries (Korjus *et al*. 2007), d) a series of forest restoration experiments, and e) the network of permanent sample plots for forest growth modelling in Estonia (Kiviste and Hordo 2003).

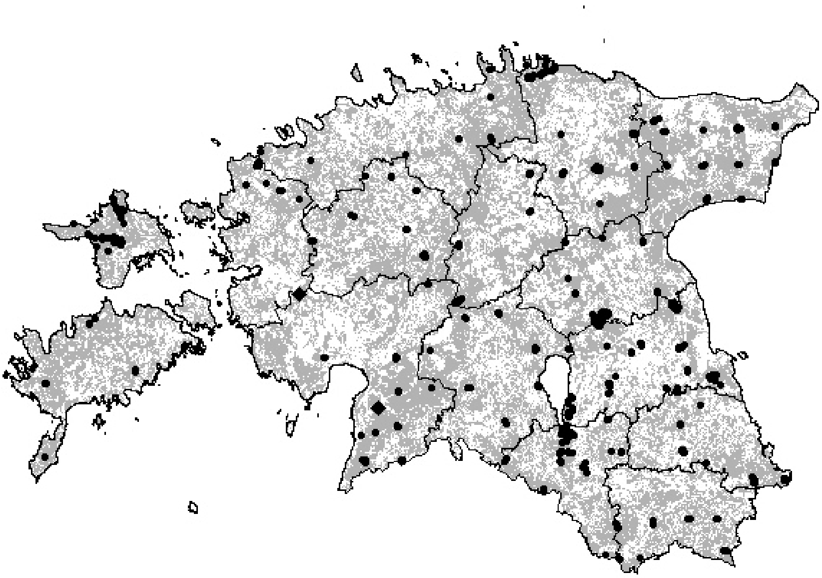

Figure 1. Map of Estonia showing the areas covered by forests (Peterson 2003) and locations of research plots

As an example, the Estonian Forest Research Plots Network currently contains 730 continually-re-measured permanent field plots for modelling forest growth. Table 1 shows the distribution of the plots according to site and forest types. The forest type is characterized by the dominant tree species. “Pine”, for example, refers to a forest where *Pinus sylvestris* either occurs as the only species or dominates by total volume. Such an infrastructure is often considered a national asset (Hasenauer 2006).

Table 1. Summary of the Estonian Forest Research plots, presented by group of types and dominant tree species (by volume)

Group of types	Pine	Spruce	Birch	Other	Total
Full drained swamp forests	13	11	11	0	35
Meso-eutrophic forests	28	94	12	1	135
Alvar forests	5	2	1	0	8
Heath forests	47	0	0	0	47

Mesotrophic forests	246	32	13	1	292
Dwarf-shrub-sphagnum paludified forests	7	1	0	0	8
Grass fen forests	0	0	7	0	7
Nemoral forests	0	30	54	43	127
Bog moss forests	13	0	0	0	13
Herb-rich mixed forests on wet glay soils	3	21	27	7	58
Total	362	191	125	52	730

Examples of forest experiments conducted over more than a century, providing an uninterrupted series of observations, are the extensive permanent networks maintained by a number of European forest research institutes (Hasenauer 2006). The extensive databases and data sets of different research series in the Estonian Forest Research Network have already provided scientists with much useful information, which has been presented at international conferences and published in international journals (Sims *et al*. 2006, Kangur *et al*. 2007). Nevertheless, the importance of combining data from earlier research series together with currently available materials is of high importance in long-term forest research.

One aspect which has received little attention is the use of previously abandoned field plots: Is it worthwhile to “revive” them and to continue with re-measurements after a long interval of abandonment? Missing data are a part of research. Data may be missing for several reasons, and there are alternative ways of dealing with these information gaps. When a previously abandoned experiment is re-established after a long time, the challenge is to make use of the entire period of observation, including the “observational gap”. In this paper, we will propose ways of estimating the missing data for the entire development of the experimental plots.

Accordingly, the objective of this study is to present examples of such abandoned experiments with an estimate of the disturbance occurrence during the measurement gap and the potential forest density for an experiment with one species and two species. We will then show examples of previously abandoned experiments which have recently been re-measured.

Long-term experiments with irregular measurement intervals

Irregular measurement intervals in forest growth studies are quite common. They often occur when previously abandoned field plots are “revived”, *i.e.* re-measured after long periods of time during which no observations are available. When analysing disturbances for irregular measurement intervals, the observed time interval between re-measurements does not match the desired modelling interval. Thus, modelling annual tree growth and survival based on data with irregular measurement intervals requires specific interpolation of the independent variables during such “measurement gaps”, as demonstrated by Nord-Larsen (2006). Our study is not concerned with tree growth, however, but with recognizing forest disturbances during irregular measurement intervals.

Reviving old field experiments at Järvselja

The history of empirical forest research in Estonia can be traced back to the 19th century. Well-designed and -documented field experiments for forest research purposes were begun after the establishment of the Järvselja Forestry Training and Research Centre in 1921 (Mathiesen and Riisberg 1932). The Järvselja experimental forest is located in the South-Eastern region of Estonia near Lake Peipsi (at 58º16´N, 27º18´E).

Among the early long-term forest experimental series in Järvselja are growth and yield experiments initiated by Andres Mathiesen (Kasesalu 2003) and thinning experiments initiated by August Karu and Lembit Muiste (Tullus and Reisner 1998). Long-term forest growth and yield monitoring plots were established between 1922 and 1935. The rectangular experimental plots were relatively small, covering between 400 and 600 m^2. The small plot size was offset by a high number of replicates in the same stand. The experimental sites were selected such that all forest sites and dominant tree species in the Järvselja region were represented. The basic stand parameters were measured and trees on the plots were numbered.

Originally, re-measurement intervals in the experimental areas were planned to range between five to ten years. However, because these areas were used in the field training of forestry students, they were re-measured more frequently during the first decade. The measurement data were stored in handwritten data journals and experiment case files. The last of these handwritten records dates back to 1959. Some of the plots were re-measured in 1977, 1984, and 1995, but for the majority of the growth and yield plots, no measurements were done between 1959 and 2004.

During the late 1990's, it was decided to systematically "revive" the old field plots, most of which had been abandoned in 1959. Altogether, 65 previously abandoned plots which were recently "revived" and re-enumerated after almost 50 years without re-measurements. The distribution of these plots over the different site types and for the different forest types, characterized by the dominant species as in Table 1, is presented in Table 2.

Table 2. Summary of 65 Järvselja Research plots, presented by group of types and dominant tree species

Group of types	Pine	Spruce	Birch	Other	Total
Fully drained swamp forests	5		1		6
Meso-eutrophic forests	6	4	1		11
Mesotrophic forests	22	13	1		36
Nemoral forests		2	2	3	7
Bog moss forests	5				5
Total	38	19	5	3	65

The first step involved the transformation of the old handwritten entries into a digital format, which was necessary for statistical analysis and for storing the data in the multinational database, the Northern European Database of Long-Term Forest Experiments (NOLTFOX).

When analyzing and exploiting old data series like the one described above, one must be aware of possible constraints induced by uncertainties and inconsistencies in measuring and data recording. These inconsistencies can be classified according to the following categories:

1) *Changes in experimental design and measurement prescription.* During long period of observation, governmental policies and general research funding principles may change, which can have severe effects on financing, including termination, of ongoing long-term study projects. Old experimental designs sometimes cannot meet the demands of new research objectives, so new measurement prescriptions may be necessary. In Järvselja during the early

years, the main focus was on compiling stand diameter distributions. Only a few tree heights were measured. However, soon a demand for yield tables arose, requiring tree heights for volume calculations. Subsequently, tree mapping was introduced in order to study forest spatial structures.

2) *High variability in measuring staff and assessment techniques.* Over long measurement periods different people are responsible for carrying out the fieldwork. The measurement accuracy within these series of consecutive enumerations may vary substantially due to changing staff. Furthermore, different measuring devices have been used over extended observation periods. In the early measurement years, tree heights were often measured using a theodolite. At the same time the heights of all the removed trees (representing the suppressed part of the plot) were measured with a measuring tape. These different methodologies could result in two different height-diameter relations.
3) *Changes in data recording and storing.* The biggest change in data recording was the replacement of the old handwritten experimental case files to digital data recording. During data conversion and digitizing it is possible to generate errors due to typing and misinterpretation of certain remarks in the old books. To minimize the likelihood of this type of error, special care was taken in the digitizing of the Järvselja experimental data. Outliers especially were double-checked (Hordo 2004). Nevertheless, some uncertainties still remain.

Recognizing disturbances

In the context of this study, we distinguish between two kinds of disturbance. "Natural disturbance" refer to the number of trees which were found dead at the end of a particular measurement interval. "Anthropogenic disturbance" refers to the trees removed during a thinning operation at the beginning of a measurement interval. Figure 2 shows a typical example of a research plot which had been measured during irregular time intervals between 1926 and 1959. The shortest interval between two successive measurements was one year. The longest interval, labelled "GAP", where data are not available during the period between 1959 and 2004, was 45 years. The measurement years in Figure 2 are indicated by black dots just below the x-axis. The graph on the left presents the quartile lines of the diameter distribution and thus shows how the forest structure has changed during the past 82 years. A pine tree which in 1895 had reached breast height (1.3 m) was cut in 2006 for stem analysis to recover the complete history of diameter and height growth. In 1920, the tree belonged to the 75% quartile of the diameter distribution. In 2006 it was in the 25% quartile of the diameter distribution.

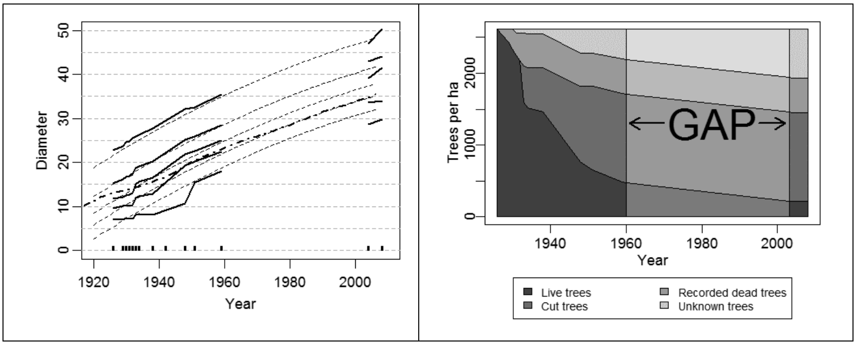

Figure 2. Empirical (solid lines) and predicted/smoothed (dashed lines) quartiles of diameter distribution over time for research plot M046_11_01 (left). The stem analysis for one pine tree is presented as a dash-dot line. The plot had been measured during irregular time intervals between 1926 and 1959, and again in 2004 and 2008 (black spots at the bottom line; the measurement years are shown in Table 3). The development of live trees and cumulative outgoing trees are shown in the graph on the right

The right-hand graph on Figure 2 shows the development of the live trees and the accumulated number of outgoing trees per ha during the 82-year observation period. At every enumeration all trees were measured, including dead snags. When trying to analyse dead trees for the entire 82-year period, during the gap period, only the number of dead trees is known, not their size distribution. Therefore, we need to distinguish between the dead trees that were recorded before 1960 and after 2004, and those that died during the gap period.

In Estonia, forest management activities are recorded in forest management plans, which provide an opportunity to recover some disturbance events. During the gap period, only sanitary cuttings were carried out in the stand, in 1974, 1976, 1977, 1980, 1996 and 1999. These cuttings removed only dead trees, but we do not know when these trees died and how many had died in a certain year. We also have no knowledge about the dimensions of the dead trees during the gap period. We know the number of trees that went missing during the gap interval and that the removed trees were not alive when cut.

For every re-measurement we calculated the accumulated number of trees cut and dead $cNx_t = \sum_{i=1}^{t} Nx_i$, where cNx_t refers to the accumulated number of trees separately for each cut (x=cut) and dead (x=dead) trees at the enumeration period t, Nx_i is number of trees at the enumeration period i; t is measurement interval (years). The number of unknown trees for a particular tree species is obtained from the initial total number of trees of that species minus the cut, recorded dead and live trees. For this plot no measurements are available between 1959 and 2004. Re-measurements started again in *2004*, after a *"gap"* of 45 years. Relevant details about the available natural and anthropogenic disturbances are listed in Table 3.

Table 3. Details about the natural and anthropogenic disturbances in research plot M046_11_01

Year	Area (ha)	Number of trees per ha			Basal area m^2 per ha					Cumul. trees per ha		
		live	cut	dead	live	cut	dead	rG	NG	unknown	cut	dead
1	2	3	4	5	5	7	8	9	10	11	12	13
1926	0.06	2617			35.65			0.00	0.00			
1929	0.06	2433		183	36.97		1.54	0.04	1.75	1		183
1930	0.06	2333		100	37.54		1.21	0.03	1.32	1		283
1931	0.06	2250		33	37.22		0.22	0.01	2.46	51		316
1932	0.06	2183		67	37.33		0.50	0.01	2.25	51		383
1933	0.06	1600	500	83	32.70	4.56	0.78	0.14	1.90	51	500	466
1934	0.06	1517	67		32.48	0.99		0.03	1.43	67	567	466
1938	0.06	1467	50		35.14	0.36		0.01	3.25	67	617	466
1942	0.06		433			6.87		0.00	0.00		1050	
1948	0.06	767			30.13			0.00	0.00	1050	1050	466
1951	0.06	650	117		28.24	3.27		0.10	1.47	1167	1167	466
1959	0.06	483	67	17	25.47	2.19	0.36	0.09	1.63	1234	1234	483
2004	0.06	217			25.13			0.00	0.00	1234	1234	483
2008	0.06	217			27.92			0.00	0.00	1234	1234	483

The weight of a disturbance may be described by the ratio between removed and total basal area. We designate this variable using the symbol rG. The preference of a disturbance refers to the relative tree size removed from the population. Murray and Gadow (1991) used the difference between the mean diameters of the removed and the remaining trees, divided by the diameter standard deviation of the whole stand to describe the type of thinning. In this study, we are using the so-called NG ratio, which is defined as follows:

$$NG = \frac{rN}{rG} = \frac{N_{thn} / N_{tot}}{G_{thn} / G_{tot}} \tag{1}$$

where N_{thn} and N_{tot} are removed and total stem number, respectively; G_{thn}, and G_{tot} are removed and total basal area, respectively The values for rG and NG for the different measurement years are shown in columns 9 and 10 of Table 3. Evidently, the thinnings were usually weak to moderate, ranging from 1 to 14 percent of basal area removed. The NG-ratio varied between 1.32 and 3.25, indicating very low thinnings.

We also recovered disturbances for an experiment involving a mixed forest with two tree species. Figure 3 shows two graphs which correspond with pure pine plot data presented in Figure 2. The two tree species are *Betula pendula* (denoted Birch in Table 4) and *Pinus sylvestris* (denoted Pine in Table 4).

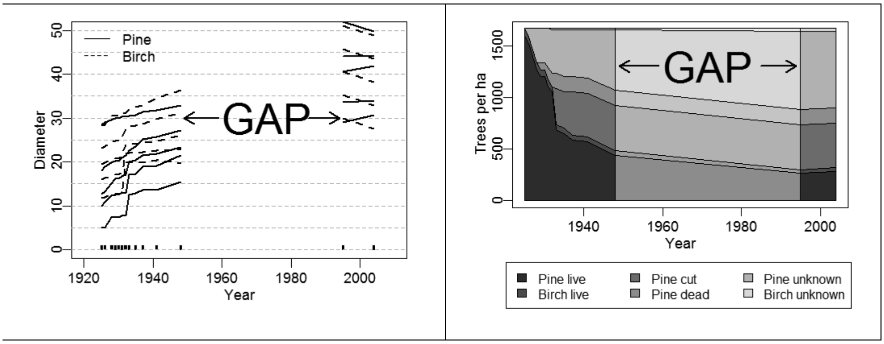

Figure 3. Development of the four quartiles of the diameter distribution of pine and birch for research plot M274_04_02 (left) and development of outgoing trees (right). The plot had been measured (spots at bottom) during irregular time intervals between 1926 and 1959, and again in 2004 and 2008

Table 4. Details about the natural and anthropogenic disturbances in research plot M274_04_02

Year	Area (ha)	Species	Number of trees (per ha)			Basal area (m^2 per ha)			rG	NG	Cumul. trees per ha		
			live	cut	dead	live	cut	dead			unknown	cut	dead
1	2	3	4	5	5	7	8	9	10	11	12	13	14
1925	0.06	Pine	1600			28.47			0.000	0.000			
1926	0.06	Pine	1517			29.04			0.000	0.000	83		
1928	0.06	Pine	1267			28.47			0.000	0.000	333		
1929	0.06	Pine	1200		67	28.34		0.57	0.020	2.658	333		67
1930	0.06	Pine	1200			28.34			0.000	0.000	333		67
1931	0.06	Pine	1100		50	28.10		0.53	0.018	2.364	383		117
1932	0.06	Pine	1050		17	27.63		0.24	0.009	1.799	417		133
1933	0.06	Pine	683	350	17	22.67	5.48	0.08	0.197	1.773	417	350	150
1935	0.06	Pine	650			22.57			0.000	0.000	450	350	150
1937	0.06	Pine	583	67		22.96	1.35		0.056	1.842	450	417	150
1941	0.06	Pine	567			23.00			0.000	0.000	467	417	150
1948	0.06	Pine	433	17		20.61	1.19		0.055	0.676	583	434	150
1995	0.06	Pine	267			33.19			0.000	0.000	750	434	150
2004	0.06	Pine	283			36.47			0.000	0.000	733	434	150
1925	0.06	Birch	67			2.23			0.000	0.000			
1926	0.06	Birch	67			2.29			0.000	0.000			
1928	0.06	Birch	67			2.54			0.000	0.000			
1929	0.06	Birch	67			2.56			0.000	0.000			
1930	0.06	Birch	67			2.56			0.000	0.000			
1931	0.06	Birch	67			2.68			0.000	0.000			
1932	0.06	Birch	50			2.54			0.000	0.000	17		
1933	0.06	Birch	50			2.61			0.000	0.000	17		
1935	0.06	Birch	50			2.65			0.000	0.000	17		
1937	0.06	Birch	50			2.71			0.000	0.000	17		
1941	0.06	Birch	50			2.90			0.000	0.000	17		
1948	0.06	Birch	50			3.13			0.000	0.000	17		
1995	0.06	Birch	33			4.58			0.000	0.000	33		
2004	0.06	Birch	33			4.11			0.000	0.000	33		

The graph shows that initially the birch was dominant, which is quite common in a Pine/Birch community. After 79 years of observation, birch has lost its dominance, and both distributions are similar.

Table 4 presents relevant details of a representative plot with two species. The number of birch trees was reduced to about one half of the original number during the 79-year observation period. The number of pine trees decreased from 1600 per ha in 1925 to 283 per ha in 2004. Only 17 percent of the pines survived during the observation period.

The basal areas has been increasing due to tree growth and decreasing due to mortality and mortality-preemptive removal of some small trees that were still alive but were expected to die in the immediate future. Therefore, the values of rG and NG can be evaluated only during a particular harvest event, i.e. if we can identify the trees which were leaving the system during a specific measurement interval. The calculation schema is described by the example with one species (Table 3) and will not be repeated here.

Stand density in long-term experiments

Populations of trees growing at high densities are subject to density-dependent mortality or *self-thinning* (Mohler *et al.* 1978). For a given average tree size, there is a limit to the number of trees per hectare that may co-exist in an even-aged stand (Nilson 2006). This limiting relationship is site- and species-specific, and the topic is highly relevant to research dealing with natural disturbances. Estimating the potential density of forest stands is one of the most difficult problems to solve, mainly because data from untreated, fully-stocked stands, such as the previously abandoned plots in Järvselja, is very scarce. We analyse the potential density using two approaches, the conventional limiting relationship and Nilson’s stand sparsity.

Reineke’s limiting line

The relationship between the average tree size (increasing over time) and the number of live trees per unit area (declining over time) may be described by means of a so-called limiting line. A convenient model for this limiting relationship was used by Reineke (1933):

$$N_{\max} = \alpha_0 Dg^{\alpha_1} \tag{2}$$

where N_{max} is maximum number of surviving trees per ha, Dg is quadratic mean diameter, α_0 and α_1 are empirical parameters.

The parameters of eq (2), which in its logarithmic form is linear, can be obtained from fully stocked, unthinned trials, such as the spruce growth series established in

Denmark (Skovsgaard, 1997, p. 97 et sqq.) or the *Correlated Curve Trend* (CCT) series of growth experiments established by O'Connor (1935) in South Africa (refer to Gadow 1987, for a description of the CCT experiments and examples of Reineke's limiting line fitted to the data from unthinned CCT experiments).

Nilson's stand sparsity

In the case of a regular spatial distribution of the trees within a forest, the average distance between the trees may be estimated by the square root of 10 000 (the square metres in one hectare) divided by the number of trees per ha. Nilson (1973) thus defined *L*, the *stand sparsity* or distance between regularly placed trees as follows

$$L = \frac{100}{\sqrt{N}} \tag{3}$$

where N is the number of trees per hectare. For a triangular placement of trees the corresponding formula would be

$$L = \frac{200}{\sqrt{3 \cdot N}} \tag{4}$$

Nilson (2006; see also Hilmi 1957) argues that the most simple and logical relation is expected between variables of the same dimension, which is not the case in eq (2), but is the case in eq (3). Therefore, Nilson (1973) proposed to estimate the potential density using the following relationship

$$L = a + b \cdot Dg \tag{5}$$

where L is the stand sparsity, and Dg is the mean squared diameter of the trees in a stand; a and b are empirical parameters.

Estimating potential density

Considering the high cost of maintaining a series of unthinned, densely-stocked stands, such data are usually not available. To overcome this deficiency, various indirect methods have to be used to estimate the limiting line. Gadow and Hui (1993) compared different methods for estimating potential density for unthinned stands of *Cunninghamia lanceolata* from the southern region of China, including the approaches used by Goulding (1972), Sterba (1975) and Clutter and Jones (1980).

We do not need such sophisticated estimation techniques because our long-term experiments had reached the limiting density. No live trees had been removed in the plots during the period 1926 to 1932 and again during the last 49 years (only the very smallest were harvested pre-emptively, i.e. assuming that they would die anyway). Figure 4 shows the estimated limiting relation for plot *M046_11_01*, – pure pines stand in a Mesotrophic forest.

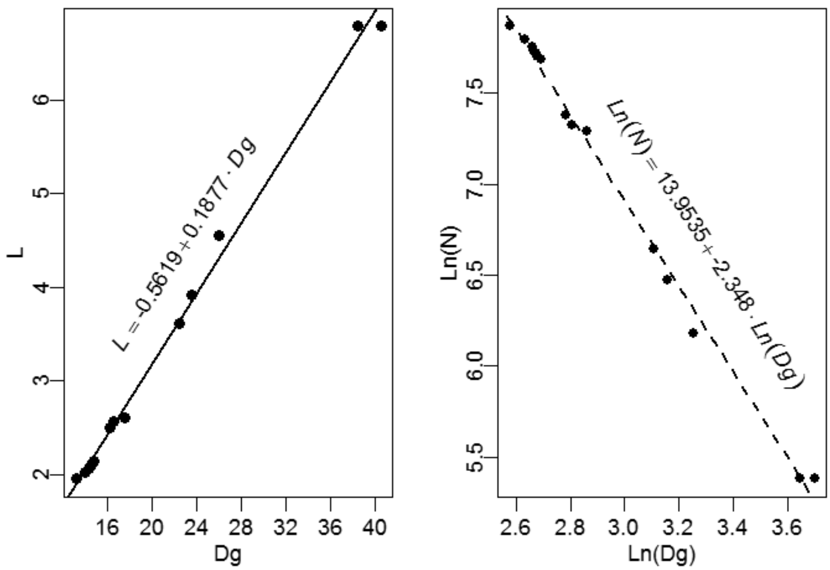

Figure 4. Nilson's Stand Sparsity estimated using eq (3, left) and Limiting Line eq (2, right) for plot M046_11_01

The corresponding analysis for the Pine/Birch experiment *M274_04_02* is presented in Figure 5. It is interesting to note the differences in the slopes and intercepts of the limiting relationships for pine and birch, given the specific relative proportions of tree numbers during the entire measurement period. In 1925, there were 67 birch and 1600 pine trees per ha. Thus four percent of the trees were birch and 96 percent pine. In 2004, ten percent of the trees were birch.

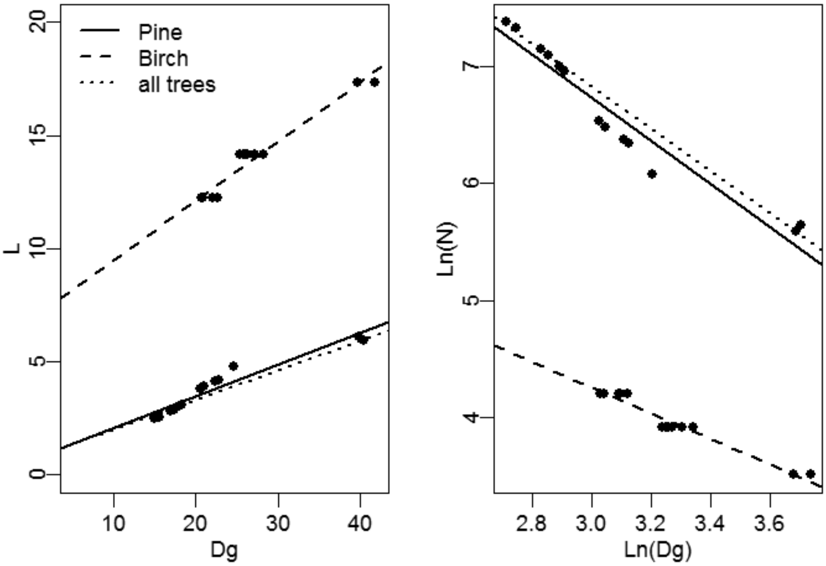

Figure 5. Nilson’s Stand Sparsity estimated using eq (3, left) and Limiting Line eq (2, right) separately fitted for birch and pine trees in plot M274_04_02.

Birch and pine are both light-demanding species and their shade tolerance decreases rapidly growing out of the seedling stage. At the beginning of the plot enumeration, the diameter distributions in Figure 3 show that the birch trees were dominant. This effect can also be seen in the early Dg-values of pine and birch in the left graph of Figure 5. Later on, after reaching a Dg of more than 40 cm, the mean diameters of pine and birch trees are almost equal. This result is not (only) due to growth, but mainly due to higher mortality of the pines in the lower ranges of the diameter distribution.

The slope parameter values of the stand sparsity line are indicative of the mortality rates for a given increase in Dg. The values in Figure 5 are 0.14 for pine and 0.26 for birch, and 0.13 for the whole population. The slope for pine slightly exceeds the slope for the whole stand. This implies a higher pine mortality rate per unit of Dg increase. The beauty of Nilson’s stand sparsity, in contrast to the widely used Reineke line, is that it allows such clear, easily understood interpretations.

Discussion and conclusions

Pickett *et al.* (1987) distinguish between pathways, causes and mechanisms of vegetation change in order to explain the dynamics of succession. They define a pathway as a temporal pattern of vegetation change and a cause as an agent, circumstance or action responsible for successional patterns. Permanent field plots can provide observations about pathways of succession, but may also generate hypotheses on mechanisms and causes. This is especially relevant if the communities are protected from human interference, but is also valid in managed forests where the objective is to explain particular response patterns following specific harvesting operations.

In this study, we defined the problem of analyzing disturbances for irregular measurement interval within the general context of forest research in Estonia. We presented examples of previously abandoned experiments which have recently been re-measured, and proposed a method which can be used to estimate historical disturbances on a specific field plot and during a particular measurement gap.

Considering the enormous investment and its usefulness for environmental research, the national importance and scientific relevance of the Estonian Forest Research database is evident. Valuable observations have been diligently collected by several generations of scientists, providing information about forest structure (Mathiesen and Riisberg 1932, Tullus and Reisner 1998, Kangur *et al.* 2007), disturbances and ecosystem dynamics in the different forest types (Kiviste *et al.* 2005). The maintenance of such a key database is considered to be of national importance in most countries today (Sims *et al.* 2006).

The history of empirical forest research in Estonia began with the establishment of well-designed and documented field experiments in the Järvselja Forestry Training and Research Centre in 1921. Among the early long-term forest experimental series in Järvselja are growth and yield experiments established by Andres Mathiesen between 1922 and 1935 (Kasesalu 2003). The measurement data were stored in handwritten data journals and experiment case files. The last of these handwritten records dates back to 1959. During the late 1990's it was decided to systematically "revive" the old field plots most of which had been abandoned in 1959. This study has shown ways to analyze human and natural disturbances for specific measurement intervals using variables which allow interpretation of the weight of the disturbance as well as its type.

We have also been able to show potential densities for a pure pine plot and a mixed pine/birch experiment using the common Reineke line and Nilson's stand sparsity. The slope parameter values of the stand sparsity line are indicative of the mortality rates for a given increase in Dg. This study has shown a higher pine mortality rate per unit of Dg increase in the mixed plot. The advantage of Nilson's stand sparsity, in contrast to the widely used Reineke line, is the fact that both variables have the same unit, which facilitates interpretations.

The natural decline of the number of surviving trees in an unthinned forest is usually characterized by intermittent brief spells of high mortality, followed by long periods of low mortality. The process is not a continuous one (Boardman 1984, Gadow 1987, p. 21). Stochastic models have been used in some cases to mimic these processes. However, for the purpose of simulating alternative silvicultural regimes, it is generally assumed that natural mortality is a continuous process. Based on the analysis in this paper, we are convinced that Nilson's approach is very useful in estimating the maximum density in Estonian forests, for different stand and site types. This topic will be pursued in future studies based on the extensive database of the Estonian Forest Research Plots Network.

Acknowledgement

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ИССЛЕДОВАНИЕ ИЗМЕНЕНИЙ В ХОДЕ РОСТА ДРЕВОСТОЕВ ОБУСЛОВЛЕННЫХ НАРУШЕНИЯМИ ЛЕСА НА БАЗЕ НЕРЕГУЛЯРНЫХ ИЗМЕНЕНИЙ ПОСТОЯННЫХ ПРОБНЫХ ПЛОЩАДЕЙ В УЧЕБНО-ОПЫТНОМ ЛЕСНИЧЕСТВЕ ЯРВСЕЛЬЯ

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Резюме

На основе повторных измерений постоянных пробных площадей можно получить информацию о сукцессии леса, а также постановитъ гипотезы об её механизме и причинах. Это уместно не только к лесным сообществам, защищенным от человеческого вмешательства, то также и к хозяйственным лесам, где целью исследования является изучение результатов специфических операций пользования лесом.

Учреждение и проведение долговременных наблюдений постоянных пробных площадей требует твердого посвящения исследователей в условиях краткосрочных экономических колебаний и политических изменений. Однако, эксперименты, первоначально разработанные для длительных промежутков времени, могут быть преждевременно оставлены из-за нехватки финансирования или изменения политики. Одним из аспектов, получившим мало внимания в прошлом, является "возрождение" ранее заброшеных постоянных пробных площадей. В этой работе анализируются данные долгосрочных лесных экспериментов в учебно–опытном лесничестве Ярвселья заброшеных в 1950-ых годах и „возрожденных“ в 1995 и 2004 годах.

Данное исследование различает два вида лесный нарушений: естественное и антропогенное. „Естественное нарушение“ леса основывается на количестве деревьев, которые были мертвыми к концу определенного интервала времени. „Антропогенное нарушение“ леса основывается количестве деревьев, которые были вырублены в течение данного интервала времени. Величины обоих видов нарушений леса оценивались изходя из количества биомассы и относительных размеров отпадающих деревьев. Наконец, в данной работе смертность при предельной густоте (зависимость самоизреживания) анализируется по закономерностям, уставленным Рейнеке и Нильсоном. По данным этой работы, подход Нильсона является более предпочтительным для интерпретации зависимости самоизреживания в смешанных лесах и для оценивания максимальной густоты для разных древостоев и условий местопроизрастания.

Ключевые слова: долговременные лесные опыты, разрыв между измерений, линия самоизреживания по Рейнике, редкость древостоя по Нильсону

III

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TAKSEERMUDELITE ANDMEBAASI LOOMISEST.
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Takseermudelite andmebaasi loomisest

Allan Sims

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Abstract. The scientific process as a whole involves creating, applying and checking models. In a forestry information system it is now possible to use information on forestry in the form of models. Different varieties of models have been created to solve narrow fields, but some of the models were never published. Thus, many models have not any published documentation. The aim of the system is to systematize and structure the information we already have about the models. Models are constantly improved; hence, adding models to the system is a continual activity. The goal is to create an on-line database of the forest management models (http://www.eau.ee/~mbaas/) where everyone can enter new models and comment on models already entered. The database currently includes 173 forest measurement models from 10 countries.

Key words: systematization of models, documentation of models

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Sissejuhatus

Kogu metsanduslikku uurimistegevust võib teatud tinglikkusega vaadelda mudelite koostamisena metsa ja metsandusega piirnevate nähtuste kohta, nende kontrollimise ning juurutamisena. Tänapäeva metsanduse infosüsteemides on võimalik metsandusalaseid teadmisi rakendada eelkõige mudelite kaasabil ning seetõttu on kaasaegse metsandusliku uurimistöö tulemuseks üldjuhul mingi mudel.

Metsandusliku modelleerimise kohta on kirjandust palju, selle kättesaadavus juhuslik, esitus keerukas. Publikatsioonide rohkuse tõttu on raske olemasolevatest mudelitest ülevaadet saada. Et igaüks ei peaks hakkama "jalgratast leiutama", sest ei ole leidnud endale vajalikke mudeleid, on vaja hakata väljatöötatud mudeleid koguma ja süstematiseerima (Nilson, 1992).

Mudelite andmebaasi loomine sunnib süstematiseerima ja kriitiliselt läbi vaatama metsanduslikke mudeleid, mille tulemusena on võimalik efektiivsemalt kasutada olemasolevat infot ning välja selgitada olulisemad uurimissuunad (Kiviste, 1994).

Paljude mudelite loomisel oli eesmärgiks lahendada mingi probleem ning mudeli avaldamine ei olnud omaette eesmärgiks. Seetõttu leidub palju mudeleid, mida ei ole kuskil avaldatud. Enamasti puudub neil ka korralik dokumentatsioon selle loomise kohta. Sellistel "tundmatutel" mudelitel põhineva teaduse avaldamine ei ole kontrollitav (Benz, Knorrenschild, 1997). Mudelite dokumentatsiooni ühtlustamiseks on loodud mõned lahendused (Rennolls *et al.*, 2002, Benz *et al.*, 2001), kuid nende süsteemide sihtmärgiks on pigem ökoloogilised mudelid.

Enamik metsamajanduslikke otsuseid põhineb mudelitel. Mudelite abil otsustatakse raiete vajadused, raieküpsuse aeg jms. Kogu RMK metsamajandus on plaanis üles ehitada metsanduse infosüsteemile, mis aitab leida igale puistule sobiva majanduse. Süsteemi korralikuks töölesaamiseks on vaja nii puistut kirjeldavaid mudeleid kui ka kasvu ja struktuuri mudeleid (Kiviste, Hordo, 2003). Viimase paarikümne aasta metsanduslikust kirjandusest (Hägglund, 1981, Pretzsch *et al.*, 2002) võib leida viiteid, et traditsioonilisi kasvukäigutabeleid hakatakse järjest enam asendama puistu kasvusimulaatoritega, mis võimaldavad simuleerida erinevaid kasvu stsenaariume.

Käesoleva uurimuse eesmärgiks on luua takseermudelite andmebaasi süsteem, valmistada mudelite sisestamise ja kontrollimise keskkond ning sisestada mudeleid. Süsteemi eesmärgiks on korrastada ja süstematiseerida olemasolevat infot mudelite kohta. Süsteemi kujundamise peamiseks eesmärgiks on lihtsustada mudelite hilisemat kasutust. Metsanduslike mudelite hulk ei ole lõplik ning neid tehakse järjest juurde, seetõttu täieneb andmebaas pidevalt. Et andmebaasi sisestatud mudelid oleksid korrektsed, tuleb neid testida, selleks on vaja luua testimise süsteem.

Takseermudelite andmebaasi süsteem luuakse veebipõhisena aadressil http://www.eau.ee/~mbaas/, et igaühel oleks kerge sisestatud mudelitele ligi pääseda ning soovi korral ka uusi mudeleid sisestada.

Materjal ja metoodika

Mudel

Süsteemi keskseks osaks on mudel, seepärast on vaja eelnevalt mõista, mida mõeldakse mudeli all ning millised mudelid kantakse andmebaasi.

Mudel on üldine mõiste või mõne reaalse aspekti lihtsustatud kirjeldus. Ta võib olla kas sõnalisel (nt kirjeldus) või materiaalsel kujul (nt mastaabi mudel). Matemaatiline mudel on nagu kirjeldav mudel, kuid kasutab matemaatilist keelt. Selline mudel on lühem ja konkreetsem kui sõnaline kirjeldus (Vanclay, 1994).

Matemaatilised metsanduslikud mudelid võimaldavad kirjeldada metsa ning selle arengut, kasutades selleks matemaatilisi valemeid. Matemaatilised mudelid on saadud enamasti regressioonanalüüsi tulemusena.

Mudelite peamisteks eesmärkideks on (Wallman *et al.*, 2002):

- esitada üldist arusaamist loodusest ning selle erinevatest osadest;
- prognoosida tulevikku, selgitamaks, miks ning kuidas on loodus käitunud minevikus.

Mudeleid võib rühmitada tasemete järgi puistu mudeliteks (*whole-stand model*), jaotuste dünaamika mudeliteks (*size class model*), üksikpuu mudeliteks (*single-tree model*) või maastiku taseme mudeliteks (*landscape-level model*) (Vanclay, 1994; Wallman *et al.*, 2002).

- Puistu taseme mudeliteks võib nimetada selliseid, kus kasutatakse vaid puistu üldandmeid ning puudub info üksikpuude kohta.
- Jaotuste dünaamika mudelid on sellised, kus kasutatakse rühmitatud andmeid (diameetriklassid jms).
- Üksikpuu taseme mudelites on modelleeritavaks elemendiks üksikpuu.
- Maastiku taseme mudelites kasutatakse lisaks puistu andmetele ka taimestiku andmeid.

Tulemused

Andmebaasi loomise põhimõtted

Takseermudelite andmebaasi loomiseks võeti aluseks järgmised põhimõtted (Sims, 2001).

- Takseermudelite andmebaasis on tabelite ja väljade nimed süsteemi rahvusvahelise kasutamise hõlbustamiseks inglise keeles.
- Andmebaasis kasutatakse tabeli väljades, mille väärtus on erinevates keeltes erinev, identifikaatori (ID) numbrit ning vastavas tabelis on selgitus. Selgituse asendamine teiskeelsega teeb mudeli arusaadavaks ka muus keeles. Seda ei kasutata ainult mudeli argumentide juures, sest ID kasutamine raskendab mudelist arusaamist.
- Andmebaas peab sisaldama piisavalt informatsiooni mudeli algallika ja autori kohta, et vajadusel oleks võimalik kerge vaevaga leida täiendavat teavet algallikast.
- Andmebaas peab olema rakendatav. Kui mudeleid on võimalik kasutada otse andmebaasist, siis on kindel, et need on korrektselt sisestatud ning mudelit ei ole vaja rakendamise eesmärgil mujale kopeerida.
- Mudelid ja info nende kohta peab olema sisestatud selliselt, et seda oleks võimalik tõlkida teistesse keeltesse, lihtsustamaks süsteemi rahvusvahelist levikut.
- Mudelite hilisem kasutus peab olema lihtsustatud.

Sisestatav mudelite info

Üldandmed

Üldandmete hulka kuuluvad järgmised mudelit kirjeldavad elemendid:

- riik – määratakse riik, kus või mille andmete põhjal vastav mudel on loodud;
- kommentaar – lühikommentaar mudeli paremaks mõistmiseks;
- kokkuvõte – kirjeldatakse pikemalt andmestikku ja metoodikat, mille alusel vastav mudel on välja töötatud. Kui mudel on võetud artiklist, siis sobib selleks hästi artikli *Summary* või *Abstract*. Kokkuvõte kirjutatakse inglise keeles, et tekst oleks ka rahvusvaheliselt mõistetav.

Argumendid

Et mudelid põhinevad argumenttunnustel, siis on oluline küllalt täpselt määratleda, millised on selle tunnuse omadused. Samuti kirjeldatakse funktsioontunnus. Kõik omadused tuleb eelnevalt sisestada kodifikaatorite tabelisse. Kirjeldatavate tunnustena on peetud oluliseks järgmisi:

- tähis – lühend, mida kasutatakse mudelis. Variantideks on OP, mis on funktsioontunnuseks mudelis, ning $P_1 ... P_n$, mis on argumenttunnusteks; on oluline ainult mudelis kasutamiseks, et vähendada segadust samanimeliste argumenttunnuste kasutamisel (vaata Objekt);
- argument – lühend, mis tähistab antud tunnust, näiteks kõrguse tähistuseks on h, diameeter on d jne;

- ühik – määratakse, millist mõõtühikut antud argumendi korral kasutatakse;
- element – määratakse, millise puu või puistu elemendi kohta antud tunnus kehtib, näiteks tüvi, võra, maa-ala jms;
- asukoht – määratakse kas ajalises või ruumilises mõttes antud tunnuse asukoht, näiteks rinnakõrgus, saja-aastane jms;
- objekt – määratakse tase, mille kohta antud tunnus kehtib, näiteks üksikpuu, puistu element jms; see määratlus on eriti oluline, eristamaks mudelis samanimelise argumenttunnuse kasutamisel samalaadset tähistust mitme erineva elemendi korral, näiteks kõrguse arvutamisel üksikule puule kasutatakse lisaks puistu keskmisele kõrgusele ja diameetrile ka üksiku puu diameetrit;
- sõltuvus – määratakse vajadusel funktsioontunnusele enamasti diferentsiaalvõrrandite korral, kui mudelis on sama argumenti kaks korda erinevate hetkede kohta, näiteks kui vanuse 1 ja kõrguse 1 järgi arvutatakse kõrgus 2 vastavalt vanusele 2, siis funktsioontunnus kõrgus 2 sõltub vanusest 2;
- protsess – muutus, mis toimub antud funktsioontunnusega, näiteks perioodi juurdekasv või kogu juurdekasv;
- periood – määratakse periood, mille kohta protsess käib; näiteks kui arvutatakse perioodi diameetri juurdekasv ning perioodiks on 5 aastat, siis perioodiks määratakse 5 aastat; kui antud argumenttunnuste põhjal arvutatakse tagavara 5 aasta pärast, siis protsessiks on kogu juurdekasv ning perioodiks on 5 aastat.

Konstandid

Enamasti koostatakse mudelid erinevate puuliikide kohta sama kujuga, kuid erinevate konstantidega. Seetõttu sisestatakse valemisse muutujad ning konstandid sisestatakse eraldi tabelisse.

- C_1...C_n – konstante asendavad muutujate nimed.

Valem

Valemite sisestamisel on oluline neid võimalikult optimeerida, sest andmebaasi peab olema võimalik ka rakendada. Näiteks on võimalik kirjutada valem kujul C1+P1*C2+P1ˆ2*C3+P1ˆ3*C4, kuid optimeeritumalt oleks selle kuju C1+P1*(C2+P1*(C3+P1*C4)). Valemite sisestamisel kirjutatakse konstandid eraldi tabelisse ning valemis kasutatakse konstandi tähiseid C_1...C_n.

Valem koosneb järgmistest osadest:

- IPF1 – kui mudel koosneb mitmest eri valemist, siis on võimalik antud lahtris kasutada põhivalemi eelvalemeid; antud valemi väärtus järgmistes eelvalemites ja põhivalemis on IPF1;
- IPF2 – sama nagu IPF1, kuid siin on võimalik juba kasutada ka eelmises valemis välja arvutatud tulemust ning seda muutuja IPF1 näol; antud valemi väärtus järgmistes eelvalemites ja põhivalemis on IPF2;
- IPF3 – sama nagu IPF1 ja IPF2, kuid siin on võimalik juba kasutada ka eelmises valemis välja arvutatud tulemust ning seda muutujate IPF1 ja IPF2 näol; antud valemi väärtus põhivalemis on IPF3;
- valem – põhivalemi lahter;

- kasutatavad funktsioonid – et mitmed funktsioonid on erinevates programmides olemas, siis on võimalik neid kasutada ka valemites; olemasolevad funktsioonid võivad olla erinevate nimedega, seetõttu on standardiseeritud nimed, mida saab kasutada andmebaasis, järgmised:
  - exp(n) – eksponent;
  - sqrt(n) – ruutjuur;
  - log(n) – naturaallogaritm;
  - log10(n) – kümnendlogaritm;
  - iif(l, n, n) – tingimusfunktsioon.

Kaaspuuliigid

Kaaspuuliikide seosed näitavad, milliste puuliikide korral milliseid konstante kasutatakse. Näiteks võivad samad konstandid sobida nii kuusele kui ka ebatsuugale. Kaaspuuliigi määrangu sisestamisel tuleb valida:

- konstandi puuliik – näidatakse, millise puuliigi konstantidele antud määrang on sihitud;
- sobiv puuliik – näidatakse, millisele puuliigile vastavad konstandid sobivad.

Tegevused

Andmebaasi haldamiseks on oluline teada, kes millega ning millal tegeles. Selleks sisestatakse iga tegevuse kohta järgmised andmed:

- aasta – sisestatakse aasta, millal antud tegevus toimus;
- tegevus – määratakse tegevus, milleks on kas mudeli sisestamine, mudeli loomine vms;
- autor – valitakse isik, kes selle tegevuse teostas.

Kirjandusviited

Kui mudel on kuskil avaldatud, on oluline anda ka viide kirjandusele. Sellisel juhul on võimalik leida kirjandusest täiendavat infot antud mudeli kohta. Kui sama mudelit on avaldatud mitmes kohtas, võib sisestada kõik viited.

Õigekirja kontroll

Mudelite sisestamisel andmebaasi on oluline kontrollida õigekirja, st kas sulud on õigesti paigas, argumentide nimed ei ole vahetuses vms. Selline funktsionaalsuse kontroll annab võimaluse hoida andmebaas kvaliteetsena. Igast mudelist on võimalik genereerida kasutaja defineeritud funktsioon ning selle abil teha kontrollarvutused. Kui funktsiooni väljund on ootuspärane, võib oletada, et mudel on sisestatud korrektselt. Selliseid kasutaja defineeritud funktsioone genereeritakse andmebaasist automaatselt. Funktsioone on võimalik saada Visual Basicu, Visual FoxPro või R keskkonna jaoks.

Arutelu

Andmebaas versus *publikatsioon*

Käesolevas uurimuses mõistetakse publikatsiooni all teaduskirjandust, millest võib leida metsanduslikke mudeleid. Nendeks on ajakirjad, raamatud, seeriaväljaanded, brošüürid vms.

Mudelite sisestamisel andmebaasi peab teatud informatsiooni sisestama standardsel kujul. Nõnda on võimalik vähendada segadust, mida kahjuks esineb publikatsioonides, kus vahel on välja jäetud mõningad mudeli olulised osad nagu konstandid, mudeli argumentide kirjeldused vms. Samuti otsustab iga publikatsiooni autor ise, millisel kujul ta valemid esitab. Käesolevas andmebaasis on kõik mudelid standardsel kujul, kõik konstandid peavad olema sisestatud ning mudeli argumendid kirjeldatud (Sims, 2003).

Olles sisestanud mudeli ja kirjandusviite, on andmebaasi kasutajal võimalik leida kirjandusest kerge vaevaga rohkem informatsiooni mudeli kohta ja mudelist paremini aru saada. Publikatsioonides leidub kirjavigu, mida on andmebaasis lihtne parandada, ning pärast vea leidmist ja selle parandamist saavad kõik kasutada korrektset mudelit. Suurendamaks avaldatud mudelite töökõlblikkust, oleks hea, kui mudeli looja sisestaks ise mudeli andmebaasi, sest autor teab kõige paremini, kuidas mudel töötab (Sims, 2003).

Publikatsioone leidub erinevates keeltes ning nendest on raske aru saada ise keelt oskamata. See, kes leiab mudeli võõrkeelsest kirjandusest ning sisestab andmebaasi, võimaldab teistel, kes vastavat keelt ei oska, mudelist paremini aru saada ja seda oma töös rakendada.

Andmebaasi on lihtne rakendada ning kvaliteetsena hoida, sest sisestusvigu on võimalik avastada erinevate kontrollide tulemusena. Mudelite rakendamiseks on võimalik genereerida andmebaasist kasutaja defineeritud funktsioonide fail, seda on lihtne teha mudelite süstematiseerituse tõttu.

Andmebaasi on sisestatud ainult mudel. Puudub mudelit kirjeldav osa (nagu publikatsioonides on materjal ja metoodika jms), samas on iga mudeli juures kirjandusviide, mis võimaldab soovi korral mudeliga lähemalt tutvumiseks leida publikatsiooni. Kuid iga mudeli juurde on võimalik lisada kokkuvõte. Tavaliselt piisab, kui kopeerida kokkuvõte artiklist, kust mudel pärineb, kuid kindlasti ei asenda see artiklit ennast.

Takseermudelite ja andmestike infosüsteem

Loodud mudelite hulk järjest täieneb, seetõttu on vaja vahendit selles mudelite hulgas orienteerumiseks. Et erinevatel andmestikel saadud mudelite hinnangud ei ole võrreldavad (Wallman *et al.*, 2002), on vaja ühtset andmestikku, mille põhjal kõiki mudeleid hinnata.

Järgmiseks etapiks peaks olema ühtne takseermudelite ja andmestike infosüsteem, mis võimaldab automatiseerida mudelite hindamist.

Andmestikuks saab kasutada nii proovitükkide kui ka lausmetsakorralduse andmeid. Samuti on olemas kasvukäigutabelid, mida on võimalik sellises süsteemis edukalt kasutada.

Kokkuvõte

Käesolev uurimus kirjeldab takseermudelite andmebaasi struktuuri ning loomise põhimõtteid. Mudelite ühtlustamiseks töötati välja reeglid, mis võimaldavad andmebaasi sisestatud mudeleid rakendada ning neid andmebaasist süstematiseeritult otsida.

Mudeleid on võimalik vaadata ning sisestada Interneti-aadressil http://www.eau.ee/~mbaas/, kus paikneb nii mudelite sisestuskeskkond kui ka dokumentatsioon. Et süsteemi kujundamisel peeti oluliseks lihtsustada mudelite edasist kasutust, siis on igaühel võimalik sellel aadressil näha nii sisestatud mudelite infot kui ka laadida alla kasutaja defineeritud funktsioone Visual Basicu, Visual FoxPro ning R keskkonna jaoks.

Andmebaasi on juba sisestatud ja analüüsitud 173 mudelit 10 riigist.

Takseermudelite andmebaasi näol on valminud kontrollitud ja standardiseeritud metsanduslike mudelite kogu, mis võiks modelleerijatele olla mugavaks ja kasulikuks abivahendiks. Iga uurimistöö tulemusena saadud mudeli peaks sisestama takseermudelite andmebaasi, sest juba praegu, mil mudelite hulk ei ole veel kaugeltki täielik, on see andmebaas leidnud rakendust ka praktilises metsanduses. Metsanduse praktikas on infosüsteemid muutumas järjest igapäevasemaks abivahendiks ning seetõttu on seal mudelite järele suur nõudlus.

Takseermudelite andmebaasis olevate mudelite loetelu ei ole lõplik ning täieneb pidevalt.

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The database of forest management models

Allan Sims

Summary

Foresters often use models, but finding a specific model is sometimes complicated. One of the solutions is to collect them into a database called the Database of Forest Management Models (ForMod). Everyone can also add models into the database.
At the moment the database contains 173 models from 10 countries.

In the database, models have a certain format which is already stated by the rules of entering models. Every model description also includes references; this simplifies finding the model's source literature. It is possible to use the database as an application; one function operates the database, searches and calculates the results according to input arguments. One of the ways to use the database is to generate a program file containing user-defined functions. The database helps to clarify the most important subjects to research, it also gives an overview what kind of models we already have and which fields are not covered yet.

An application for handling the database allows model testing. There are two methods to test the models, one by drawing models on a chart using argument values from a user, and another by calculating the result into a table using the test data.

For improving the quality, procedures for model testing and visualisations have been created. The initial test is the verification and checking whether the model has been entered correctly into the database. To analyse functionality, the system has procedures for validating models based on empirical data.

For testing purposes, sample plot data is used.

The information system is expected to become a useful tool for modellers as well as end-users of models. As the number of models in the system is not limited, new models can continually be added into the system.

IV

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Comparative modeling of stand development in Scots pine dominated forests in Estonia

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Abstract

In general, forests in Estonia are characterized by great variability, not only in protected areas but in commercial forests as well. The data needed for the derivation and calibration of growth models can be obtained by continuous observation of permanent growth plots (also known as longitudinal studies) or by establishing chronosequences with temporary plots distributed over a wide range of growing sites, densities and ages (also known as cross-sectional studies). A compromise may be achieved by a system of ‘‘interval plots’’ (also known as a short-time series: series which covers a short time). Since the measurement interval is a period of undisturbed growth, it is possible to measure change rates as in a longitudinal study and at the same time cover a wide range of initial conditions as in a cross-sectional study. Numerous models of stand growth have been derived from re-measured sample plots. This study, which uses the data of 142 five-year intervals from 134 unmanaged Scots pine stands, compares six different model combinations involving algebraic difference equations and fixed time-step increment equations. New stand-level diameter and basal area increment equations and a tree survival model which showed close correspondence with the existing stand-level model for Estonia were developed. The main advantage of the use of algebraic difference equations over the fixed-step increment equations is the ability to use flexible time steps. However, the projection intervals should not deviate too much from the time steps of the measurement data. An important constraint when using the algebraic difference equations is to avoid long-term predictions in one projection sequence.

Keywords: Forest management planning; Short-term growth modeling; Interval plots; Algebraic difference equation; Fixed-step increment equation

1. Introduction

In many regions of the world, people depend on forests for their livelihood and well-being. Forests represent an important renewable reservoir of raw materials for the wood processing industry and a remnant wilderness of high recreational and spiritual value in urbanized societies. To meet the demands of society, foresters have been developing silvicultural treatment schedules which are assumed to be optimal for a given set of site and market conditions. Changes in human populations, cultures and attitudes can rapidly shift the effect of human intervention on the natural processes. These shifts alter the patterns of anthropogenic disturbance and lead to changes in patterns of natural disturbance which became apparent many decades later (Oliver and Larson, 1996).

Forest dynamics is affected by many processes at different levels of ecosystem regulation. The growth and change in the number of trees belonging to various age and size classes has been a classic approach to describing forest dynamics. However, the long-term processes include great variation in the factors affecting the dynamic patterns of forest development. The patterns of change shows considerable variation on the temporal and spatial scale: a great number of trees can be removed from a stand within a short period (natural disturbances, cuttings) or the number of trees may decrease gradually by natural mortality or gap formation (Kangur et al., 2005).

There has been considerable debate about empirical modeling of stand growth and yield processes. The purpose of using a growth model is to make reasonable predictions about tree growth and stand development, which may be achieved in different ways and at varying levels of detail, depending on the data available about the trees and the growing site. Models based on stand variables have been used for more

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Nomenclature

$c_1, \ldots, c_4$	regression coefficients
D_t, D_{t_1}, D_{t_2}	stand quadratic mean diameter (cm) at the age of t, t_1 and t_2, respectively
D_{t+5}	stand quadratic mean diameter for the next 5-year period (cm)
ΔD_{t+5}	5-year stand quadratic mean diameter increment (cm per 5-year period)
G_t, G_{t_1}, G_{t_2}	stand basal area (m^2/ha) at age t, t_1, and t_2, respectively
G_{t+5}	stand basal area (m^2/ha) at the end of the 5-year period
ΔG_{t+5}	stand basal area increment in 5-year periods (m^2/ha per 5 years)
H_t, H_{t_1},H_{t_2}	stand mean height (m) at the age of t, t_1 and t_2, respectively
H_{100}	site index (stand mean height (m) at the age of 100 years)
HF	form height (m)
L_t	stand sparsity (average distance between trees (m)) at age t
L_{t+5}	stand sparsity at the end of the 5-year period (m)
ΔL_{t+5}	5-year stand sparsity change (m)
N_t, N_{t_1}, N_{t_2}	stand density (the number of trees per hectare) at age t, t_1, and t_2, respectively
N_{t+5}	stand density (the number of trees per hectare) at the end of the 5-year prediction
OHOR	thickness of soil organic layer (cm)
P_{t+5}	tree survival probability after the 5-year period
R	correlation coefficient
RMSE	root mean square error
RD$_t$	degree of stocking at age t
V_t, V_{t_1}, V_{t_2}	stand volume (m^3) at the age t, t_1 and t_2, respectively
Δy	observed change
$\Delta \hat{y}$	predicted change
Greek letter	
ε	error component

practical purposes. Single-tree modeling leads to greater flexibility in attempting to use details of spacing (Hägglund, 1981; Söderberg, 1986; Nabuurs and Päivinen, 1996; Hynynen et al., 2002; Pretzsch et al., 2002; Hasenauer, 2005).

Since most growth and yield models are developed on the basis of existing empirical data, the most appropriate modeling technique is determined by the level of detail of the available data and the level of resolution of the projection. The data needed for development and calibration of growth models can be obtained by continuous observation of permanent growth plots (also known as longitudinal studies) or by establishing chronosequences with temporary plots distributed over a wide range of growing sites, densities and ages (also known as cross-sectional studies). A compromise may be achieved by a system of ‘‘interval plots’’ (also known as a short-time series: series which covers a short-time). Since the measurement interval is a period of undisturbed growth, it is possible to measure change rates as in a longitudinal study and at the same time cover a wide range of initial conditions as in a cross-sectional study (Glenn-Lewin and van der Maarel, 1992; Gadow and Hui, 1999).

Forest growth and yield tables have traditionally been used in Estonia to offer predictions of forest growth for decision-making in forest management planning. In general, the forests in Estonia are characterized by wide variability in tree species composition and stand structure, both in protected areas and commercial forest (Pärt et al., 2006). The great natural diversity of our forests in combination with the growing role of environmental and socio-cultural values in forest management planning has created a situation in which traditional growth and yield tables do not meet these new requirements (Nilson, 1996, 1999).

A considerable number of growth and yield tables (Krigul, 1969; Kiviste, 1988), several stand growth equation systems (Tappo, 1982; Kiviste, 1999a,b) and some single-tree models (Jõgiste, 1998) have already been developed for stand growth prediction in Estonia. Most of those models are available for public use and have been incorporated into the Database of Forest Management Models (ForMod) which provides open access through an internet-based information system (Sims, 2003, 2005). In principle, the existing growth and yield tables and growth equation systems in Estonia have been created for long-term general growth and yield prediction for practical forest management planning at landscape level.

The concept of adaptive forest management planning has been elaborated in Estonia by Nilson (1996). The idea of this method is adaptive planning of the cutting age for every stand depending on its individual characteristics. The full exploitation of this method requires more detailed growth model systems for stand-level modeling than we have today. An Estonian network of permanent forest growth plots for modeling stand variables and construction of stand growth simulators, which require individual tree growth measurement series, was established in 1995 (Kiviste and Hordo, 2003).

For predicting the main stand variables (height, diameter, density, basal area and volume) requires a complete set of models including both growth and static models. One of the objectives of the current study was the development of short-term stand growth models based on interval plot data for analyzing the performance of various sets of growth models to predict Scots pine dominated stand development during a period of undisturbed growth. The individual model components may be combined in many ways to predict the growth of previously disturbed stands as a whole using the changed initial state of stands functioning as growth predictors as the indirect indicators of previous disturbances. We might thus expect to see great differences when using different types of model with different combinations of predictor variables. Accordingly, the second objective of this study was to analyze various simulation combinations to find the best set of model components for describing short-term Scotch pine stand growth.

2. Material and methods

This section introduces the Estonian network of permanent forest growth and yield plots. We also describe the type of growth model used.

2.1. Interval measurement data

For the study of growth and yield of Estonian forests, we used 5-year interval measurement data provided by the Estonian network of permanent forest growth and yield monitoring plots This network was established in 1995 and was designed using experience of Finnish studies (Gustavsen et al., 1988) to provide empirical data for developing forest growth and yield models (Kiviste and Hordo, 2003). The 679 permanent growth and yield monitoring plots were distributed randomly in 2–10 plots clusters over the entire land surface of Estonia, mainly following the grid of ICP Forest level I monitoring plots (Karoles et al., 2000). The spatial distribution of the plot cluster locations appears in Fig. 1.

The network of permanent plots covers the main forest types and the age range of typical commercial forests in Estonia, re-measurements on the permanent plots being carried out at 5-year intervals. The plots are of circular shape with varying radius, containing at least 100 upper storey trees. The polar coordinates and breast height diameters of all trees are assessed on each plot. In addition, the total tree height and crown length of selected sample trees are measured (Kiviste and Hordo, 2003). The dataset from the re-measurements of 679 plots includes almost 190,000 single-tree measurements.

For this study, Scots pine dominated plots were selected from the database. The stand was considered as pine dominated if the proportion of pine volume exceeded 50%. Since most of the plots selected were pure pine stands (93% of trees on selected plots being pines) all other tree species in the main storey included in model development and for stand mean variables (*H*, *D*, *N*, *G*, *V*) calculation were considered as Scots pine. The 5-year changes in stand height (*H*), quadratic mean diameter (*D*), density (*N*), basal area (*G*) and volume (*V*), at various measurement intervals appear in Fig. 2.

The current study used 142 growth intervals from 134 unmanaged Scots pine dominated plots (Table 1), the average size being 0.1456 ha. Since no silvicultural treatments took place in these plots during the monitoring period, the data represents the stand growth over a 5-year growth interval, undisturbed by forest management. Unfortunately, since there are no reliable records available about the previous management in these plots, we applied a modeling technique "without memory" in which the prediction is a function of the initial system state.

2.2. Model components

Several model components are presented in this section, including difference models based on Estonian forest inventory data and an alternative set of growth models based on interval plot data.

2.2.1. Difference models based on Estonian forest inventory data

The algebraic difference models of Kiviste (1999a,b) are being employed as general growth and yield prediction functions in practical forest management planning in Estonia. These models were developed from Cieszewski and Bella type stand growth equations (1989). The model parameters were estimated using the data of the state forest inventory in Estonia in 1984–1993 (Kiviste, 1995, 1997). The average height, quadratic mean diameter at breast height, and volume of

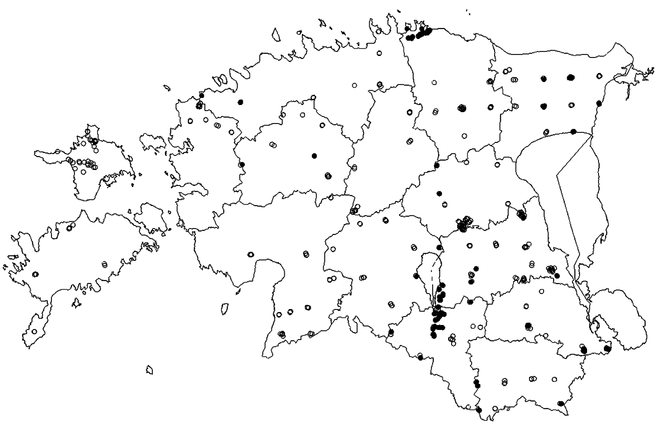

Fig. 1. Geographic location and spatial distribution of Estonian network of permanent forest growth and yield monitoring plots. Each circle on the map presents a cluster of 2–10 sample plots. On the map the circles represent all monitoring areas and the filled dots Scots pine dominated sample plots used in this study.

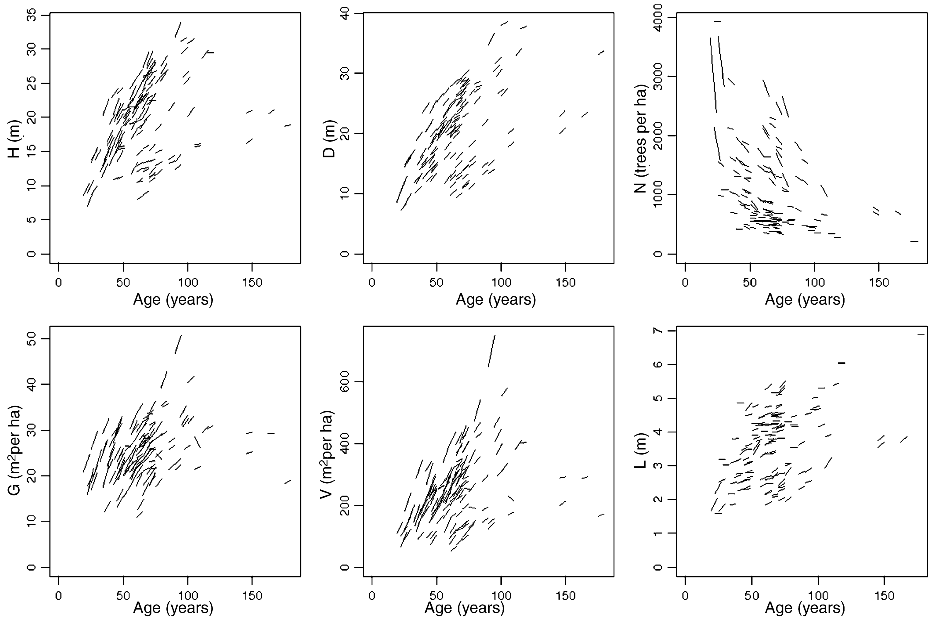

Fig. 2. Change in height (H), diameter (D), density (N), basal area (G) and volume (V) over age and LD relationship in Scots pine dominated stands on the Estonian network of permanent forest growth and yield monitoring plots.

423,919 stands were grouped by forest site type, dominant tree species, stand origin (naturally regenerated or cultivated), and stand age-class (using 5-year intervals). This grouping produced a total of 171 age-series of height, diameter, and volume. Data from young stands (under 20 years for coniferous and hardwood, and 10 years for deciduous forests), over-mature stands and outliers were excluded before the calculation.

Kiviste's difference models were developed from stands in which both natural and anthropogenic disturbances were included. The presumed maximum stand age in these models was fitted with the optimal rotation period of the dominant tree species. In pine-dominated stands this age is 120 years. Future stand mean height (H_{t_2}) at the desired age (t_2) was calculated from the initial age (t_1) and height (H_{t_1}) as follows:

$$H_{t_2} = \frac{H_{t_1} + \mathrm{d}H + \mathrm{r}H}{2 + 4\beta H({t_2}^{-1.58})/H_{t_1} - \mathrm{d}H + \mathrm{r}H} \qquad (1)$$

where $\beta H = 8319 - 493\ \ln(\mathrm{OHOR} + 1)$, $\mathrm{d}H = \beta H/50^{1.58}$ and $\mathrm{r}H = \sqrt{(H_{t_1} - \mathrm{d}H)^2 + 4\beta H H_{t_1}/{t_1}^{1.58}}$.

The stand quadratic mean diameter (D_{t_2}) at the desired age (t_2) was calculated as follows:

$$D_{t_2} = \frac{D_{t_1} + \mathrm{d}D + \mathrm{r}D}{2 + 4\beta H({t_2}^{-1.33})/D_{t_1} - \mathrm{d}D + \mathrm{r}D} \qquad (2)$$

where $\beta D = 6051 - 306\ \ln(\mathrm{OHOR} + 1)$, $\mathrm{d}D = \beta D/50^{1.33}$, $\mathrm{r}D = \sqrt{(D_{t_1} - \mathrm{d}D)^2 + 4\beta D D_{t_1}/{t_1}^{1.33}}$.

The stand volume (V_{t_2}) at the desired age (t_2) was calculated as follows:

$$V_{t_2} = \frac{V_{t_1} + \mathrm{d}V + \mathrm{r}V}{2 + 4\beta H(t_2^{-1.93})/V_{t_1} - \mathrm{d}V + \mathrm{r}V} \qquad (3)$$

Table 1
Summary statistics of 142 growth intervals of unmanaged Scots pine dominated monitoring plots

Variable	Minimum	0.25 quantile	Mean	0.75 quantile	Maximum
Stand age (years)	19.0	50.0	63.5	70.0	175.0
Basal area (m^2/ha)	10.8	20.8	24.5	28.4	46.7
Quadratic mean diameter (cm)	7.2	14.4	19.9	24.7	38.0
Stand density (stems/ha)	212.2	551.3	1039.0	1387.0	3930.0
Stand height (m)	6.9	13.9	19.0	22.9	31.7
Stand volume (m^3/ha)	53.0	157.3	231.0	284.8	647.0

where $\beta V = 380,540 - 54,348 \ln(\mathrm{OHOR} + 1)$, $\mathrm{d}V = \beta V/50^{1.93}$ and $\mathrm{r}V = \sqrt{(V_{t_1} - \mathrm{d}V)^2 + 4\,\beta V V_{t_1}/{t_1}^{1.93}}$.

2.2.2. Growth models based on interval plot data

The predictor variables (quadratic mean diameter, stand density, basal area and sparsity) should be selected as closely as possible to the originally measured variables for reducing the error propagation, collinearity and variance inflation generated during derivation. The model forms should be selected according to the principles of model simplicity (i.e., parameter parsimony) (Burkhart, 2003) and biological realism (Gadow, 1996; Schmidt et al., 2006). The following equations were selected to describe the change in stand variables (growth and survival). The following model was used for stand basal area growth:

$$\Delta G_{t+5} = c_1\,\mathrm{e}^{-c_2 D_t} + c_3 H_{100} + c_4 G_t + \varepsilon \qquad (4)$$

where ΔG_{t+5} is the stand basal area increment in a 5-year period (m^2/ha per 5 years), D_t the stand quadratic mean diameter (cm) at the beginning of the 5-year period, H_{100} the site index (stand mean height (m) at the age of 100 years), G_t the stand basal area (m^2/ha) at the beginning of the 5-year period, $c_1, \ldots, c_4$ the regression coefficients and ε is the error component. Stand basal area at the end of the 5-year period (G_{t+5}) can be calculated as follows:

$$G_{t+5} = G_t + \Delta G_{t+5} \qquad (5)$$

The following regression equation was applied to estimate the stand quadratic mean diameter increment ΔD_{t+5}:

$$\Delta D_{t+5} = c_1 + c_2 D_t + c_3 H_{100} + c_4 G_t + \varepsilon \qquad (6)$$

Stand quadratic mean diameter at the end of the 5-year period (D_{t+5}) can be calculated as follows:

$$D_{t+5} = D_t + \Delta D_{t+5} \qquad (7)$$

A classic approach to predicting stand density at the end of a 5-year period is to estimate the probability of tree survival (P_{t+5}) during the prediction interval (Vanclay, 1994). The logistic equation with logit-transformation was used for this purpose:

$$P_{t+5} = \frac{\mathrm{e}^x}{1 + \mathrm{e}^x} \qquad (8)$$

with $x = c_1 + c_2\,\mathrm{RD}_t + c_3 D_t + c_4 H_{100} + \varepsilon$, where RD_t is degree of stocking at age t. The number of trees per hectare at the end of the period (N_{t+5}) is calculated as follows:

$$N_{t+5} = N_t P_{t+5} \qquad (9)$$

Hart (1928) proposed calculating the average distance between the trees in a forest with N stems per hectare as the square root of the growing space $L = \sqrt{10,000/N}$. This approach assumes regular spacing of trees. The variable L is known as the sparsity of a stand (average distance between trees (m) at time t). The linear dependence between stand mean diameter and stand sparsity has been shown by earlier studies (Nilson, 1973, 2005). Following Nilson, we fitted the separate tree distance based regression equation for estimating the development of variable L:

$$\Delta L_{t+5} = c_1 + c_2 D_t + c_3 H_{100} + G_t + \varepsilon \qquad (10)$$

where ΔL_{t+5} is the 5-year stand sparsity change. Stand sparsity at the end of the 5-year period (L_{t+5}) can be calculated as follows:

$$L_{t+5} = L_t + \Delta L_{t+5} \qquad (11)$$

The difference equation for tree survival published by Gurjanov et al. (2000) was used:

$$N_{t_2} = 1000 \times \left[\left(\frac{N_{t_1}}{1000}\right)^{c_1} + c_2\left(H_{t_2}^{c_3} - H_{t_1}^{c_3}\right)\right]^{1/c_1} + \varepsilon \qquad (12)$$

where N_{t_1} is the number of trees per hectare at the beginning of the prediction period and N_{t_2} is the number of trees per hectare at the end of the prediction period.

For describing basal area growth, the difference equation presented by Gadow and Hui (1999) was applied:

$$G_{t_2} = G_{t_1} N_{t_2}^{\,1 - c_1 H_{t_2}^{c_2}}\, N_{t_1}^{\,c_1 H_{t_1}^{c_2} - 1} \left(\frac{H_{t_2}}{H_{t_1}}\right)^{c_3} + \varepsilon \qquad (13)$$

where G_{t_2} is stand basal area (m^2/ha) at the end of the prediction period.

For comparison of model fit, we calculated the predicted change ($\Delta\hat{y} = \hat{y}_2 - y_1$) and observed change ($\Delta y = y_2 - y_1$) during the period for every model. The correlation coefficient (R) and root mean square error (RMSE) between predicted $\Delta\hat{y}$ and observed Δy were calculated to analyze the model residuals.

2.3. Designing simulation combinations

Six different simulation combinations were used to analyze model predictions of five important stand variables (height, quadratic mean diameter, density, basal area and volume) at the end of a 5-year prediction period. Table 2 shows the calculations of projected stand variables in these combinations. In simulation combinations, some stand variables were calculated using growth models (Eqs. (1)–(13)) while other variables were calculated using static models (Eqs. (14)–(16)). The calculations of stand variables differ in simulation combinations in the use of different formulas or different calculation sequences. The simulations were carried out on the data on 142 intervals from the Estonian network of permanent growth and yield sample plots. Stand volume, form height and degree of stocking in the simulations were calculated according to the Estonian forestry inventory practice:

$$V_t = \mathrm{HF}_t\, G_t \qquad (14)$$

$$\mathrm{HF}_t = H_t \times \left(-0.0309 + \frac{2.5936}{H_t} + -0.0617\sqrt{H_t} + 0.2107 \ln(H_t)\right) \qquad (15)$$

Table 2
The sequence of modeling steps and equations used in simulation combinations showing the sequence of calculation of projected variables with corresponding formula or formula reference of each simulation

Simulation combination	Sequence of model components in the six simulation combinations				
	1	2	3	4	5
$D \times G$	H_{t_2} = Eq. (1)	D_{t_2} = Eq. (7)	G_{t_2} = Eq. (5)	$N_{t_2} = \frac{40{,}000}{\pi}\frac{G_{t_2}}{D_{t_2}^2}$	V_{t_2} = Eq. (14)
$D \times L$	H_{t_2} = Eq. (1)	D_{t_2} = Eq. (7)	$N_{t_2} = \left(\frac{100}{\text{Eq. (11)}}\right)^2$	$G_{t_2} = \frac{\pi N_{t_2} D_{t_2}^2}{40{,}000}$	V_{t_2} = Eq. (14)
$D \times N$	H_{t_2} = Eq. (1)	D_{t_2} = Eq. (7)	N_{t_2} = Eq. (9)	$G_{t_2} = \frac{\pi N_{t_2} D_{t_2}^2}{40{,}000}$	V_{t_2} = Eq. (14)
$G \times N$	H_{t_2} = Eq. (1)	G_{t_2} = Eq. (5)	N_{t_2} = Eq. (9)	$D_{t_2} = \sqrt{\frac{40{,}000}{\pi}\frac{G_{t_2}}{N_{t_2}}}$	V_{t_2} = Eq. (14)
Dif	H_{t_2} = Eq. (1)	N_{t_2} = Eq. (12)	G_{t_2} = Eq. (13)	$D_{t_2} = \sqrt{\frac{40{,}000}{\pi}\frac{G_{t_2}}{N_{t_2}}}$	V_{t_2} = Eq. (14)
Est	H_{t_2} = Eq. (1)	V_{t_2} = Eq. (3)	D_{t_2} = Eq. (2)	$G_{t_2} = \frac{V_{t_2}}{\text{Eq. (15)}}$	$N_{t_2} = \frac{40{,}000}{\pi}\frac{G_{t_2}}{D_{t_2}^2}$

$$\mathrm{RD}_t = \frac{V_t}{-30.5946 + 16.6305 H_t + 0.0254 H_t^2} \tag{16}$$

The root mean square errors (RMSE) were calculated for each stand variables in all simulation combinations.

3. Results and discussion

The growth and yield models routinely used in decision support systems for forest management planning in general lack sensitivity to the interactions of successional dynamics over various ages. They are stand development curves fitted to observed stand growth data describing the net production of a stand of trees. The trend in forest management planning towards ecosystem-based forest management principles has created a need to apply more sophisticated decision support systems. Several more detailed modeling approaches, such as individual tree models using competition indices, hybrid and process based models have already been developed and applied. One way of strengthening the traditional growth and yield modeling approach is to construct compatible tree and distribution models in addition to stand-level models (Richardson et al., 2006).

3.1. Model parameter estimates

Table 3 shows the parameter estimates for the growth models both developed and calibrated from the data on 142 intervals of unmanaged interval plots dominated by Scots pine. The fit statistics R and RMSE of these models are not comparable in the case of different dependent variables, but different equations for the same dependent variable are comparable (e.g., Eq. (4) with Eq. (13) for basal area prediction and Eq. (8) with Eq. (12) for survival prediction). The fit statistics (R = 0.655 and RMSE = 0.952) of the basal area growth model (Eq. (4)) for 5-year growth projection show better results than those for the basal area difference model (Eq. (13)). Similarly, the fit statistics (R = 0.530 and RMSE = 0.045) of the survival probability model (Eq. (8)) perform better than those of the survival difference model (Eq. (12)).

An important aspect of increment functions is that because the actual increment rates are estimated directly from the observed data, the functions are based on a limited set of independent variables (Hasenauer, 2005), but this also restricts prediction of stand variables for a given time interval (usually 5 years, depending on the calibration data measuring interval). The prediction of stand development using algebraic difference

Table 3
Parameter estimates and fit statistics for growth models based on unmanaged Scots pine interval plot data

Model	Parameter estimates				R	RMSE
	c_1	c_2	c_3	c_4		
Basal area growth model (Eq. (4))	12.0422	0.1712	0.1039	−0.0506	0.655	0.952
Diameter growth model (Eq. (6))	1.1909	−0.0256	0.0403	−0.0198	0.585	0.336
Survival probability model (Eq. (8))	3.7012	−0.0210	−2.5612	0.0997	0.530	0.045
Stand sparsity model (Eq. (10))	0.1103	−0.0033	−0.0004	0.0017	0.246	0.075
Gurjanov et al. survival diff. model (Eq. (12))	−2.1023	0.0002	2.5313		0.363	0.055
Gadow and Hui basal area diff. model (Eq. (13))	0.8747	−0.0340	0.9732		0.640	1.134

R: correlation coefficient between observed Δy and predicted $\Delta\hat{y}$; RMSE: root mean square error.

Table 4
RMSE values of projected vs. observed stand variables at the end of the 5-year prediction period according to different simulation combinations

Simulation combination	*H*	*D*	*N*	*G*	*V*
$D \times G$	0.617	0.336	98.232	0.952	21.252
$D \times L$	0.617	0.336	105.634	0.935	21.107
$D \times N$	0.617	0.336	99.434	0.986	21.138
$G \times N$	0.617	0.340	99.434	0.952	21.252
Dif	0.617	0.584	94.850	1.132	24.585
Est	0.617	0.395	160.204	1.695	24.194

models offers more flexibility in terms of prediction interval length.

3.2. Comparing different combinations of model components

The RMSE has been calculated for every stand variable in the simulations (Table 4). In all simulation combinations, the stand height was the first projected variable in the calculation sequence obtained by the same stand height model (Eq. (1)) and where the same RMSE value (0.617 m) occurred. The set of RMSE values showed negligible difference for the first four simulation combinations in Table 4, where projected variables were calculated based on increment equations.

The "Dif" simulation combination showed considerably higher RMSE values for quadratic mean diameter, basal area and volume calculations. It has a higher RMSE, because the stand density and height were predicted independently, and especially since the height model was calculated using a different data set. Both height and stem number already contain a prediction error. The results of the "Est" combination showed the highest RMSE values in stand basal area and density calculations. Both variables were calculated via volume and form height (HF_t, Eq. (14)) and were therefore dependent on the prediction error of the form height model. Fig. 3 shows poorer performance between the observed and predicted basal area of the "Dif" and "Est" simulation combinations in comparison with other simulation combinations. The solid line in Fig. 3 generated by Kernel regression indicates the bias between the observed and predicted basal areas.

The simulation combinations in which diameter was predicted directly using growth equation (7) showed the lowest RMSE values for quadratic mean diameter. The simulations with different combinations of diameter, basal area and tree survival models conducted in the current study showed that the "$D \times G$", "$D \times N$", "$D \times L$" and "$G \times N$" combinations give almost as good or better results than the difference equations.

3.3. Long-term simulation of stand development

We can only predict growth and survival if the interval is a period of undisturbed growth. However, to evaluate different management scenarios, we must be able to model the disturbance events as well as the growth. A basic assumption with interval plots is that the interval is a period of undisturbed

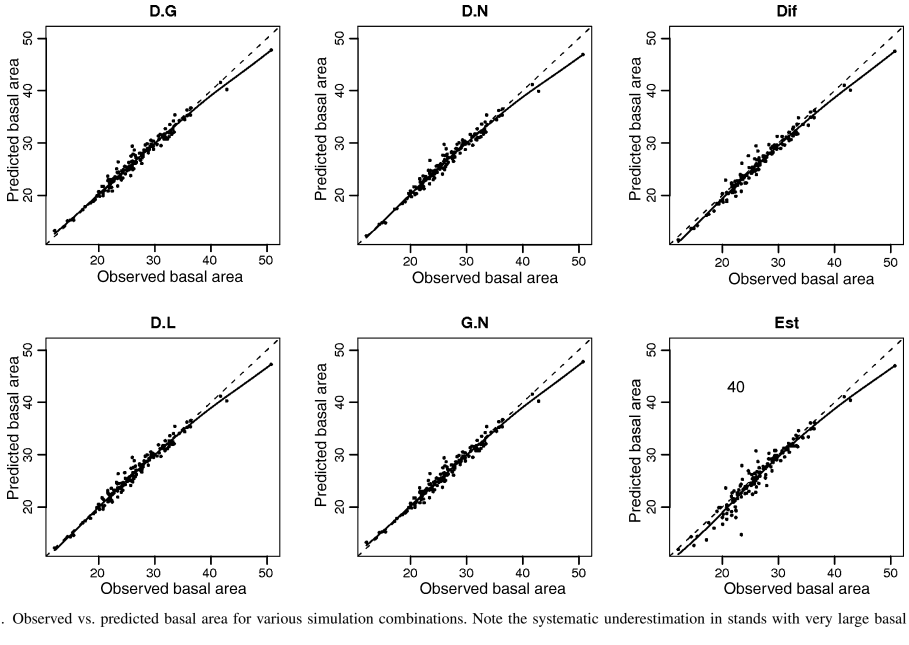

Fig. 3. Observed vs. predicted basal area for various simulation combinations. Note the systematic underestimation in stands with very large basal areas.

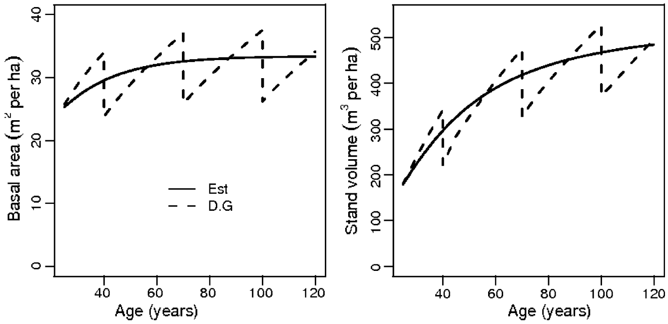

Fig. 4. An example of long-term prediction with the “Est” and “$D \times G$” simulations. The initial data from one sample plot was used (A = 25 years, D = 14.4 cm, H = 13.3 m, G = 25.7 m^2/ha, V = 179 m^3/ha).

growth. All models in this study, except the Kiviste difference equations (Kiviste, 1999a,b), were developed or calibrated on the undisturbed interval plot data. The growth models include natural growth and natural single-tree survival but they do not include anthropogenic interference as can be expected in the case of commercial forests. These models therefore allow us to predict stand growth in commercial forests between harvest events in the long run.

“Est” simulation models have been developed on the basis of forest inventory data, which contain both natural mortality (gap phase disturbances) and thinnings and can be used for long-term prediction. The use of growth models developed on interval plot data in long-term prediction necessitates including both natural and anthropogenic disturbances. An example of the long-term prediction of stand basal area and volume development simulated with the “$D \times G$” simulation combination in comparison with “Est”, which represents the average development of Estonian stands, appears in Fig. 4. In the “$D \times G$” model combination (Table 2), calculations were repeated with 5-year intervals up to 120 years, and the degree of stocking was calculated for every step with the Eq. (16) model. When the degree of stocking exceeded a value of 0.9, the basal area and number of trees was then reduced by 30%, following the Estonian thinning instructions. In spite of different performance in short-term prediction, both simulation combinations showed quite comparable performance in long-term projections.

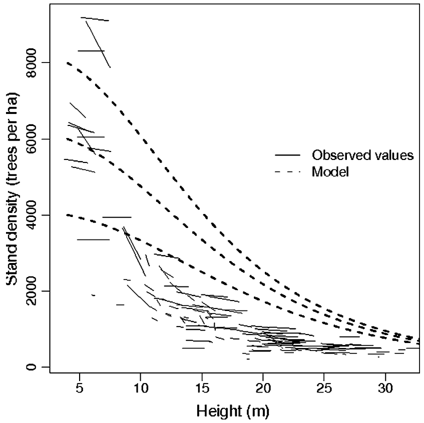

Fig. 5. The algebraic difference models prediction trajectories with three different initial states in comparison with the observed data from the Estonian network of permanent forest growth and yield monitoring plots.

The main advantage of the use of algebraic difference equations over the fixed-step increment equations is the ability to use flexible time steps. However, experience has shown that the projection intervals should not deviate too much from the time steps of the measurement data. An important constraint when using the algebraic difference equations is to avoid long-term predictions in one prediction sequence. Fig. 5 shows an example of the long-term projection of stand density in three different initial densities. A considerable variance in model predictions in comparison of observed values can be seen. This typically happens when only non-overlapping intervals have been used in the model parameter estimation. It is often advisable to use all possible intervals, but even in that case one has to be careful with long-term projections in one sequence.

4. Conclusions

This study compares the results of stand simulation using fixed interval increment functions and algebraic difference functions with variable interval lengths. To compare the flexibility of two different types of empirical model in stand-level prediction, we tested the performance of: (a) increment equations developed in the current study on the basis of interval plot data (Eqs. (4), (6), (8) and (10)), (b) algebraic difference equations calibrated on interval plot data (Eqs. (12) and (13)) and (c) algebraic difference equations developed on Estonian forest inventory data (Eqs. (1)–(3)). The model tests were carried out by comparing the projections of five stand variables (height, quadratic mean diameter, basal area, survival and volume) in different combinations.

The results do confirm the assumption that using different types of model for obtaining projected stand variables makes the projections differ, but not the assumption that considerable differences can be expected in projections when using different combinations of predictor variables in calculation sequences for obtaining projected variables. In this regard, the 5-year projections of dependent stand variables with simulation combinations using increment equations showed negligible difference from each other, but considerable difference from difference equations.

Stand density development is one of the most important but still complicated aspects of forest modeling. The algebraic difference models allow us to predict the average long-term stand development in accordance with a given initial state. The growth models developed in the current study predict growth by 5-year intervals and are therefore inconvenient for the end-user to apply. On the other hand, they are more flexible when taking the limiting line of self-thinning into account. The stands on interval plots used for model parametrizations have not reached the self-thinning state yet and show relatively high basal area and diameter growth. Improving the prediction abilities of these models requires longer intervals of undisturbed development.

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Estimating tree survival: a study based on the Estonian Forest Research Plots Network

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Tree survival, as affected by tree and stand variables, was studied using the Estonian database of permanent forest research plots. The tree survival was examined on the basis of remeasurements during the period 1995–2004, covering the most common forest types and all age groups. In this study, the influence of 35 tree and stand variables on tree survival probability was analyzed using the data of 31 097 trees from 236 research plots. For estimating individual tree survival probability, a logistic model using the logit-transformation was applied. Tree relative height had the greatest effect on tree survival. However, different factors were included into the logistic model for different development stages: tree relative height, tree relative diameter, relative basal area of larger trees and relative sparsity of a stand for young stands; tree relative height, relative basal area of larger trees and stand density for middle-aged and maturing stands; and tree relative height and stand density for mature and overmature stands. The models can be used as preliminary sub-components for elaboration of a new individual tree based growth simulator.

Key words: forest growth, logistic regression, generalized linear mixed model, mortality, survival probability, tree and stand variables

Introduction

Tree mortality is a key factor influencing forest dynamics, and estimating tree survival therefore requires special attention (Yang *et al*. 2003). The accuracy of growth models depends largely on the accuracy of estimating tree survival. The main purpose of survival research is to understand how and why tree mortality occurs. This information is essential for developing strategies of forest management (Hamilton & Edwards 1976). Modelling tree survival is not a trivial task. In her overview Hawkes (2000) highlighted the main problems associated with such models:

Lack of long-term observations. Mortality may be caused by different biotic and abiotic factors which become relevant at different points in time. As a result, the probability of tree survival is usually rather fluctuating and irregular (Gadow 1987).

Improper use of models. Models of tree survival that have been developed on a specific data set and with specific assumptions, should not be used outside the range of their validity. Mortality patterns may differ substantially between different tree species (Dale *et al*. 1985).

Influence of human activity. Human activity is an important factor to natural which complements natural processes and complicates model prediction. It is hard to estimate the effects future management activity, because even in the case of well-defined cutting rules it is difficult to forecast the impact of the real cutting performance in terms of its weight and quality.

According to Vanclay (1994), the causes of tree mortality may be divided into three major groups:

Catastrophic: Large-scale mortality of trees, caused by storms, game damage, insect-pests, flooding or other extraordinary events.

Anthropogenic: Tree mortality caused mostly by harvesting operations, but also by industrial pollution or changes in water tables.

Regular: Tree mortality caused by tree age and competition, but also by pests and diseases and unfavourable weather conditions (storm, drought or flooding).

Catastrophic and anthropogenic mortality are hard to predict and the modeling of such processes requires long-term measurement series on permanent sample plots. Such data are lacking and for this reason, the present study deals only with modeling regular mortality.

A number of models were used to estimate tree survival, including the linear (Moser 1972, Leak & Graber 1976, West 1981), Weibull (Somers *et al*. 1980, Kouba 1989), gamma-distribution (Kobe & Coates 1997), exponential (Moser 1972), Richards (Buford & Hafley 1985), and Gompertz function (Kofman & Kuzmichev 1981). The logistic function has been used mostly for estimating individual tree survival (*see* for example, Hamilton & Edwards 1976, Monserud 1976, Buchman 1979, Hamilton 1986, Vanclay 1991, Vanclay 1995, Dursky 1997, Murphy & Graney 1998, Albert 1999, Monserud & Sterba 1999, Eid & Tuhus 2001, Yao *et al*. 2001, Hynynen *et al*. 2002, Soares & Tomé 2003, Yang *et al*. 2003, Diéguez-Aranda *et al*. 2005). The majority of the more recent survival models have been concentrating on the individual tree level (Mabvurira & Miina 2002). One reason is that the single tree level seems to allow more specific estimates in uneven-aged, species rich forests. In tree survival studies (Hynynen *et al*. 2002, Alenius *et al*. 2003) multilevel logistic regression models for hierarchically structured data are becoming more common.

Until recently, the research covering tree survival in Estonia has not been very extensive. Noteworthy is the model for estimating mortality on the stand level by Jõgiste (1998) and the research by Nilson (2006) about the relation between number of trees and mean stand diameter. Models for estimating individual tree survival are still lacking in Estonia. Only recently it has been possible to use the data from the network of permanent forest growth plots, which covers entire Estonia. Thus, the objective of the present study is to identify from that database variables which influence tree survival. We will present a first attempt to model individual tree survival in Estonia.

Our specific hypotheses were that (i) different sets of driving variables influence tree survival at different stand development stages; (ii) at the tree level, variables of relative size (e.g. ratio of tree and stand diameter) describe tree survival better than variables of absolute size; (iii) at the stand level, variables of maximum density influence survival the most; and (iv) shade-tolerant tree species are more vital than light-demanding, and fast growing species have lower rates of survival.

Factors influencing tree survival

In modeling tree survival, a variety of variables have been considered. Hamilton (1986) classified the factors that affect tree survival into four groups: tree size, tree competition status in the stand, tree viability and stand density. In the present analysis, the main factors that influenced tree survival in other studies, are considered. For that purpose, more than 20 logistic models of tree survival and mortality were analyzed. The logistic models for estimating tree survival can be presented in the following general form:

$$P=\left(1+e^{-f(X)}\right)^{-1}=\frac{1}{1+e^{-f(X)}}=\frac{e^{f(X)}}{1+e^{f(X)}} \qquad (1)$$

where P is the probability of tree survival, $(1 - P)$ is the probability of tree mortality, and $f(X)$ is the function (mostly linear) of diverse influencing factors (Vanclay 1994). Several authors have used Eq. 1 for different tree species, where every species has a specific set of coefficients (Hamilton 1986, Vanclay 1991, Monserud & Sterba 1999, Eid & Tuhus 2001, Hynynen *et al.* 2002). Factors, influencing mortality may be regarded at the single tree or stand level. The most frequently used variables are listed in Table 1.

Material and methods

Data set

The network of permanent forest growth research plots, established during the period 1995–2004 and covering entire Estonia was used in the present study. The first forest growth research plots of the network were established in the nemoral forests and mesotrophic forests of central Estonia in 1995–1996 and in the heath forests of northern Estonia in 1997–1998 (Kiviste & Hordo 2002). Since 1999, the network of forest research plots has been extended, representing the most common forest types and age groups in Estonia. For extension of the network of forest research plots, sample grid of International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (Karoles *et al.* 2000) was used for placement centres of plot groups. The plot locations in the field were selected randomly on a map.

Generally, the permanent forest growth plots are circular with radii of 15, 20, 25 or 30 meters. The plot size depends on the forest age and density, such that, as a rule, on every plot there are at least 100 trees of the upper tree storey. Trees of the second storey and shrub layer were measured in a smaller concentric circle with a radius of eight (at plot radius 15 m) or 10 meters (at plot radius more than 15 m). On each plot, the polar-coordinates (azimuth and distance from the plot centre), the diameter at breast height, and defects were assessed for each tree. The tree height and height to crown base were measured in every fifth tree and also on dominant and rare tree species. The height to the first dry branch of old coniferous trees was also assessed (*see* Kiviste & Hordo 2002 for more details).

In 2004, the network consisted of 730 of permanent forest growth plots. The tree coordinates and breast height diameters of 101 311 living trees were measured. The total tree height and the height to crown base was assessed on 33 045 trees. During 2000–2004, altogether 380 sample plots were re-measured. It was then found, that of 49 814 trees measured during the previous survey, 4658 trees (9.4%) had been harvested and 2883 trees (5.8%) had died (broken or fallen down) during the period between the two measurements.

During the period between the measurements, trees were harvested on 134 plots; 130 of these were excluded from the analysis because the condition of the trees at the time of harvest was not known. Fourteen plots, where the period between the measurements was not exactly five years, were also excluded from the analysis. Thus, the data set used in the present study contains 31 097 trees from 236 plots. Their locations are shown in Fig. 1.

Figure 2 presents distributions of permanent sample plots analyzed in this study by forest site types, dominant species and stand development stages. Most plots are located in the nemoral and mesotrophic forest types. The site type ’others’ includes alvar, transition bog, and fen forests. Pine stands are more represented than stands with other tree species. The alder forests include four black alder plots and five grey alder plots. Almost all groups by site type and by main species include stands of all development stages. Regarding stand age, it appears that the distribution of plots is quite balanced between the ages of 20 and 80 years (Fig. 3). Four plots stocked with pine forests have an age of 150 years or more.

Variables investigated

The list of variables which are assumed to influence tree survival and their statistical characteristics are presented in Table 2. The majority of the variables are continuous (age, height, diameter, etc.), but there are also some nominal variables (storey, tree species, forest site type) and binary variables as a transformation of nominal variables (tree species indicator, sign of moose damage, etc.) in the data set. The investigated data set was hierarchical, some of the variables were appointed at tree level (storey, tree species, tree diameter, tree height, etc.) and others at plot level (dominant tree species, forest site type, age of the first storey, mean diameter, mean height, etc.).

Table 1. Most frequently used tree and stand variables for estimating tree survival.

Individual tree		Forest stand	
Tree status	Source	Stand variable	Source
Tree diameter at breast height (*D*)	Monserud (1976), Hamilton & Edwards (1976), Hamilton (1986), Vanclay (1991), Dursky (1997), Monserud & Sterba (1999), Eid & Tuhus (2001), Yao *et al.* (2001), Mabvurira & Miina (2002), Hynynen *et al.* (2002), Soares & Tomé (2003), Yang *et al.* (2003)	Stand basal area	Hamilton & Edwards (1976), Hamilton (1986), Vanclay (1991), Eid & Tuhus (2001), Yao *et al.* (2001), Hynynen *et al.* (2002), Yang *et al.* (2003), Diéguez-Aranda *et al.* (2005)
Tree relative diameter (the ratio of tree diameter and stand mean diameter)	Hamilton (1986), Eid & Tuhus (2001), Mabvurira & Miina (2002)	Stand dominant height	Palahi & Grau (2003), Diéguez-Aranda *et al.* (2005)
The estimated tree diameter increment for a specified time	Monserud (1976), Hamilton (1986), Vanclay (1991), Yao *et al.* (2001), Yang *et al.* (2003)	Stand age	Hynynen *et al.* (2002), Diéguez-Aranda *et al.* (2005)
Tree height	Hamilton & Edwards (1976), Dursky (1997), Palahi & Grau (2003)	Stand mean diameter	Hamilton (1986), Eid & Tuhus (2001), Mabvurira & Miina (2002)
Tree age	Hynynen *et al.* (2002)	Relative proportion of tree species in stand (measured interms of basal area, volume or number of trees)	Yao *et al.* (2001), Eid & Tuhus (2001)
Relative length of tree crown	Hamilton & Edwards (1976), Monserud & Sterba (1999)	Stand site quality	Dursky (1997), Eid & Tuhus (2001), Yao *et al.* (2001), Mabvurira & Miina (2002)
The sum of basal area of larger trees (BAL index)	Vanclay (1991), Monserud & Sterba (1999), Eid & Tuhus (2001), Hynynen *et al.* (2002), Palahi & Grau (2003)	Number of trees per ha	Eid & Tuhus (2001), Soares & Tomé (2003), Diéguez-Aranda *et al.* (2005)
The sum of basal area of larger broadleaf trees	Yang *et al.* (2003)		
Tree defects caused by game, insects or some other damages	Hamilton & Edwards (1976)		

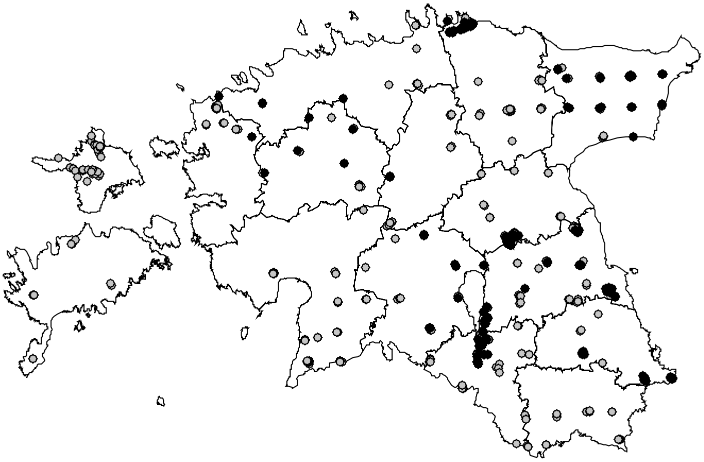

Fig. 1. Location of re-measured permanent sample plots in Estonia. Points in the map indicate locations of 3–6 permanent sample plots. Black dots = plots used in this study, grey dots = other plots in the network.

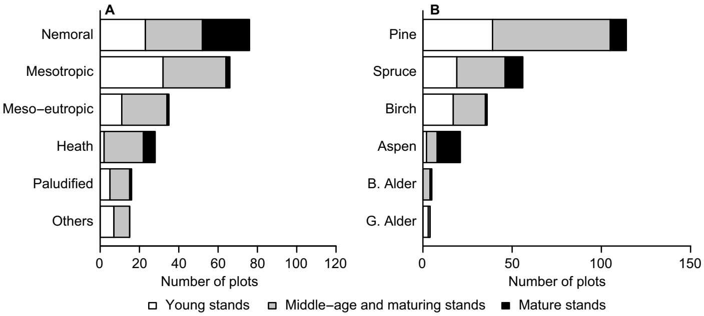

Fig. 2. Distribution of plots by groups of (**A**) forest site types and (**B**) main tree species.

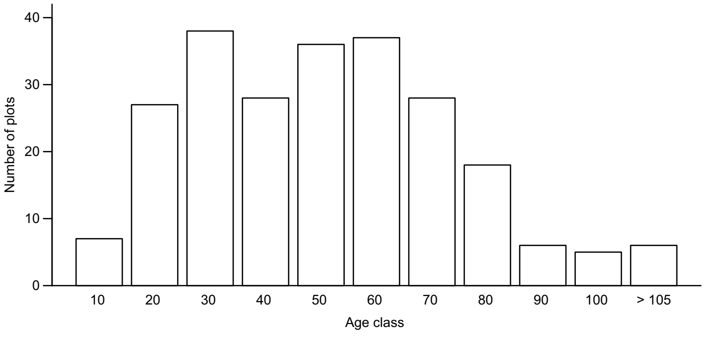

Fig. 3. Distribution of plots by age classes.

The tree storey (RIN) was defined during the field assessment according to the rules of a forest survey. The majority of trees on plots were assigned to the I storey (81.9%). Altogether 17.3% of the trees belong to the second storey (II storey), but substantially less trees were measured from the regeneration and shrub layer (respectively, 0.6% and 0.2%). In some plots, the second story (II storey) and the regeneration trees and the shrub layer were measured in the smaller concentric circle. In some sample plots, the small regeneration and shrub layer trees were not measured at all.

Almost one half of the trees (46.8%) were

Table 2. Variables influencing tree survival and their descriptive characteristics.

Variable code	Description	Unit	Type	Level	Observ. no.	Mean	Min	Max	SD
Tree Level									
RIN	Storey		Nominal	Tree	31097				
PL	Tree species		Nominal	Tree	31097				
D	Breast height diameter	cm	Continuous	Tree	31097	14.5	1.0	74.0	8.0
DS	Relative tree diameter (D/D1)		Continuous	Tree	31097	0.866	0.048	3.91	0.345
H	Tree height	m	Continuous	Tree	9226	16.3	2.0	37.1	7.1
HS	Relative tree height (H/H1)		Continuous	Tree	9226	0.868	0.083	1.79	0.223
KUDS	Relative tree diameter for spruce		Continuous	Tree	31097	0.154	0	3.91	0.355
HNLS	Tree height (calculated)	m	Continuous	Tree	31097	14.8	1.2	37.5	6.3
HNLSS	Relative calculated height (HNLS/H1)		Continuous	Tree	31097	0.868	0.083	1.79	0.223
HV	Height of crown base	m	Continuous	Tree	7807	8.9	0.1	30.3	5.6
SHV	Relative height of crown base (HV/H)		Continuous	Tree	7807	0.526	0.01	0.986	0.185
BAL	Basal area of larger trees	$m^2\ ha^{-1}$	Continuous	Tree	31097	17.5	0	56.0	9.7
BALS	Relative basal area of larger trees (BAL/Gtot)		Continuous	Tree	31097	0.682	0	1.000	0.276
HEG5	Competition index in 5 m radius by Hegyi		Continuous	Tree	31097	4.3	0	194.5	8.2
HEGH	Competition index in 0.4H1 radius by Hegyi		Continuous	Tree	31097	4.3	0	193.7	7.3
PKAHJ	Moose damage		Binary	Tree	31097	0.050	0	1	
RIK	Other damage		Binary	Tree	31097				
Stand Level									
KKTR	Class of forest site type		Nominal	Plot	236				
A1	Age of 1st storey	year	Continuous	Plot	236	53.6	10	230	27.4
N1	Number of trees in 1st storey	$1\ ha^{-1}$	Continuous	Plot	236	1582	143	9372	1737
G1	Basal area of 1st storey trees	$m^2\ ha^{-1}$	Continuous	Plot	236	22.2	4.2	44.5	6.9
D1	Breast height diameter of the 1st storey	cm	Continuous	Plot	236	18.2	4.1	41.1	8.3
H1	Height of the 1st storey	m	Continuous	Plot	236	18.2	3.9	35.2	7.0
M1	Volume of the 1st storey	$m^3\ ha^{-1}$	Continuous	Plot	236	210	19	745	109
T1	Relative density of the 1st storey		Continuous	Plot	236	0.61	0.08	1.53	0.27
L1	Sparseness of the 1st storey	m	Continuous	Plot	236	3.42	1.03	8.36	1.42
VG	Stand development stage		Nominal	Plot	236				
NOOR	Young stand		Binary	Plot	236	0.339	0	1	
KESK	Middle-aged stand		Binary	Plot	236	0.517	0	1	
VANA	Mature stand		Binary	Plot	236	0.144	0	1	
H100	Site index	m	Continuous	Plot	236	26.4	13.1	40.5	5.9
LTJ	Self-thinning sparseness by Tjurin	m	Continuous	Plot	236	2.59	0.76	5.45	1.05
TTJ	Relative sparseness by Tjurin		Continuous	Plot	236	0.77	0.33	1.19	0.14
PIIRT	Limit density by relative density		Binary	Plot	236	0.076	0	1	
PIIRTJ	Limit density by sparseness		Binary	Plot	236	0.064	0	1	

pines, 23.3% were spruces, 18% birches, 3.9% were aspens and 5.1% were alders.

Tree height (H) was measured on 29.7% of trees and the height to crown base (HV) on 25.1% of all trees. To estimate the height of all trees, Nilson's diameter/height relations were used (Kiviste *et al.* 2003). These relations were applied separately to every combination of tree species and storey of each plot (tree cohort). A two-parameter diameter/height regression is being used, when more than five trees per tree cohort were measured

$$\mathrm{HNLS} = \frac{H_{\mathrm{C}}}{1-b\left[1-\left(\frac{D_{\mathrm{C}}}{D}\right)^{c}\right]} \qquad (2)$$

where D is the tree breast-height diameter; D_{C} is the mean square diameter of the respective tree cohort; b and H_{C} are parameters of the diameter-height regression, calculated from sample trees; c is a parameter which depends on the tree species (listed in Table 3). The variable H_{C} represents the mean height of the tree cohort.

When between 1 and 5 trees of each tree cohort were measured on a plot, the following one-parametric diameter-height relation was used

$$\mathrm{HNLS} = \frac{H_{\mathrm{C}}}{1-\left(a-0.0056D_{\mathrm{C}}\right)\left[1-\left(\frac{D_{\mathrm{C}}}{D}\right)^{c}\right]}$$

$$H_{\mathrm{C}} = \frac{1}{N}\sum_{i=1}^{N}\left(H_i\left\{1-\left(a-0.0056D_{\mathrm{C}}\right)\left[1-\left(\frac{D_{\mathrm{C}}}{D_i}\right)^{c}\right]\Big]\right\}\right) \qquad (3)$$

where D is the tree breast height diameter; D_{C} is the mean square diameter of the respective tree cohort; a and c are parameters which depend on the tree species (listed in Table 3); H_i and D_i are sample tree height and diameter respectively.

The diameter/height relation (Eq. 3) was also used in the case of a tree cohort where the heights were not measured. This was the case, for example, in rare tree species which occurred on a particular plot. The mean height H_{C} of a tree cohort was calculated with the formula

$$H_{\mathrm{C}} = 1.3 + k_1\left[1-\exp\left(-k_2 D_{\mathrm{C}}\right)\right]^{k_3} \qquad (4)$$

where D_{C} is the mean square diameter of the tree cohort, and k_1, k_2 and k_3 are species-specific parameters (Table 3).

Relative tree diameter (DS), relative tree height (HS), basal area of larger trees (BAL), relative basal area of larger trees (BALS) and Hegyi competition indices (HEG5 and HEGH) were the investigated variables characterizing individual tree competitive status. Four of these (DS, HS, BAL and BALS) do not require known tree positions and it is relatively easy to calculate them. The relative tree diameter (DS) is calculated as

$$\mathrm{DS} = D/D_1 \qquad (5)$$

where D is the tree diameter and D_1 is the mean square diameter of the first storey trees. The relative tree height is calculated as follows

$$\mathrm{HS} = H/H_1 \qquad (6)$$

where H is the tree height and H_1 is the mean height of the first storey, weighted by the species-specific basal areas. The BAL index is calculated as basal area of trees having a diameter larger than the diameter of the reference tree. The relative basal area (BALS) is equal to the BAL index divided by the basal area of all trees in the plot.

Tree position coordinates and tree-size data are used to define a competition index which requires that the tree positions are known. An example of such a position-dependent quantity is the Hegyi (1974) competition index (HEG5), which is calculated as follows:

$$\mathrm{HEG}_5 = \sum_i \frac{D_i}{DL_i^2} \qquad (7)$$

Table 3. The parameters of the diameter/height relationship for different tree species (Kiviste *et al.* 2003).

Species	a	c	k_1	k_2	k_3
Pine	0.369	1.31	92.4	0.0110	1.0437
Spruce	0.394	1.47	72.7	0.0171	1.112
Birch	0.359	1.38	45.0	0.0320	1.038
Aspen	0.359	1.38	44.6	0.0387	1.290
Other	0.359	1.38	31.0	0.0529	1.144

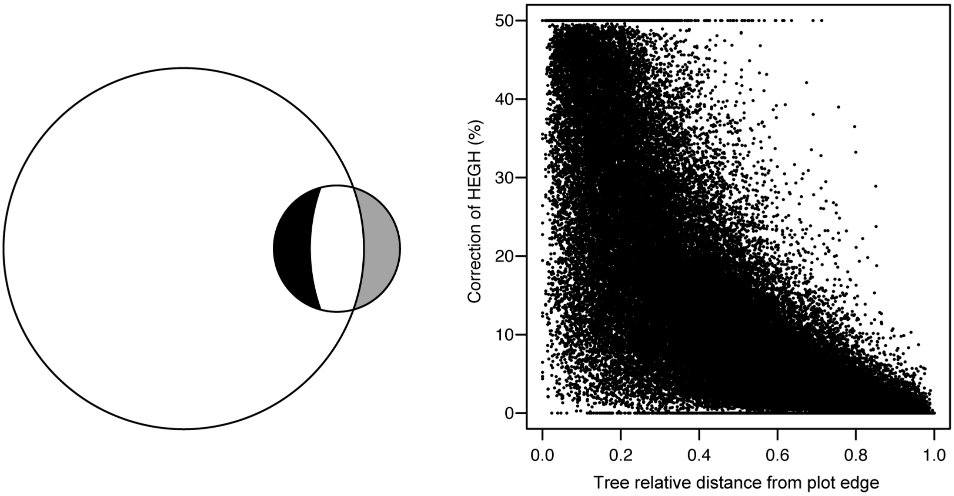

Fig. 4. Left-hand-side panel: adjustment of competition index by Hegyi. The section remaining outside the sample plot (grey) is compensated by considering the section of the same size inside the plot (black). Right-hand-side panel: correction of the edge effect of competition index by Hegyi.

where D is the diameter at breast height of the reference tree (cm); D_i is the diameter at breast height of the competitor tree (cm); L_i is the distance between the reference tree and the competitor tree ($L_i \leq 5$m).

When a tree is located near the external edge of the sample plot, Eq. 7 produces a systematic underestimate, because the influence of neighbouring trees outside the sample plot (light grey area in the Fig. 4 left) are not considered. To compensate for this lack of information, the light grey area was mirrored inside the plot (dark grey area in Fig. 4).

The relative amount of the corrections of the Hegyi index of the trees that are near the plot edges are shown in Fig. 4 (right-hand-side panel). Near the sample plot edge, the value of the competition index is increasing considerably, due to the adjustment.

The value of the Hegyi index depends on stand density and the radius of the influence zone. Thus, a fixed radius (e.g. HEG_5 = 5 m) does not always make sense. For this reason, Hegyi's competition index (HEGH) was also calculated, using an influence zone radius which was equal to 40% of the mean tree height in the first storey.

At the sample plot level, the investigated measurement variables of the first storey were stand age (A_1), density (N_1), basal area (G_1), mean square diameter (D_1), mean height (H_1), stem volume (M_1), and relative density (T_1). To calculate the stem volume of each tree, the volume equation by Ozolins (2002) was used. Stand volume (M_1) was calculated as the sum of the first storey tree stem volumes per hectare.

The site index (H_{100}, average height of dominant species at reference-age 100 years) was calculated according to the current age and height of the dominant tree species using the model developed by Nilson (1999) which is an approximation of Orlov's tables (Krigul 1969).

In the Estonian forestry practice, relative density is widely used. For tree cohorts with a mean height over 5 m, relative density (T_C) was calculated as follows

$$T_{\mathrm{C}} = \frac{M_{\mathrm{C}}}{a_0 + a_1 H_{\mathrm{C}} + a_2 H_{\mathrm{C}}^2 + a_3 H_{\mathrm{C}}^3} \quad (8)$$

where M_C is the volume of the cohort trees ($\mathrm{m}^3\ \mathrm{ha}^{-1}$), and H_C is the mean height of the cohort trees (m). Parameters a_0, a_1, a_2, a_3 are listed in Table 4.

In the case of the mean height being less than 5 m, the relative density (T_C) was calculated according to the National Forest Inventory Instruction (SMI 1999) based on tree cohort height (H_C) and density (N_C). In the case of pine cohorts with a height of less than 5 meters, the relative density was calculated with Eq. 9 and in the case of other tree species with Eq. 10.

$$T_C = \frac{N_C}{5610 H_C^{-0.154}} \quad (9)$$

$$T_C = \frac{N_C}{0.2966 H_C^4 - 8.9075 H_C^3 + 105.48 H_C^2 - 603.85 H_C + 3633} \quad (10)$$

The relative density for the first storey is calculated as the sum of the relative densities of the first storey tree cohorts. As indicator of high relative density, a binary variable PIIRT was used. PIIRT assumes a value of 1 if T_C is greater or equal to 1, otherwise it equals 0.

In addition to traditional stand variables, the stand sparsity (L_1), recommended by Nilson (2006), was also used in the present study:

$$L_1 = \frac{100}{\sqrt{N_1}} \quad (11)$$

where N_1 is the number of trees of the first storey per hectare. L_1 is an estimate of the average distance between trees, assuming a rectangular distribution of tree positions. A. Nilson (pers. comm.) calculated the self-thinning standard (LTJ), based on Tyurin's growth and yield tables of normal forest (Krigul 1969).

$$\text{LTJ} = k_4 + k_5 D_1 + k_6 D_1 H_{100} + k_7 H_{100} \quad (12)$$

where D_1 is the mean square diameter of the first storey trees (cm); H_{100} is the site index; k_4, k_5, k_6, k_7 are species-specific parameters (listed in Table 4).

Analogically to the relative density calculated by the self-thinning model (Eq. 12), the relative sparsity of a stand (TTJ) may be calculated as follows

$$\text{TTJ} = \text{LTJ}/L_1 \quad (13)$$

We assume that if the value of the relative sparsity (Eq. 13) is greater than 1, then the stand has exceeded the self-thinning line which will result in greatly increased mortality of trees. As an indicator of crossing of the self-thinning line, a binary variable PIIRTJ was used. PIIRTJ assumes a value of 1 if TTJ is greater or equal to 1, otherwise it equals 0.

According to a conceptual model of forest stand development based on the study of the Estonian long-term permanent sample plot data (Kangur *et al.* 2005), stand dynamics can be divided into four stages: stand initiation, stem exclusion, demographic transition and old multi-aged. These stages are characterised by different ecological processes. In this study, we have the data from after the stand initiation stage, thus we determined three different stand development stages (VG) according to dominant species and stand age (Table 5), which is common practice in Estonian forest management.

Methods

In the present study, the dependent variable is EJ, which defines the probability that a tree will survive during the next 5-year period. The value of EJ was set equal to 1, if the tree was still alive after five years, and 0 if it was not. Thus, the probability of tree mortality is equal to

$$\text{VL} = 1 - \text{EJ} \quad (14)$$

Table 4. The species-specific parameters of the relative density model $T_c = M_c/(a_0 + a_1 H_c + a_2 H_c^2 + a_3 H_c^3)$ developed on the basis of Tretyakov's standard tables (Krigul 1969) and of the self thinning model LTJ = $k_4 + k_5 D_1 + k_6 D_1 H_{100} + k_7 H_{100}$ developed on the basis of Tjurin's growth and yield tables (Krigul 1969).

Species	a_0	a_1	a_2	a_3	k_4	k_5	k_6	k_7
Pine	–30.595	16.631	0.0254	0	–0.00437	0.1834	–0.00216	0.008641
Spruce	–7.988	9.279	0.3473	0	0.1807	0.1556	–0.00181	0.003598
Birch	15.344	0	0.7411	–0.0087	0.4083	0.1822	–0.00151	0.00671
Aspen	–18.758	8.385	0.3233	0	0.02032	0.1991	–0.00277	0.01046
Other	–11.713	8.474	0.2767	0	0.3867	0.1878	–0.00277	0.0000325

where EJ is the survival probability and VL is the mortality probability. One advantage of modeling the survival probability EJ is that it can be treated as a Markovian process so that the survival probability over a period of N years is given by the Nth power of the annual probability of survival (Vanclay 1994: p. 178).

Simple linear functions are not suitable for modeling survival because they may give predictions of the survival probability outside the feasible range (0, 1). For modeling a variate which follows a binomial distribution, a logistic model may be used where the dependent variable is logit-transformed as follows:

$$\mathrm{logit(EJ)} = \ln[\mathrm{EJ}/(1 - \mathrm{EJ})] \tag{15}$$

Through logit-transformation the dependent variable is transformed into a variate with a normal distribution, which can be analyzed using logistic regression:

$$\mathrm{logit(EJ)} = f(\boldsymbol{X}) \tag{16}$$

where $f(\boldsymbol{X})$ is a linear function of the vector $\boldsymbol{X}$ of measurement variables.

The inverse of the logit-transformation (Eq. 15) is the model that we are using to predict tree survival probability:

$$\mathrm{EJ} = e^{f(X)}/[1 + e^{f(X)}] \tag{17}$$

where $f(X)$ is the equation of a logistic regression.

In logistic regression analysis, the *deviance* (also called as *log-likelihood statistic*) is used to characterize goodness of fit, calculated by logarithmic likelihood. The *likelihood-ratio test* helps to estimate the influence of new arguments, added into the model. The likelihood ratio follows a χ^2 distribution $\chi^2(p)$; where p is the number of parameters, which allows estimation of the statistical significance of added arguments (Dobson 2002). To select the best subset of variables the score statistic was calculated for every single tree variable for ranking single tree influence on survival using PROC LOGISTIC (Freund & Littell 2000) in SAS. The *score statistic* is asymptotically equivalent to the likelihood-ratio test statistic but avoids the need to compute maximum-likelihood estimates (Schaid *et al* 2002).

In the case of the traditional linear regression analysis (with the assumption of a normal distribution of residuals) to characterize the goodness of fit of a model, the root mean square error or coefficient of determination (R^2) are being used (Dobson 2002). By analogy with R^2 for ordinary regression, the generalized R^2 was used which represent the proportional improvement in the log-likelihood function due to the terms in the model of interest as compared with the minimal model (Dobson 2002, Shtatland *et al*. 2002).

$$R^2 = 1 - \frac{\log L(M) - p - 1}{\log L(0) - 1} \tag{18}$$

where $\log L(M)$ is the maximized log-likelihood for the fitted model with number of parameters p; $\log L(0)$ is the “null” model containing only the intercept term.

The SAS LOGISTIC procedure presents two different definitions of generalized coefficients of determination. One has been developed by Cox and Snell (1989: pp. 208–209), the other is an adjusted one by Nagelkerke (1991). In this study the coefficient of determination defined by Eq. 18 was used because Shtatland *et al* (2002) has shown that it has a number of important

Table 5. Age criteria by dominant tree species for stand development stages (VG).

Species	Young stands (NOOR)	Middle-age and maturing stands (KESK)	Mature and over-mature stands (VANA)
Pine	< 50	50–99	≥ 100
Spruce	< 40	40–79	≥ 80
Birch, black alder	< 35	35–69	≥ 70
Aspen	< 25	25–49	≥ 50
Grey alder	< 15	15–29	≥ 30

Table 6. Characteristics of survival probability by storey.

Layer	Number of trees	Number of sample plots	Proportion of spruce (%)	Number of surviving trees	Survival probability (%)	95% CL of survival probability		Survival probability at DS = 0.5 (%)	95% CL of survival probability (DS = 0.5)	
						Lower	Upper		Lower	Upper
1st storey	25477	236	13.5	23654	92.8	92.5	93.2	79.2	78.1	80.3
2nd storey	5380	154	68.3	4927	91.6	90.8	92.3	91.9	91.1	92.5
Regeneration	178	14	74.7	160	89.9	84.5	93.5	92.3	85.3	96.1
Shrub layer	62	5	27.4	37	59.7	47.1	71.0	60.5	45.3	73.9

advantages over the coefficients of determination of Cox and Snell (1989) and Nagelkerke (1991).

For the logistic ANOVA, the procedure GENMOD of the SAS software (Littell *et al* 2002) was used for analysing the tree cohort influence. For multilevel analysis of tree and stand variable influences the generalized linear methods (SAS procedure GLIMMIX) (Schabenberger 2005) and the R function **lmer** (Crawley 2007) were used. The SAS procedure GLIMMIX fits statistical models to data with correlations or non-constant variability and where the response is not necessarily normally distributed. Function **lmer** is used for fitting mixed-effects models in R (package lme4). Both allow analysing a a response variable with a binomial distribution and logit transformation. However, the SAS procedure GLIMMIX implements a restricted pseudo-likelihood (RPL) method whereas a restricted maximum likelihood (RML) method is used in the R function **lmer**.

Results and discussion

Tree survival probability dependence on tree storey

In the present study, four storeys were separately identified on the analyzed sample plots — the first storey (1), the second storey (2), the regeneration (J) and shrub layer trees (A). The results show that the survival probability of the trees which belong to the first storey is higher than that of trees in other storeys (*see* Table 6). The difference in survival probabilities is statistically significant between the first and the second storeys and between the first storey and the regeneration.

We assume that the difference of the survival probability in the storeys in the stand is largely caused by the differences in the relative diameter. To evaluate that assumption, a model of logistic covariance analysis was applied using the procedure GENMOD of SAS

$$\mathrm{logit}(\mathrm{EJ}_{ij}) = \mu + \tau_i + (\beta + \delta_i)\mathrm{DS}, \qquad (19)$$

where EJ_{ij} is the survival probability of a tree in the *i*th storey and the *j*th relative diameter; logit() is the logit-transformation (15); μ is the model intercept; τ_i is the influence of the storey to the intercept; β is the slope of the regression line between the logit-transformation and the relative tree diameter DS; δ_i is the influence of *i*th storey on the slope of the regression line; DS is the ratio between the tree diameter and the first storey mean squared diameter.

Table 6 presents survival probabilities, calculated with Eq. 19 and their confidence limits for different storeys. These results are interesting because of the differences in the viability of the suppressed trees in the different layers. The value of the relative diameter DS was set to 0.5 at each layer. In the case of the suppressed trees in the second storey and regeneration layer, the tree survival was found to be substantially higher than the viability of the trees in the first storey (where DS was also equal 0.5). Much less viable were the shrub layer trees. The relatively high viability of the regeneration and second storey trees is probably due to the fact that spruce, a shade-tolerant tree species, is very prominent in these storeys, and is found here in greater proportions than in the first storey and in the shrub layer.

In many sample plots the smaller understorey trees (trees of the second storey, and of the regeneration and shrub layer) were either not present at all, were measured within a smaller circle, or were not measured at all. Therefore, only the trees from the first storey are considered in the following analysis.

Tree survival probability depending on a single variable

At first, the influence of each variable on tree survival was investigated individually without considering the influence of other variables. The influences were assessed separately for the entire data set as well as for the data sets of the three stand development stages (young, middle-aged, mature).

Table 7 presents the score statistics on different data sets, characterizing the influence of the measurement variable X in the logistic regression formula

$$\mathrm{logit}(\mathrm{EJ}) = \mu + \beta X, \qquad (20)$$

where EJ is the survival probability; logit() is the logit-transformation; X is the measurement observation; μ, β are parameters of the regression equation.

The results in Table 7 show that for the entire dataset and also on separate data sets of all stand development stages, the tree survival probability EJ depended most on the relative height of a tree HNLSS. As mentioned before, the tree heights which were not measured were calculated using a specific diameter/height relationship. For the total database, the second most important variable was the tree relative diameter DS. But in middle-aged and older stands this variable was not in the first triple. The third most important variable in the total data set was BALS (the ratio between the relative basal area of larger trees and the stand basal area).

Table 7. Variables, influencing tree survival probability the most. The numbers in the table represent score statistics of differences between intercept only and intercept with variable.

Variable	All data	Young stands	Middle-aged and maturing stands	Mature and overmature stands
HNLSS	1881	640	1166	109
DS	1300	435	810	73
BALS	1099	403	620	70
HEGH	907	247	920	85
D	859	188	800	88
HEG5	776	187	932	82
BAL	725	435	249	74
HNLS	606	88	610	60

Considering the total data set, effective variables were also both Hegyi competition indices (HEGH and HEG5) and then the tree height *H*, the tree diameter *D* and the basal area of larger trees BAL. Stand variables (both versions of relative density and quality class) and tree species were clearly less important than the measured variables which characterize the relative state of a tree. From the practical viewpoint, the tree diameter *D* and the tree relative diameter DS are explanatory variables which can be used in distance-independent forest-growth models. Therefore, these variables are often preferred to competition indices which require known tree positions.

The influence of the height to crown base and of the relative height of crown base on the tree survival probability was analyzed for sample tree data sets where the height to crown base was measured and the spruce trees were left out. The results show that in young and middle-aged stands, the influence of the height to crown base on the tree survival probability was less than the influence of the other variables listed in Table 7. Old stands were an exception; there, the influence of relative and absolute height to crown base on mortality was clearly higher than the influence of other variables.

Tree survival probability dependence on several variables

Tree survival probability EJ was modeled with the two-level mixed model

$$\begin{aligned}\operatorname{logit}\left(\mathrm{EJ}_{ij}\right) &= \beta_{0j} + \beta_1 X_{1ij} + \beta_2 X_{2ij} + \dots \\ &\quad + \beta_m X_{mj} + \beta_{m+1} X_{m+1j} + \dots\end{aligned} \qquad (21)$$

where EJ_{ij} is the tree survival probability; logit() is the logit transformation (Eq. 15), β_{0j} is the random intercept ($\beta_{0j} = \beta_0 + u_j$:$u_j \sim \mathrm{N}(0, \sigma_u^2)$, *i* is the tree number; *j* is the plot number; X_{1ij}, X_{2ij} are tree level variables; X_{mj}, X_{m+1j} are stand level variables; β_0, β_1, β_2, β_m, β_{m+1}, ... are model parameters.

Taking a great number of arguments into the model may be justified in the case of a random sample, such as a forest inventory, where all elements of a population have the same probability to be part of the sample. Unfortunately, the selection of stands in the Estonian forest research plot network was not entirely random, which is also revealed in the distribution histograms in Figs 2 and 3. That is why the principle of developing a model which is as parsimonious as possible (Burkhart 2003) was followed in this study.

The selected variables (Table 2) were divided into three groups: vertical size variables (HNLS, HNLSS, H_1, etc.), horizontal size variables (*D*, DS, D_1, etc.) and competition variables (BALS, BAL, HEG5, HEGH, etc.). Variables of relative size (relative diameter, relative height) could be handled as size group variables as well as competition group variables. However, in this study relative size variables were handled as size group variables, because we assume that they are indicative of the amount of resources needed for tree survival. For selecting variables into the multiple model, an ordered list of score statistics was calculated for all variable combinations using the LOGISTIC procedure. However, not all variable combinations on top of the list of score statistics were biologically interpretable and with statistically significant parameter estimates. For multilevel logistic modeling with a random intercept (Eq. 21) we selected one tree level variable from each group, a stand level competition variable, and the tree species as regressors (HNLSS, DS, BALS, TTJ, KUDS, PL). The results of this multilevel logistic modelling on different data sets are presented in Table 8.

Table 8 presents two sets of results of multilevel logistic modelling, one obtained with the SAS procedure GLIMMIX and the other with the R function **lmer**. Both procedures use different methods for parameter estimation. Nevertheless, both methods established the same set of significant variables and produced similar parameter estimates which is somewhat reassuring. All terms in the model are biologically sound: tree survival (EJ) is increasing with increasing relative height (HNLSS) and decreasing with increasing competition status (BALS, TTJ). Considering the effect of different tree species, spruce survival was significantly higher and grey alder survival significantly lower than other tree species for all development stages. This can be explained by the shade tolerance of spruce and the short life of grey alder. Significance of variable KUDS for old stands indicates a relatively lower survival of bigger spruces because of wind- and fungi damages (Laarmann 2007).

Conclusions

Tree mortality is a key factor in the understanding of forest dynamics. The accuracy and relevance of a growth model depends on the accuracy of predicting tree survival. The present study has shown which tree and stand variables affect tree survival probability most in Estonian forests.

Tree survival was analyzed using a data set which includes 31 097 trees from 236 research plots, measured twice during 1995–2004. During the 5-year period between measurements, altogether 2319 trees (or 7.5%) had died (dead standing, broken or fallen).

The survival probabilities, presented in Table 6 are interesting because of the differences in the viability of the suppressed trees in the different layers. In the case of the suppressed trees in the

Table 8. Results of generalized linear mixed modeling with PROC GLIMMIX (SAS) and function lmer (R) for Eq. 21.

Regressor		All data		Young stands		Middle-aged and maturing stands		Mature and overmature stands	
Coefficients of model with GLIMMIX									
		Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
Intercept		2.1624	0.4232	4.8111	0.9713	–1.2635	0.4227	10.2931	2.2789
HNLSS		4.3433	0.2559	4.5473	0.6140	4.6567	0.5607	3.4531	1.1361
DS				–1.7344	0.7159	1.7057	0.3859		
BALS		–1.8928	0.2319	–4.1013	0.7873			–2.3698	0.8679
TTJ		–2.1976	0.2510	–1.7800	0.3975	–1.8281	0.3929	–9.9323	1.8795
KUDS								–3.8111	1.7460
PL	Aspen	–1.3529	0.1125	–1.3610	0.1885	–1.4853	0.1609	–1.1760	0.5093
	Birch	0.0796	0.0871	0.0317	0.1583	0.0179	0.1261	–0.1850	0.4064
	Spruce	0.2272	0.1032	0.2561	0.1470	0.3762	0.1732	1.7442	1.7761
	B. alder	–0.1938	0.2058	–0.6747	0.2605	1.0037	0.5192	–1.6863	0.9211
	G. alder	–1.9203	0.1083	–1.5491	0.2054	–2.2703	0.1403	–2.6151	0.4481
Type III Tests of Fixed Effects									
		F	Den df	*F*	Den df	*F*	Den df	*F*	Den df
HNLSS		288.06	24906	54.85	8718	68.99	14203	9.24	1969
DS				5.87	8718	19.53	14203		
BALS		66.63	24906	27.14	8718			7.46	1969
TTJ		76.66	234	20.05	78	120	21.65	27.93	32
KUDS								4.76	1969
PL		94.40	374	25.95	138	173	71.49	7.42	53
Coefficients of model with lmer									
		Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
Intercept		1.9623	0.6442	4.7740	1.2959	–0.7766	0.7268	8.9933	2.3692
HNLSS		5.3326	0.3016	4.8669	0.8782	4.8496	0.6391	3.5957	1.0692
DS				–1.0344	0.9549	1.8207	0.4109		
BALS		–1.6489	0.2420	–3.8207	0.8970			–2.2355	0.8047
TTJ		–2.8763	0.6070	–2.8202	1.0808	–2.4132	0.7999	–8.4635	2.1181
KUDS								–3.5764	1.6793
PL	Aspen	–0.8172	0.1998	–0.6762	0.3882	–0.9910	0.2642	–1.1893	0.5332
	Birch	0.1714	0.1479	0.4230	0.2951	0.1042	0.1910	–0.3125	0.4440
	Spruce	0.4109	0.1701	0.7031	0.2699	0.3845	0.2434	1.6453	1.7147
	B. alder	–0.2659	0.2540	–0.6531	0.3643	1.0362	0.5261	–2.0163	0.8827
	G. alder	–2.0647	0.1924	–1.5209	0.3300	–2.6542	0.2577	–2.5840	0.5444
Fit statistics									
logLik		–4856		–1692		–2752		–363.1	
Deviance		9712		3384		5505		726	
R^2		0.168		0.189		0.168		0.084	

second storey and regeneration layer, the tree survival was found to be substantially higher than the viability of the trees in the first storey (for a given value of DS = 0.5).

The logistic form was used for modeling tree survival probability. The influence of 35 tree and stand measurement variables (Table 2) to tree survival probability was estimated using the score statistics of a logistic regression.

The research of separate single variables revealed that the mortality of trees is mostly influenced by tree measurement variables (presented in decreasing order of score statistic, Table 7): tree calculated relative height HNLSS, tree relative diameter DS, relative basal area of larger trees BALS, Hegyi competition index HEGH in a circle with radius $0.4H_1$, tree diameter D, Hegyi competition index HEG5 in a circle with a 5-m radius, basal area of larger trees BAL and tree height H. The study revealed that it is useful to divide the total data set into three development stages defined by dominant tree species and age: young, middle-aged and maturing, mature and very old stands. In each of these categories, different influencing factors turned out to be dominant.

The obtained results improve our knowledge of Estonian forest stand dynamics. It is possible to apply the proposed models in forest simulation studies as a preliminary approximation of a tree mortality component. The development of flexible simulators, which complement existing yield-tables, will significantly improve decision-making in practical forest management.

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