Forstw. Cbl. 121 (2002), 138–151

ISSN 0015-8003

Recommendations for Standardized Documentation and Further Development of Forest Growth Simulators[1]

Empfehlungen für die standardisierte Beschreibung und Weiterentwicklung von Waldwachstumssimulatoren[1]

By H. PRETZSCH, P. BIBER, J. ĎURSKÝ, K. VON GADOW, H. HASENAUER, G. KÄNDLER, G. KENK, E. KUBLIN, J. NAGEL, T. PUKKALA, J. P. SKOVSGAARD, R. SODTKE and H. STERBA

Summary

The present paper documents the practical applicability of growth simulators, gives an overview of current model approaches, defines standards for the description and evaluation of growth models and growth simulators and indicates research needs. The recommendations aim to give users of growth simulators confidence in the transition to modern prediction systems and to increase the level of acceptance of new information technologies. The recommendations provide developers with guidelines for model description, model evaluation and software development and thus contribute towards efficient co-operation.

Keywords: Growth simulator, evaluation, validation, standardization, model description

Zusammenfassung

Der Beitrag dokumentiert die praktische Relevanz von Wachstumssimulatoren, gibt einen Überblick über aktuelle Modellansätze, definiert Standards zur Beschreibung und Evaluierung von Wachstumsmodellen und -simulatoren und weist auf Forschungsbedarf in diesem Bereich hin. Die Empfehlungen sollen Anwendern von Wachstumsmodellen Vertrauen beim Übergang zu zeitgemäßen Prognosesystemen vermitteln und die Akzeptanz neuer Informationstechnologien erhöhen. Indem dieses Papier Modellentwicklern Leitlinien für die Modellbeschreibung, Modellevaluierung und Softwareentwicklung gibt, kann es zu einer effizienten Kooperation aller Beteiligten beitragen.

Schlüsselwörter: Wachstumssimulator; Evaluierung; Validierung; Standardisierung; Modellbeschreibung

1 Introduction

Since HUNDESHAGEN (1837) for a long time even-aged management was assumed to be ***the*** method for sustainable forest management. Since the declarations of Rio (WORLD COMMISSION OF ENVIRONMENT AND DEVELOPMENT 1987, UNITED NATIONS CONFERENCE ON ENVIRONMENT AND DEVELOPMENT 1992) and Helsinki (MINISTERIAL CONFERENCE 1993, LOISKEKOSKI and HALKO 2000) through a redefinition of sustainability, former "unconventional" forest management methods have gained terrain. Several European states decided upon regulations that force at least the state forests, and in some cases all forest owners, to uneven-aged forest management methods, such as "structural thinning", "target diameter harvesting" and to the establishment and care of mixed stands. During the past two decades this development has been partly prepared and followed by the development of

[1] The recommendations originate from the Forest Yield Science Section of the German Association of Forestry Research Organizations belonging to IUFRO. They became the nucleus of project No. QLK5-CT-2000−01349 "Implementing tree growth models as forest management tools" funded by the European Community. The project partners reviewed and revised the original paper.

forest growth simulators in Central Europe which rely less and less on conventional yield tables for pure stands. With the objective of overcoming the limited applicability of yield tables a great and confusing variety of new model approaches and growth simulators has been created. In contrast to yield tables they lack, as yet, any form of standardization that could serve as guide for users and developers. Efforts to develop such guidelines have been undertaken by the Forest Yield Science Section of the German Association of Forest Research Institutions, which issued a document recommending the introduction and further development of growth simulators (Pretzsch et al. 1999). Within project QLK5-CT-2000−01349 "Implementing tree growth models as forest management tools" funded by the European Community these guidelines have been revised and generalized to support the transition from yield tables to simulators more suitable for contemporary forest management.

2 Background and objectives of the recommendations

The recommendations presented here document the practical applicability of growth simulators, aim to give an overview of current model approaches, define standards for the description and evaluation of growth models and growth simulators and indicate additional research needs. The recommendations aim to give users of growth simulators confidence in the transition to modern prediction systems. By providing developers with guide-lines for model description, model evaluation and software-processing the recommendations contribute toward efficient co-operation.

The recommendations refer to forest growth models and growth simulators that serve the following purposes: (1.) predictions for short-term and medium-term planning, (2.) long-term scenario calculations for the development of stand management strategies and (3.) information on growth responses to stand treatment and to disturbance factors. The criteria for model description, model evaluation and further development, carefully and reasonably applied, may also be transferred to other models of a different type, e. g. models based on eco-physiological processes.

For a better understanding, the following strict differentiation is being made between the concepts of forest growth model and growth simulator. The biometric and mathematical representation of growth processes leads to a growth model. The conversion of this growth model into a practicable computer program for prediction and scenario calculations leads to the creation of a growth simulator. A model is therefore always the precondition for the development of a simulator, but the development of a model needs not necessarily result in a simulator.

3 Arguments for a transition to new growth simulators

The development of forest growth and yield simulators based on stand-level models, diameter distribution models and individual-tree models is a response to changing management objectives. It is also a response to changes in the availability, the needs and the flow of information in forestry practice. Yield tables were well adapted to the state of information in forestry practice at the time they were first established as they were based on available data on tree species, age, height and stocking density. Today, comprehensive stand and site data exist as a result of forest inventories, e. g. based on systematic sampling grids, site mappings etc. These may be used as initial values and controlling parameters for the new generation of growth simulators to achieve better and more relevant predictions. Today, forestry practice expects prediction instruments to provide more than just a statement on the assumed stand development under standardized stand treatment regimes as is the case with yield tables. Faced with different demands from the public and a changed legal frame, supra-regional disturbance factors, new stand treatment practices, new species mixtures and stand structures, modern forestry expects "if – then" statements on the consequences of these influencing factors on the development of trees, stands and management options.

As long as the need for information in practice was restricted to a few variables of natural production and a limited spectrum of forest types, it sufficed to compile the "normal" course of stand development in a compendium of yield tables. However, for modern forest eco-system management a wider range of options is required which can be provided only by more complex computerized models. Apart from tree and stand attributes such as growth, assortment yield and financial characteristics, other structural, economic and socio-economic variables become increasingly important which should be taken into account in forest growth simulation in the future. Forestry is being equipped with modern information technology and the way paved for the use of computer-aided prediction tools. All three information system components, i.e. hardware, software and trained personnel, have now reached a standard in forest administrations that makes it feasible to introduce growth simulators into forestry practice.

4 Forest growth simulators and their application potential

4.1 Simulators based on stand-level models

The idea of modelling stand growth based on average data on the age-dependent stand development in order to create a working basis for the evaluation, planning and control of forestry operations goes back more than two hundred years. The development of the series of yield tables established for example by Schwappach (1889, 1890), Guttenberg (1915) and Wiedemann (1949), based on graphically smoothed experimental results, into stand growth simulators reveals an increasing tendency toward greater flexibility. This refers to the use of biologically plausible growth functions, greater precision due to a widening of the database and increasing mathematization by strategic evaluation and biometric formulation of principal relationships (Assmann and Franz 1965).

Simulators based on stand-level models are systems of equations that control the age-related development of biometrical stand variables (e.g. maximum height, average height, average diameter). Based on a relatively small database from yield-related stand inventories any site-specific stand development may be simulated on the computer for a limited range of different treatment options. The simulation results are compiled in tables with a structure similar to that of the yield tables, but often more comprehensive. For parameterization and calibration of stand-level models commonly time series of data collected from permanent experimental plots, or temporary inventories which can be grouped to form artificial time series are used.

4.2 Simulators based on distribution models

In response to changes in information needs the first diameter distribution models were created in the 1960s for even-aged pure stands which, apart from average stand values also provided information on the frequencies of tree dimensions (Clutter and Bennett 1965). They aimed at a more distinctive assessment of grade and value development in pure, even-aged stands. Stand growth models providing information on stem number frequencies included differential equation models, frequency prognosis models and stochastic evolution models. Not all of these, however, were converted into simulators. With differential equation models it is possible to simulate the changing rate of yield measures for the diameter classes of any stand, e.g. the change in stem numbers, basal area and stocking volume in relation to the actual stand variables. Frequency distribution models are used to characterize stand structures of forest stands (e.g. von Gadow 1987, Sloboda 1977, Suzuki 1971). Diameter and height distributions are smoothed out using e.g. statistical probability density functions. The development of diameter and height distributions is related to the predicted development of mean stand and site characteristics. Stochastic evolution models (e.g. Suzuki 1971, Sloboda 1977) simulate development dynamics as the movement in the initial frequency distribution of single tree dimensions by updating a given initial diameter or height distribution.

4.3 Simulators based on tree-level models

Growth simulators based on individual trees break a stand down into a mosaic of its individual trees and generally simulate their interactions in a spatio-temporal system. In most cases the main component of individual-tree simulators is a system of different equations controlling the growth behavior of individual trees in relation to spatial stand or plot structure. The underlying individual-tree models therefore have a higher resolution than stand growth models based on average stand characteristics or estimating stem number frequencies. A distinction may be made between distance-dependent and distance-independent individual-tree models (Munro 1974), depending on whether or not they use data on individual tree positions and/or distances between the trees to control individual tree growth. Although the actual information unit in both of these model types is the individual tree, through aggregation, the output from low resolution models, i.e. the development of stand characteristics like mean diameter, or mean height and diameter frequency distributions, can be derived easily from individual-tree models, too.

The first individual-tree model was developed by Newnham (1964) for pure Douglas fir stands. This was followed by models developed for pure stands by for example Arney (1972), Bella (1971), Lee (1967), Lin (1970) and Mitchell (1969 and 1975). In the mid-1970ies Ek and Monserud transferred the design principles of individual-tree growth models from pure stands to uneven-aged pure and mixed stands (Ek and Monserud 1974; Monserud 1975). More recently, individual-tree models developed since the 1980ies, inter alia by Biber (1996), Burkhart et al. (1987), van Deusen and Biging (1985), Eckmüllner and Fleck (1989), Hasenauer (1994), Kahn and Pretzsch (1997), Kolström (1993), Nagel (1996, 1999), Pretzsch (1992, 1997, 2001), Pukkala (1987), Sterba et al. (1995), Wensel and Daugherty (1984) and Wensel and Koehler (1985), largely rely on the methodical principles of their precursors but are much more easy to use than older individual-tree models thanks to the developments of graphical user interfaces.

In the following, six different forest growth simulators are briefly introduced. They represent the state-of-the-art of individual-tree based management models. MOSES (Hasenauer 1994) and SILVA 2.2 (Pretzsch and Kahn 1995, Pretzsch 2001) represent the diversity of age and species so that it is possible to assess consequences of treatment strategies depending on the position of each individual tree within all-aged pure and mixed stands. They consist of different sub-models (diameter increment, height increment, crown, mortality). The current annual height and diameter increment are calculated depending on the potential height, potential diameter increment and a dynamic growth reduction function (crown ratio) representing changing growth conditions and competition (e.g. resulting from the stand treatment). The simulator MOSES was calibrated with full information Maximum likelihood (FIML) methods (Hasenauer 2000).

SILVA 2.2 consists of different sub-models (stand structure generator, thinning, competition, allocation, regeneration). Several stand measures (such as dbh, tree height, crown diameter and others) are calculated on stand and tree level from site conditions, initial stand measures and tree-level competition. Furthermore, stem quality, assortment yield, different financial measures and structural indices indicating habitat and species diversity are calculated.

PROGNAUS (Monserud and Sterba 1996, Sterba and Monserud 1996) and BWIN (Nagel 1997) use a distance-independent approach in order to predict individual tree growth via inventory data on a larger scale. PROGNAUS also consists of different sub-models (basal area increment, height growth, mortality, dynamic crown ratio, harvesting). Growth and yield on tree level are calculated from tree size, site factors, stand density and competition factors. A relation between tree growth and age or site indices is not included. The simulator was parameterized with data from the Austrian forest inventory (Hasenauer et al. 1998, Hasenauer 2000).

BWIN calculates stand measures (diameter and height growth, change in crown base) from stand input variables (crown surface area, crown competition) within several functions on tree level. With this, the height increment is regarded as a function of potential height growth and increment and a dynamic reduction function representing the competition situation depending on age and thinning. Similarly the diameter increment is calculated from crown surface area and competition situation.

The Stand Management Support System STAND (Pukkala and Miina 1997) considers individual tree growth as one part of a multi-functional system within the landscape. STAND consists of a stand simulator linked with an optimization system. It is able to optimize stand treatment strategies simultaneously for several management objectives (profitability, liquidity, amenity) using an additive utility function. Different units and characters of the objectives are made commensurable via normalized sub-utility functions.

CORKFITS is a derivative of the SILVA model and specifically designed to optimize cork production and to estimate the optimum cork extraction period. The growth model within the simulator depends on site, stand characteristics and climate and includes equations to predict timber growth, cork growth, height and crown development and mortality rates. The cumulative cork growth is based on the potential increment modifier principle.

4.4 Combining different types of models

It is also possible to combine elements of stand-level, tree-level and distribution models, and to use all of them in the same simulator. This is even needed in order to guarantee the compatibility of growth predictions made by different model types. For example, natural mortality (stems per hectare) may be calculated by a self-thinning model which is a stand-level model (e.g. Reineke 1933, Yoda et al. 1963, Pretzsch 2001), and the trees which will die during the next growing period are selected by a tree-level survivor function. One way to use different model types together is to calculate the tree list for tree-level models using stand-level and distribution models. This is a common way only if stand-level characteristics are measured in forest inventory, but the predictions and calculations are needed on tree level and no validated stand structure generator is available (Pukkala and Miina 1997).

5 Standards for model description

The recommendations for a standardized model description are designed to help users in their choice of simulator, interpretation of prediction results, assessment of precision and accuracy, and assessment of limitations of the model of their choice. For developers the list of criteria serves as an organizing principle for model description. In Table 1 the most important characteristics of models and simulators are compiled for each of the ten criteria described below.

(1) Model approach

The approach for the description of summarized stand characteristics and average stand values, frequency distributions, or individual trees with or without consideration of position, determines the input and generated output data. Whether, and in what manner, site variables, inventory data, or treatment alternatives are being processed by the model, determines its flexibility and the required input and calibration data. A flow diagram helps users understand the model philosophy based on some of the essential model components as well as the calculation process for the prediction.

(2) Range of application

A precise definition must be given for the range of applications with regard to spatial dimension (single tree, stand, management, region, supra-regional area) and time scale (short-term predictions for forest inventory, long-term predictions for the development of tending models, simulation of successions through regeneration and ingrowth models, thus involving several generations).

(3) Parameterization and calibration specifications

To characterize the model validity calibration data should be specified in terms of geographical region, site conditions, tree species composition, stand structure, stand treatment, range of tree sizes and stand variables, etc. The user also needs to be aware of limitations to parameterization or calibration data.

(4) Input

For the user the following information is essential: which initial values must be taken into account, which initial information and starting values of trees are needed for predictions and to what extent can missing initial values (e. g. crown parameters, stem co-ordinates) be complemented realistically by the model.

(5) Program control

The control of prediction runs may comprise, for example, the silvicultural treatment conditions, changing site conditions, and the formation of artificial or natural regeneration. It should be stated whether control is possible interactively or within batch-mode via control files.

(6) Output

A complete overview of stand variables and single tree information estimated by the simulator, the process used for the evaluation of results and potential interfaces for subsequent databases, are all important for making the simulator an integral part of the information flow in forestry practice.

(7) Growth model

The database, model equations, model parameters and parameter estimation methods for the simulation of the development of stem, crown, regeneration and mortality should be given.

(8) Additional algorithms

Further model components which enable e. g. initial structures to be generated, assortment yield and financial performance to be quantified, results to be visualized or edge effects to be compensated, should be described by the model equations, the model parameters and the data material used. Information should also be included on the model's and/or the simulator's potential for continuous updating of predictions as new inventory data or other relevant information becomes available.

(9) Model validation

Conventional statistical information on the precision and accuracy of model equations and predictions may prove helpful in assessing whether a simulator is suitable for a specific purpose. Characteristics of statistic validation procedures (e. g. Mayer and Butler 1993, Pretzsch and Dursky 2001, Reynolds et al. 1981, Sterba and Monserud 1996, Vanclay and Skovsgaard 1997) as well as a statement characterising the validation material may help users to decide which simulator to use. If the described forest growth simulator contains random variables, predictions may always give somewhat different results even with all other conditions being equal. Therefore, information on the random-controlled model components should be provided. If results from sensitivity analysis are available these should also be included.

(10) Software and hardware

For the current version of any growth simulator the software and hardware requirements programming languages and memory capacity requirements to the computer should be given in detail to enable potential users to assess the suitability for specific purposes. A

Table 1. List of criteria for the standardized description of growth simulators. The criteria model approach, range of application, calibration specifications, etc., with up to 11 model properties each, should be described in concise form, with relevant literature references.

Tabelle 1. Kriterienliste für eine standardisierte Beschreibung von Wachstumssimulatoren. Die Kriterien Modellansatz, Anwendungsbereich, Gültigkeitsbereich usw. mit den bis zu elf Modelleigenschaften sollten in knapper Form beschrieben und mit relevanten Literaturhinweisen belegt werden.

Criterion	Model properties	
1 Model approach	1.1	Spatial resolution (competition, regeneration, treatment)
	1.2	Age dependency
	1.3	Principle of growth model (e.g., potential/reduction, direct estimation, growth equations using site factors or site indices, site-specific growth potential)
	1.4	Deterministic and stochastic model components
	1.5	Flow chart
2 Range of application	2.1	Silvicultural scenario studies
	2.2	Updating of forest stands
	2.3	Updating of larger assessment units
	2.4	Instruction, professional training, research
3 Calibration specifications	3.1	Specifications with regard to region
	3.2	Site specifications
	3.3	Types of mixtures and stand structure
	3.4	Treatment variants
	3.5	Tree species
	3.6	Tree dimensions covered
4 Input	4.1	Area shape and size
	4.2	Minimum input data requirements
	4.3	Additional input data to be possibly processed
	4.4	Automatic generation of missing information
	4.5	Database interface
	4.6	Maximum number of trees per calculated area
5 Software control	5.1	Use (interactive, batch-mode)
	5.2	Possibilities of program control (visual, algorithmic)
	5.3	Interactive changing of equations
	5.4	Interactive changing of coefficients
	5.5	Saving of interim results with continuation
6 Output	6.1	Tree lists
	6.2	Stand characteristics
	6.3	Yield characteristics at forest enterprise level
	6.4	Structural characteristics at stand and forest enterprise level
	6.5	Economic measures
	6.6	Biomass components
	6.7	Visualization methods (spatial representation, diagrams)
	6.8	Interfaces with other programs

Criterion	Model properties	
7 Sub-models of the growth simulator (concise description)	7.1	Database
	7.2	Increment model (model principles)
	7.3	Representation of liberation felling effects
	7.4	Crown model (dynamic, static)
	7.5	Mortality model
	7.6	Ingrowth model
	7.7	Stochastic components of sub-models
	7.8	Derivation of coefficients
8 Additional algorithms	8.1	Statistical timber grading
	8.2	Thinning algorithms
	8.3	Determination of ingrowth co-ordinates
	8.4	Biomass equations
	8.5	Inventory interface
	8.6	Prediction loops for forestry enterprises
	8.7	Abort criteria and data complementation
	8.8	Three-dimensional stand visualization
	8.9	Consideration of edge effects
	8.10	Quantification of spatial structure
	8.11	Continuous updating
9 Model validation	9.1	Precision
	9.2	Bias
	9.3	Accuracy
	9.4	Sensitivity analyses
10 Software and hardware	10.1	Operating system
	10.2	Hardware requirements
	10.3	Current version giving year and date
	10.4	Programming language
	10.5	Program approach (structured, object-oriented)

model description standardized along the lines of the criteria shown above concludes with a list of references to which the text on the 10 criteria may refer. However, this list should not serve in lieu of precise information on each criterion.

6 Criteria for model evaluation

The evaluation of models should be related to the suitability of the selected model approach for given objectives and purposes, to the validity and logic of the developed biometric model and the suitability of the software developed from the biometric model. Evaluation is understood to be "[...] the check-up on the efficiency and success of a model under test. [...]" (BROCKHAUS 1997, vol. 6, p. 716). One of the aspects of evaluation is validation (BROCKHAUS 1994, vol. 23, p. 42): "[...] Validation defines the degree of accuracy with which a process measures what it purports to measure [...]". A growth model may, in actual fact, not be verifiable at all, because "[...] given general empirical statements (hypotheses, laws) no final verification is possible, while final falsification certainly is. [...]" (BROCKHAUS 1994, vol. 23, p. 213, POPPER 1984). Model evaluation is an important part of model building, and some examination of the model should be made at every stage of model design, fitting and implementation (VANCLAY and SKOVSGAARD 1997).

6.1 Evaluation of model approach

The selected model approach should be checked for suitability regarding the user's objectives and purposes. The following criteria are considered essential:

(1) Does the model approach make full use of existing information from forestry practice to meet the user's needs?

Depending on the user's objectives detailed information for individual stands or only more general information from linguistic stand descriptions comprising initial structures, site variables, disturbance factors, risks and stresses, may be needed. It may be available from an individual stand inventory, from stand based inventories and site mappings or from inventories on the enterprise level, based on statistical sampling.

(2) Does the model approach fulfil the user's information requirements?

The model approach should take changes in silvicultural practices, changing social demands on forests and forestry, and disturbance factors affecting forests into account.

(3) Does the model approach make the best possible use of existing data and the state of knowledge on biology to solve user problems?

The model should be erected on a solid empirical basis. In past decades a vast amount of information has been gathered on the dimensions, structure and growth characteristics of individual stand components. A number of growth laws (e.g. law of optimum basal area from Assmann 1953, 1956, self-thinning rule from Reineke 1933 and Yoda et al. 1963, law of crown efficiency from Assmann 1970) have been derived, may be used to evaluate individual-tree models. At the same time information on site and disturbance factors, based on more detailed inventories of test and inventory sites, has improved greatly.

(4) Does the selected degree of complexity correspond to the model objectives?

Yield tables or growth models based on size class distributions were well suited to predict stand development of pure even aged stands, whereas this kind of model approach has its limitations in pure stands in which tending concentrates mainly on certain parts of the population (e.g. selective thinning, final crop-tree thinning, structural thinning, target tree system).

6.2 Validation of the growth model

(5) How accurate is the model compared with reality?

Certainly, the most significant validation of growth models consists of a comparison between model predictions and actual growth behavior. Here, forest inventory data from permanent investigation sites are an important and independent data source. Their usefulness may, however, be modified on account of pronounced climate and increment variations during certain periods. A comparison between model predictions and results from long-term experimental plots may give better results because a comparison of prediction versus reality is possible at stand level as well as at individual-tree level. These comparisons should be made using data not used as input for model parameterization.

The distribution of variations between predictions and reality informs on the accuracy of a model. Systematic errors as well as random variations need to be calculated. Real and predicted values may also be graphically presented and compared by correlation. The validation characteristics may also help users to decide which growth simulator to use.

(6) Does the performance of the model correspond to mathematical relationships and to general biological experience?

For example, it is possible to check whether a model corresponds to various concepts of maximum density from Yoda et al. (1963) or the concept of optimum and critical basal area management established by Assmann (1953 and 1956).

(7) Do prediction results correspond to those from other models?

If the use of several models to solve the same problem has produced similar results, this will enhance the level of acceptance of results and the simulators used.

6.3 Evaluation of the software

(8) Is the growth simulator designed for easy use?

The type of software used in the conversion of the biometric growth model is of crucial importance for the acceptance of the simulator. Ease of use of the program is an important aspect and is most easily warranted if the user interface is adapted from the conventional design of standard software. These programs are usually self-explanatory and require little training.

(9) Are the simulator and its components flexible in use?

It is advisable to use a programming language for the growth simulator that is largely platform neutral. It also appears essential that the core program consist of modules so that individual program routines may be exchanged between different working groups making further, independent development possible.

(10) Is it possible to integrate the growth simulator into the information flow in forestry practice?

For use in practice well defined interfaces to user input data are essential, as well as defined data formats for the output of results. Interactive use of the model is considered best for professional training purposes and for silvicultural scenario calculations for the development of tending programs. By contrast, simulators for growth forecasts at forest enterprise level that could, for example, support harvesting planning will probably operate in batch-mode. In the latter case a great number of individual stands are monitored within a large time span. For this purpose program control is done via external control data files in which the type of tending and regeneration measures as well as harvesting times have been laid down.

(11) Has the growth simulator been adequately documented?

Apart from the standard description recommended in section four any growth model that is designed for use in instruction, research or practice requires a manual describing the model structure, instructions for the use of the simulator, and giving examples for model calculations as well as potential uses and limitations of the growth simulator. The literature references in this manual should list the most important sources about the database for the model parameterization, the model parameters and model functions, model evaluation and technical conditions for model installation.

7 Research and development needs

Currently, the following main deficits exist in the database on the growth of pure and mixed stands, knowledge about mathematical relationships in single tree and stand development, and the model software.

7.1 Database for model parameterization and model validation

Forest growth models are usually calibrated on two types of data sources which are indispensable for growth modelling and which complement each other: (1) long-term field experiments, which provide long time-series, with detailed information on tree and stand growth. These data reveal mathematical relationships of growth at individual-tree and stand level and permit model development, parameterisation and validation. (2) Inventory data that will impart less detailed information, but will give rather more general information on growth on larger areas. Continuous forest inventories based on permanent sample-plot design are well suited for the parameterization and evaluation of models. The two data sources complement each other.

While the tree species Norway spruce, Scots pine, beech and sessile oak in pure stands appear to have been well researched, the database for the growth of these tree species in mixed stands as well as for the growth of Douglas fir, European larch, sycamore ash and black alder in pure and mixed stands of all age compositions needs to be improved. Long-term test plots that cover growth responses to a large range of treatment methods, intensities and consequences, even including extreme treatments not usually carried out in practice, permit the application of simulators for an enlarged range of situations and help advance new research topics. Further development needs are seen in the fields of test planning, experimental plot establishment and test results evaluation. Here, methods and techniques are not yet directed toward the information requirements of new model approaches.

7.2 Further development of growth models

One of the priorities is the improvement of the simulation of survival probabilities and tree mortality processes, areas in which most models have large deficiencies. The consequences are imprecise to biased estimates of growing stock in age-class forests and poor predictions of spatial structuring in uneven-aged stands. The over 30 % occurrence of salvage cuts after random events, such as storm damages, emphasizes the importance of risk modelling. Only if risk factors are taken into account in management models will realistic predictions of forest growth be possible in practice. There is also a strong need to model the regeneration process with consideration of effects by game browsing so that more realistic predictions for overlapping generations can be made. Modelling of wood quality (annual ring width, density, knot diameters etc.) appears indispensable for realistic value calculations and multi-criteria optimisation of management regimes, especially in the present transition to wide spacing and early, severe treatment measures as currently favoured in forestry.

7.3 Software development

A standardized development of modularised programs may lead to a division of labor and prevent overlapping developments. Standardized interfaces will warrant compatibility of developed modules and their interchangeability and use by different research institutions. Many algorithms from the library of approved yield evaluation programs such as the calculation of height curves, diameter increment graphs and volume are also being used in modern growth simulators. A break-down into modules ensures the use of these algorithms as components for either evaluation or prediction software. New program modules, e.g. for stand structure analyses or value calculations may also be used for actual state evaluations and prediction calculations.

8 References

Arney, J. D., 1972: Computer simulation of Douglas-fir tree and stand growth. Ph. D. thesis, Oregon State Univ., 79 pp.

Assmann, E., 1953: Bestockungsdichte und Holzerzeugung. Forstwissenschaftliches Centralblatt, 72, 3/4: 69–101.

Assmann, E., 1956: Natürlicher Bestockungsgrad und Zuwachs. Forstwissenschaftliches Centralblatt, 75: 257–265.

Assmann, E., 1970: The principles of forest yield study. Pergamon Press Ltd., Oxford, New York, Toronto, Sydney, Braunschweig, 507 pp.

ASSMANN, E. and FRANZ, F., 1965: Vorläufige Fichten-Ertragstafel für Bayern. Forstwissenschaftliches Centralblatt 84, 1: 13−43.

BELLA, I. E., 1971: A new competition model for individual trees, Forest Science 17, 3: 364−372.

BIBER, P., 1996: Konstruktion eines einzelbaumorientierten Wachstumssimulators für Fichten-Buchen-Mischbestände im Solling. Berichte des Forschungszentrums Waldökosysteme 142, Reihe A, 252 pp.

BROCKHAUS, 1994: Die Enzyklopädie in 24 Bänden. 20th ed., Brockhaus, Leipzig, Mannheim.

BROCKHAUS, 1997: Die Enzyklopädie in 24 Bänden. 20th ed., Brockhaus, Leipzig, Mannheim.

BURKHART, H. E., FARRAR, K. D., AMATEIS, R. L. and DANIELS, R. F., 1987: Simulation of individual tree growth and stand development in loblolly pine plantations on cutover, site-prepared areas, Virg. Polytechn. Inst. and State Univ., Publication No. FWS-1−87, 47 pp.

CLUTTER, J. L. and BENNETT, F. A., 1965: Diameter distributions in old-field slash pine plantations, Georgia For. Res. Council Rep., No. 13, 9 pp.

DEUSEN, P. C. VAN and BIGING, G. S., 1985: STAG a Stand Generator for Mixed Species Stands. Version 2.0, Northern California Forest Yield Cooperative, Dept. of For. and Res. Mgt., Univ. of California, Res. Note No. 11, 25 pp.

ECKMÜLLNER, O. and FLECK, W., 1989: Begleitdokumentation zum Wachstumssimulationsprogramm WASIM Version 1.0, Inst. f. Forstl. Ertragslehre, Univ. f. Bodenkultur, Wien, 30 pp.

EK, A. R. and MONSERUD, R. A., 1974: Trials with program FOREST: Growth and reproduction simulation for mixed species even- or uneven-aged forest stands, In: FRIES, J. (ed.): Growth models for tree and stand simulation, Royal College of Forestry, Stockholm, Sweden, Research Notes 30: 56−73.

GADOW, K. von, 1987: Untersuchungen zur Konstruktion von Wuchsmodellen für schnellwüchsige Plantagenbaumarten. Forstliche Forschungsberichte München 77, 147 pp.

GUTTENBERG, A., VON, 1915: Wachstum und Ertrag der Fichte im Hochgebirge, Wien, Leipzig, 153 pp.

HASENAUER, H., 1994: Ein Einzelbaumwachstumssimulator für ungleichaltrige Kiefern- und Buchen-Fichtenmischbestände, Forstliche Schriftenreihe Universität für Bodenkultur, Wien, 152 pp.

HASENAUER, H., MONSERUD, R. A. and GREGOIRE, T. G., 1998: Using simultaneous regression techniques with individual-tree growth models. Forest Science 44 (1): 87–95.

HASENAUER, H., 2000: Die simultanen Eigenschaften von Waldwachstumsmodellen. Paul Parey Verlag. Berlin. 131 p.

HUNDESHAGEN, J. C., 1837: Encyclopädie der Forstwissenschaft. Laupp, Tübingen, 3rd ed., 368 pp.

KAHN, M. and PRETZSCH, H., 1997: Das Wuchsmodell SILVA 2.1 − Parametrisierung für Rein- und Mischbestände aus Fichte und Buche, Allgemeine Forst- und Jagdzeitung, 168, 6/7: 115−123.

KOLSTRÖM, T., 1993: Modelling the development of unevenaged stand of Picea abies, Scandinavian Journal of Forestry Research 8: 373−383.

LEE, Y., 1967: Stand models for lodgepole pine and limits to their application, Ph. D. thesis, Fac. Forestry, Univ. B. C., Vancouver, 333 pp.

LIN, J. Y., 1970: Growing space index and stand simulation of young western hemlock in Oregon, Ph. D. thesis, Duke Univ., Durham, N. C., 182 pp.

LOISKEKOSKI, M., HALKO, L. (ed.), 2000: European List of Criteria and Most Suitable Quantitative Indicators. Ministerial Conference on the Protection of Forests in Europe 16−17 June 1993 in Helsinki. Ministry of Agriculture and Forestry of Finland: http://www.mmm.fi/english/forestry/policy/minkonf/criteria.htm, 28 Nov 2000.

MAYER, D. G., BUTLER, D. G., 1993: Statistical validation. Ecological Modelling 68: 21−32.

MINISTERIAL CONFERENCE, 1993: Resolution H1: General Guidelines for the Sustainable Management of Forests in Europe, Second Ministerial Conference on the Protection of Forests in Europe, Helsinki/Finland, 5 pp.

MITCHELL, K. J., 1969: Simulation of the growth of even-aged stands of white spruce Yale University, School of Forestry, Bulletin No. 75, 48 pp.

MITCHELL, K. J., 1975: Dynamics and simulated yield of douglas-fir, Forest Science Monograph 17, 39 pp.

MONSERUD, R. A., 1975: Methodology for simulating Wisconsin northern hardwood stand dynamics. Univ. Wisconsin, Madison, Dissertation Abstracts 36 (11), 156 pp.

MONSERUD, R. A., STERBA, H., 1996. A basal area increment model for even- and uneven-aged forest stands in Austria. Forest Ecology and Management 80: 57−80.

MUNRO, D. D., 1974: Forest growth models − a prognosis, pp. 7−21. In: FRIES, J. (ed.): Growth models for tree and stand simulation. Royal College of Forestry, Stockholm, Sweden, Research Notes 30, 397 pp.

NAGEL, J., 1996: Anwendungsprogramm zur Bestandesbewertung und zur Prognose der Bestandesentwicklung, Forst und Holz 51, 3: 76−78.

NAGEL, J., 1997: BWIN − Program for Standard analysis and Prognosis. User's Manual for Version 3.0. Niedersächsische Forstliche Versuchsanstalt Göttingen.

NAGEL, J., 1999: Konzeptionelle Überlegungen zum schrittweisen Aufbau eines waldwachstumskundlichen Simulationssystems für Norddeutschland. Schriften aus der Forstl. Fakultät der Universität Göttingen und der Niedersächs. Forstl. Versuchanstalt 128, J.D. Sauerländer's Verlag, Frankfurt/M., 122 pp.

NEWNHAM, R. M., 1964: The development of a stand model for Douglas-fir, Ph. D. thesis, Fac. of Forestry, Univ. B. C., Vancouver, 201 pp.

POPPER, K. R., 1984: Logik der Forschung, Verlag J. C. B. Mohr (Paul Siebeck), Tübingen, 477 pp.

PRETZSCH, H., 1992: Konzeption und Konstruktion von Wuchsmodellen für Rein- und Mischbestände, Forstl. Forschungsberichte München 115, 358 pp.

PRETZSCH, H., 1997: Analysis and modeling of spatial stand structures. Methodological considerations based on mixed beech-larch stands in Lower Saxony, Forest Ecology and Management 97: 237−253.

PRETZSCH, H., 2001: Modellierung des Waldwachstums, Blackwell Wissenschafts-Verlag, Berlin, Wien, 341 pp.

PRETZSCH, H. and DURSKY, J., 2001: Evaluierung von Waldwachstumssimulatoren auf Baum- und Bestandesebene, Allgemeine Forst- und Jagdzeitung 172, 8/9: 146−150.

PRETZSCH, H. and KAHN, M., 1995: Modelling growth of Bavarian mixed stands in a changing environment. In: Caring for the forest: Research in a changing world., 20th IUFRO world congress, Tampere/Finland, pp. 234−248.

PRETZSCH, H., BIBER, P., DURSKY, J., VON GADOW, K. HASENAUER, H., HRADETZKY, J., KÄNDLER, G., KENK, G., KUBLIN, E., NAGEL, J., POMMERENING, A., STERBA, H., 1999: Empfehlungen zur Einführung und Weiterentwicklung von Waldwachstumssimulatoren. Allgemeine Forst- und Jagdzeitung 171, 3: 52−57.

PUKKALA, T. and MIINA, J., 1997: A method for stochastic multiobjective optimization of stand management. Forest Ecology and Management 98: 189−203.

PUKKALA, T., 1987: Simulation model for natural regeneration of pinus sylvestris, picea abies, betula pendula and betula pubescens, Silva Fennica 21: 37−53.

REINEKE, L. H., 1933: Perfecting A Stand-Density Index For Even-Aged Forests. Journal of Agricultural Research 46, 7: 627−638.

REYNOLDS, M., BURKHART, H., DANIELS, R., 1981: Procedures for Statistical Validation of Stochastic Simulation Models. Forest Science 27, 2: 349−364.

SCHWAPPACH, A., 1889: Wachsthum und Ertrag normaler Kiefernbestände in der norddeutschen Tiefebene. Springer, Berlin, 72 pp.

SCHWAPPACH, A., 1890: Wachstum und Ertrag normaler Fichtenbestände. Springer, Berlin, 100 pp.

SLOBODA, B., 1977: Kolmogorow-Suzuki und die stochastische Differentialgleichung als Beschreibungsmittel der Bestandesevolution. IUFRO-Congress: Beitraege zur Zuwachsforschung (part 3), Mitteilungen der FBVA Wien 120: 71−82.

SUZUKI, T., 1971: Forest transition as a stochastic process. IUFRO-Congress: Beitraege zur Zuwachsforschung, Mitteilungen der FBVA Wien 91: 69−86.

STERBA, H., MOSER, M. and MONSERUD, R., 1995: Prognaus − Ein Waldwachstumssimulator für Rein- und Mischbestände, Österreichische Forstzeitung 5: 19−20.

STERBA, H., MONSERUD, R., 1997: Applicability of the forest stand growth simulator PrognAns for the Austrian part of Bohemian Massif. Ecological Modelling 98: 23–34.

UNITED NATIONS CONFERENCE ON ENVIRONMENT AND DEVELOPMENT, 1992: Report of the United Nations Conference on Environment and Development (Rio de Janeiro, 3−14 June 1992), Rio de Janeiro, 114 pp.

VANCLAY, J. K. and SKOVSGAARD, J. P., 1997: Evaluation of forest growth models. Ecological Modelling 98: 1−12.

WENSEL, L. C. and DAUGERTHY, P. J., 1984: CACTOS User's Guide: the California conifer timber output simulator. Northern California Forest Yield Cooperative, Dept. of Forestry and Res. Mgt., Univ. of California, Research Note 10, 91 pp.

WENSEL, L. C. and KOEHLER, J. R., 1985: A Tree growth projection system for Northern California coniferous forests, Northern California Forest Yield Cooperative, Dept. of Forestry and Res. Mgt., Univ. of California, Research Note 12, 30 pp.

WIEDEMANN, E., 1949: Ertragstafeln der wichtigen Holzarten bei verschiedener Durchforstung, Schaper, Hannover, 100 pp.

WORLD COMMISSION OF ENVIRONMENT AND DEVELOPMENT, 1987: Our Common Future. Report of the World Commission of Environment and Development ("Brundtland Report"), 374 pp.

YODA, K., KIRA, T., OGAWA, H., and HOZUMI, K., 1963: Self-thinning in overcrowded pure stands under cultivated and natural conditions (Intraspecific competition among higher plants XI). Journal of the Institute of Polytechnics 14, Osaka City University, Series D: 107−129.

Authors' addresses: Prof. Dr. HANS PRETZSCH, Chair of Forest Yield Science, Technical University of Munich, Am Hochanger 13, D-85354 Freising, Germany, Tel.: ++49-8161−71−4710, Fax: ++49-8161−71−4721, E-Mail: H. Pretzsch@lrz.tum.de; P. BIBER, Chair of Forest Yield Science, Technical University Munich, Germany; J. ĎURSKÝ, Institute of Forest Management and Geodesy, Technical University Zvolen, Slovakia; K. VON GADOW, Institute for Forest Planning and Yield Science, University Göttingen, Germany; H. HASENAUER, Institute for Forest Growth Research, University of Agricultural Sciences, Vienna, Austria; G. KÄNDLER, G. KENK AND E. KUBLIN, Forest Research Station Baden-Württemberg, Freiburg, Germany; J. NAGEL, Forest Research Station Niedersachsen, Göttingen, Germany; T. PUKKALA, Faculty of Forestry, University of Joensuu, Joensuu, Finland; J. P. SKOVSGAARD, Danish Forest and Landscape Research Institute, Hørsholm, Denmark; R. SODTKE, Chair of Forest Yield Science, Technical University Munich, Germany; H. STERBA, Institute for Forest Growth Research, University of Agricultural Sciences, Vienna, Austria.