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Application and Evaluation of the Growth Simulator SILVA 2.2 for Forest Stands, Forest Estates and Large Regions

Anwendung und Evaluierung des Waldwachstumssimulators SILVA 2.2 auf Bestandes-, Betriebs- und Großregion-Ebene

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Summary

The focus of this paper is on the application and validation of the forest growth simulator SILVA 2.2 at the level of forest stands, forestry enterprises and large regions. The Design concept and structure of this distance-dependent and site-sensitive individual tree simulator have been presented in PRETZSCH (1992), KAHN (1994), KAHN and PRETZSCH (1997), PRETZSCH (2001). The simulator owes its flexibility at stand level to the spatially explicit model approach and the parameter estimation, which is based on long-term experimental plots in pure and mixed stands. Some of the included time series date back to the year 1870. The simulator can be applied for various purposes and at different scales, and the results of the scenario calculations include estimates of timber yields as well as ecological and socio-economic indicators. In this paper, the development of a pure and mixed stand are compared by simulation at stand level. Thereafter, different silvicultural policies are investigated at enterprise level. The long-term consequences of forest management decisions at stand level become transparent once the growth projections are carried out at enterprise level. Thus, individual treatment regimes can be modified in order to achieve desired developments at enterprise level. Finally, the site-sensitive approach of SILVA 2.2, which is described in this paper, allows the analysis of the consequences of climate change. This is demonstrated in scenario calculations, which investigate the consequences of climate change on the growth and wood supply of spruce in Bavaria. The model validation was based on long-term experimental plots and showed a bias of −1.9 % to 4.8 %, an accuracy of 19.2 % to 38.6 % and a precision of 18.5 % to 38.6 % for the estimate of current stand volume increment. Similar results were obtained for mean diameter increment and, furthermore, for individual tree level. In case of short increment periods and extraordinary climatic conditions the values of bias and accuracy may prove less favourable. In a qualitative comparison with inventory data the prediction behaviour of the site-growth model was proved to be fairly robust. Currently, however, the modelling of regional and temporal peculiarities such as nitrogen immissions or snow-break events has to be improved.

Keywords: Individual tree model, site-sensitive growth modelling, climate change, simulation, evaluation, validation

Zusammenfassung

Der einzelbaumorientierte Waldwachstumssimulator SILVA 2.2 wurde so konzipiert, dass er die Forstwirtschaft in ihren Entscheidungen auf Bestandes-, Betriebs- und Großregion-Ebene unterstützt. Das Konzept und der Aufbau dieses positionsabhängigen und standortsensitiven Einzelbaumsimulators wurde wiederholt vorgestellt PRETZSCH (1992), KAHN (1994), KAHN und PRETZSCH (1997), PRETZSCH (2001). Im folgenden stehen die Anwendung und Validierung dieses Simulators im Vordergrund. Die große Flexibilität beim Einsatz auf Bestandesebene verdankt der Simulator seinem räumlich expliziten Modellansatz und seiner Parametrisierung mit langfristigen Versuchsflächen in Rein- und Mischbeständen, die bis in das Jahr 1870 zurückdatieren. Szenariorechnungen erbringen ertragskundliche Kennwerte, ökologische und sozioökonomische Ergebnisgrößen. Der Simulator macht die waldbaulichen Einzelentscheidungen auf Bestandesebene hinsichtlich ihrer langfristigen Konsequenzen für den Gesamtbetrieb transparent. Behandlungsprogramme auf Bestandesebene können dann so modifiziert werden, dass sie eine gewünschte Entwicklungen des Gesamtbetriebes erbringen. Der in dem Aufsatz vorgestellte standortsensitive Aufbau von SILVA 2.2 ermöglicht den Einsatz des Modells für die Klimafolgenforschung. Am Beispiel der Baumart Fichte werden die Konsequenzen von Klimaveränderungen für Wachstum und Holzaufkommen in Bayern mit Hilfe von Szenariorechnungen analysiert. Die Modellvalidierung auf der Basis langfristiger Versuchsflächen erbrachte für die Schätzung des jährlichen Bestandesvolumenzuwachses einen Bias von −1.9 % bis 4.8 %, eine Genauigkeit von 19.2 % bis 38.6 %

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und eine Präzision von 18.5 % bis 38.6 %. Ähnliche Größenordnungen ergeben sich für den Zuwachs des Mitteldurchmessers. Die Validierung auf Einzelbaumebene erbringt ähnliche Resultate, bei kurzen Zuwachsperioden und außergewöhnlichen Klimabedingungen können Bias und Genauigkeit auch ungünstiger ausfallen. Der qualitative Vergleich mit Inventurdaten belegt ein robustes Prognoseverhalten des Standort-Leistung-Modells; die Nachbildung von regionalen und temporären Besonderheiten, wie Stickstoffeinträgen oder Schneebruchereignissen ist noch verbesserungsbedürftig.

Schlüsselwörter: einzelbaumorientiertes Bestandesmodell, standortsensitive Wachstumsmodellierung, Klimaänderung, Simulation, Modellevaluierung, Validierung

1 Introduction

Distance-dependent individual tree models have proved extremely flexible and are therefore designed for a wide range of application in practice, research and teaching. The first individual tree model was developed by Newnham for pure Douglas fir stands (Newnham, 1964). This was followed by models developed for pure stands by Arney (1972), Bella (1971), Lee (1967), Lin (1970) and Mitchell (1969 and 1975). In the mid-1970s Ek and Monserud transferred the design principles of individual tree growth models for pure stands to uneven-aged pure and mixed stands (Ek and Monserud, 1974; Monserud, 1975). More recent individual tree models developed since the 1980s, inter alia by Biber (1996), Burkhart et al. (1987), van Deusen and Biging (1985), Eckmüller and Fleck (1989), Hasenauer (1994), Kahn and Pretzsch (1997), Kolström (1993), Krumland (1982), Larson (1986), 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 methodological principles of their precursors but are much more easy to use than older individual tree models thanks to the novel developments in user interfaces of modern computer science.

Several contributions to the research project „German Forest Sector under Global Change: An Interdisciplinary Impact Assessment“ and articles in this volume are based upon and refer to SILVA 2.2. This simulation model was the heart of the project and the working horse of the scenario calculations. The papers' intention is to introduce the model approach, the applicability und validation of SILVA 2.2. The reader should get the necessary methodological background information to understand the succeeding articles in this volume.

The site-sensitive and distance-dependent individual tree simulator SILVA 2.2 has been developed and perfected at the Munich Chair of Forest Yield Science since the late 1980s (Pretzsch 1992, Pretzsch and Kahn 1996, Pretzsch and Ďurský 2001, Pretzsch 2001). This simulator with its various modules for stand generation and economic as well as ecological evaluation is capable of predicting and analysing the forest development of inventory plots, entire stands, forestry enterprises and large regions. The evaluation approaches presented here follow the recommendations of Deutscher Verband Forstlicher Forschungsanstalten (2000). The application and evaluation of the SILVA 2.2 simulator on different spatial scales is dealt with by, inter alia, Deegen et al. (2000), Densborn (1999), Kahn and Pretzsch (1997), Knoke (1998), Utschig (1999), Pretzsch (1997, 1998, 2001) and Pretzsch, Ďurský, Pommerening, Fabrika (2000).

2 Prediction Algorithm, an Overview

Growth models, which are based on individual trees, break stands down into a mosaic of individual trees and simulate the individual tree interactions in a space-time system (Figure 1). The growth model SILVA 2.2 proceeds from only a few start and control parameters, which characterise a stand and its site conditions, and then models the stand dynamics in five-year cycles from stand establishment to the regeneration phase. To start, data on the dimensions and positions of the individual trees and the site parameters are needed. The site-growth-model is then adapted to given site conditions. The missing

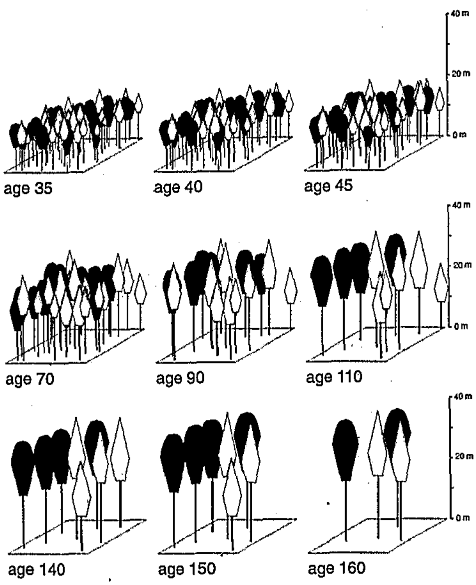

Fig. 1. Individual tree models break down a stand into a mosaic of individual trees and simulate their development in 5-year steps. The simulation of a mixed spruce-beech stand (*Picea abies* (L.) Karst. and *Fagus silvatica* L.) using the individual tree simulator SILVA is represented (PRETZSCH 1992) for ages 35 to 160 on a plot from the Oberbayerisches Tertiärhügelland (South Bavarian tertiary uplands). The top height site index for spruce amounts to 34 m according to ASSMANN and FRANZ (1963) while beech shows a site index of II.0 according to SCHOBER (1967) under moderate thinning. The stands are subjected to intense selective thinning.

Abb. 1. Einzelbaumorientierte Managementmodelle lösen einen Bestand in sein Mosaik von Einzelbäumen auf und bilden deren Entwicklung in 5-Jahres-Schritten nach. Dargestellt ist die Simulation eines Fichten-Buchen-Mischbestandes (*Picea abies* (L.) Karst. bzw. *Fagus silvatica* L.) mit dem Einzelbaumsimulator SILVA (PRETZSCH 1992) vom Alter 35 bis 160 im Oberbayerischen Tertiärhügelland. Die Oberhöhenbonität der Fichte liegt bei 34 m nach ASSMANN und FRANZ (1965) und die Buche weist eine II.0 Bonität nach SCHOBER (1967), mä. Df., auf. Die Bestände werden einer starken Auslesedurchforstung unterzogen.

data can be compensated by the supplement of realistic data (PRETZSCH 1997). Once the start and control parameters have been compiled, the simulation run can proceed. The actual growth prognosis is carried out in 5-year cycles. The number of cycles, i.e. the length of the simulation period, can be determined by the user. Each cycle comprises four steps. The first step is to quantify the three-dimensional growth constellation for each tree via a competition index. As a second step, the trees to be removed are identified according to the rules of the user-defined thinning concept. After that, the previously determined competition index is used to control the dimension changes of all trees within the stand. The fourth step involves the use of a mortality model to determine which trees did not survive due to competition effects. Steps 1 to 4 are repeated until the entire prediction period has been covered.

Prediction results cover a range of subjects and are available in the form of tables, diagrams or stand images: the state of any stand through the whole forecast period can be characterised by the classical, yield-related stand characteristics, frequency distributions and information on individual trees. Furthermore, each tree may be classified into timber grades according to user-defined specifications, since the stem dimensions are known. How the value of a stand and individual trees develops can be followed, because wood prices and harvesting costs are taken into account. For the ecological evaluation, spatial stand structure on different scales is characterised by calculating correlation functions and indicies for stand structure. Moreover, results on the total biomass production of trees (separated for stem, branches, leaves/needles, thin and thick roots), carbon dioxide and nitrogen fixation are included (MESCHEDERU 1997). Besides the numerical information the visualisation module provides vivid impressions of the three-dimensional forest structure at stand and landscape level (PRETZSCH and SEIFERT 2000).

3 Data base

The parameter estimation of the models is based on the following three data sets of different origin, extent and geographical coverage.

(1) Collection of the data for the site-growth-model of the main tree species. The data were compiled through the cooperation between the Lower Saxony Forestry Research Institution (Niedersächsische Forstliche Versuchsanstalt) in Göttingen, the Technical University of Munich Chair of Forest Yield Science and the Swiss Federal Research Institute for Forest, Snow and Landscape (Schweizerische Versuchsanstalt für Wald, Schnee und Landschaft) in Birmensdorf. The spectrum of sites and test plots ranges from the lowlands in Schleswig-Holstein to the mountain regions of Switzerland and covers

Switzerland and Bavaria, Saarland, Rhineland-Palatinate, Hesse, North Rhine-Westphalia, Lower Saxony and Schleswig-Holstein in Germany. The material comprises a total of 330 long-term experimental plots and is based on measurements taken at 3,120 different points of time. The oldest measurements date back to the year 1870 (KAHN 1994). The measured data cover an extremely wide spectrum of growth and site conditions in Central Europe and as such are the optimum prerequisite for the realistic prognosis of forest growth under diverse site conditions.

(2) Stem shape and bark thickness are predicted by using the approach of KUBLIN and SCHARNAGL (1988). The stem periphery is modelled in relation to the data on diameter and height by means of spline functions. The model assumptions of the stem shape are based on about 30,000 stem section measurements from former West Germany, viz. 5,100 spruces (*Picea abies* (L.) Karst.), 3,900 firs (*Abies alba* Mill.), 1,200 Douglas firs (*Pseudotsuga menziesii* Mirb.), 3,500 pines (*Pinus silvestris* L.), 2,600 larches (*Larix decidua* Mill.), 5,900 beeches (*Fagus silvatica* L.), 4,000 oaks (*Quercus petraea* (Mattuschka) Liebl.) and 3,400 red oaks (*Quercus rubra* L.). We may therefore assume that the stem shape functions have been calculated from a very representative data base.

(3) The long-term network of experimental areas established by the Munich Chair of Forest Yield Science forms the basis for the parameterisation of all further models, e.g. increment simulation, crown form and mortality. The network comprises not only Bavarian data, but also some plots in Rhineland-Palatinate and Lower Saxony. The fitting of the increment models is based on 404 experimental plots with readings taken at 578 different points of time from over 150,000 trees (Table 1). These data contain information on the development of diameter, height, crown base height and crown width in relation to site, growth constellation and vitality of individual trees. Thanks to the spatial inventories of pure and mixed stands, which were introduced fairly early by ASSMANN (1953/54), MAGIN (1959), KENNEL (1965), FRANZ (1972 and 1981) and PREUHSLER (1979 and 1989) and to the new growth series of 100 plots in mixed stands, the fitting of a distance-dependent individual tree model has become possible.

The stands within the network cover basal areas of up to more than 80 m^2/ha and standing volumes of up to over 1,400 m^3/ha[1] for spruce as well as stem numbers amounting up to over 17,000 trees per

Table 1. Silvicultural and site-related characteristics of the experimental plots used to fit the difference equations for the increment models in SILVA 2.2. The overview provides data on total precipitation in the vegetation period (P_V), mean temperature in the vegetation period (T_V), duration of the vegetation period (DT_{10}), moisture of soil (MOIST) and soil nutrient supply (NUT). The letter A behind the year means, that the first survey occurred in autumn, at the end of the growth period.

Tabelle 1. Waldwachstumskundliche und standortskundliche Merkmale der Versuchsparzellen für die Parametrisierung von SILVA 2.2. Die Übersicht vermittelt die Niederschlagssumme in der Vegetationsperiode (P_V), mittlere Temperatur in der Vegetationszeit (T_V), Länge der Vegetationszeit (DT_{10}), Bodenfrische (MOIST) und Nährstoffversorgung des Bodens (NUT). Der Buchstabe A hinter den Jahreszahlen bedeutet, dass die erste Aufnahme im Herbst, zum Ende der Vegetationszeit erfolgte.

species	plots	surveys	trees	dbh	1.survey	age
Fagus silvatica L.	148	187	35323	5.1-103.4	1952A	5-398
Quercus petraea (Matt.) Liebl.	63	67	10026	7.1-90.1	1952A	18-208
Alnus glutinosa Gaertn.	5	5	498	0.8-47.5	1992A	9-94
Picea abies (L.) Karst.	89	151	44394	5.1-93.1	1953A	5-170
Pinus silvestris L.	61	88	57822	5.1-85.5	1958A	5-240
Abies alba Mill.	38	80	4129	4.5-96.5	1953A	24-177
total	404	578	155183			

species	P_V	T_V	DT_{10}	MOIST	NUT
Fagus silvatica L.	310-1048	11.9-16.1	84-180	3-6	1-4
Quercus petraea (Matt.) Liebl.	310-469	14.7-16.0	149-180	3-5	1-4
Alnus glutinosa Gaertn.	486-578	14.7-15.4	155-165	5-7	3
Picea abies (L.) Karst.	334-1048	11.9-15.4	107-165	3-6	1-4
Pinus silvestris L.	330-954	13.1-15.6	148-170	3-6	1-4
Abies alba Mill.	486-1326	10.0-15.2	51-165	3-6	3-4

[1] This and any subsequent expression of m^3/ha refers to cubic metres of timber with diameters over 7 cm.

hectare for pine. The yield classes of the stands vary from values beyond class I.0 to class IV. related to the yield tables quoted in Table 2. The values of CLARK and EVANS (1954) index R range from 0.5 to 1.5 and indicate stand structures in which the horizontal distribution patterns vary from strong clustering to pronounced regularity. Intermingling has been quantified by using the PIELOU index (1975 and 1977) and the obtained values between S = −1 and +1 indicate a great variety of structural patterns. For additional growth and yield information and structural characteristics of the long-term experimental plots used see PRETZSCH and KAHN (1998). In total, the model parameters of the SILVA system are based on a very wide range of data on different sites and with varying stand structures. For model validation, data from a total of 1,010 surveys covering the observation period from 1870 to 1995 have been used. This material has not been taken into account in the model-fitting process.

Table 2. Characteristic stand values of the experimental plots used to fit SILVA 2.2: $\bar{h}$ = mean height (m) based on basal area, $\bar{d}$ = mean diameter (cm) based on basal area, N = number of stems (trees/hectare), BA = basal area of the stand (m^2/hectare), VOL = standing volume (m^3/hectare), site = top height at age 100 for spruce and relative yield classes for beech, oak, alder, *Alnus glutinosa* Gaertn, pine and fir, dense = degree of stocking, mix = portion of other tree species in the stand, R = CLARK and EVANS index, S = PIELOU index, A = vertical species profile. Some of the plots were observed since stand establishment, therefore the minima of their yield elements are 0.0 and not included in the table.
The following yield tables and regimes were used: for beech, moderate thinning according to SCHOBER (1967), for oak, moderate thinning according to JÜTTNER (1955), for alder, intense selection thinning according to LOCKOW (1995), for spruce, staggered thinning, mean yield level according to ASSMANN and FRANZ (1963), for pine, moderate thinning according to WIEDEMANN (1943) and for fir, moderate thinning according to HAUSSER (1956).

Tabelle 2. Bestandeskennwerte der Versuchsparzellen für die Parametrisierung von SILVA 2.2: $\bar{h}$ = Höhe des Grundflächenmittelstammes (m), $\bar{d}$ = Durchmesser des Grundflächenmittelstammes (cm), N = Stammzahl (Stück/ha), BA = Bestandesgrundfläche (m^2/ha), VOL = Bestandesvolumen (VfmD/ha), site = Oberhöhen im Alter 100 für Buche und Fichte und relative Ertragsklassen für Eiche, Erle, Kiefer und Tanne (*Alnus glutinosa* Gaertn.), dense = Bestockungsgrad, mix = Mischungsanteil anderer Baumarten, R = CLARK und EVANS-Index, S = PIELOU-Index, A = vertikales Artenprofil. Einige der Parzellen wurden von der Bestandesbegründung an unter Beobachtung genommen, sodass die Minima ihrer Kennwerte 0,0 betragen.
Zugrundegelegt sind die Ertragstafeln für Buche, mä. Df. von SCHOBER (1967), für Eiche, mä. Df. von JÜTTNER (1955), für Erle, starke Auslesedurchforstung von LOCKOW (1995), für Fichte, gest. Df. mittleres Ertragsniveau von ASSMANN und FRANZ (1963), für Kiefer, mä. Df. von WIEDEMANN (1943) und für Tanne, mä. Df. von HAUSSER (1956).

		$\bar{h}$	$\bar{d}$	N	BA	VOL	site	dense	mix	R	S	A
Fagus silvatica L.	min	8.0	6.4	3	0.1	1	II.3	0.0	1	0.0	-0.6	0.0
	mean	24.5	28.1	326	13.0	175	0.6	0.5	54	0.9	0.3	0.5
	max	41.5	60.3	2431	47.0	880	-0.2	1.5	100	1.7	1.0	1.1
Quercus petraea (Matt.) Liebl.	min	9.0	5.0	28	10.4	10	III.6	0.0	1	0.0	-0.6	0.0
	mean	26.6	35.7	327	15.0	207	-0.1	0.6	53	1.1	0.2	0.3
	max	37.3	83.3	7233	41.0	616	-I.5	1.6	100	2.1	1.0	0.8
Alnus glutinosa Gaertn.	min	5.9	3.3	263	0.3	0	II.3	0.0	0	0.0	-0.2	0.0
	mean	16.0	18.6	730	8.0	69	-2.5	0.4	34	0.6	0.1	0.2
	max	26.4	36.6	5733	28.0	355	-V.1	1.3	100	1.5	1.0	1.0
Picea abies (L.) Karst.	min	5.1	5.5	1	0.2	2	26.9	0.0	0	0.0	-1.0	0.0
	mean	24.7	29.9	911	24.0	295	40.9	0.5	60	1.1	0.4	0.6
	max	43.1	59.6	9890	81.0	1430	45.3	1.6	100	1.9	1.0	1.1
Pinus silvestris L.	min	4.6	3.4	1	0.3	4	III.8	0.0	1	0.0	-0.4	0.0
	mean	15.9	20.0	2947	18.0	121	0.5	0.7	82	1.1	0.6	0.5
	max	37.2	60.1	17148	37.0	618	-I.2	1.2	100	1.5	1.0	1.0
Abies alba Mill.	min	8.1	8.5	3	0.2	1	III.6	0.0	0	0.0	-1.0	0.0
	mean	27.1	38.6	73	8.0	112	II.0	0.2	30	0.9	0.0	0.4
	max	45.1	67.0	294	29.0	393	-0.9	0.7	69	1.9	0.8	0.8

4 Site-Growth Model

The principles of controlling individual tree growth by means of site factors

The model for height increment is used as an example as the principle with which the site-growth-model controls the dimensional development of individual trees is explained. The expected height increment ih_{exp} in any given five-year period is estimated from the potential height increment of the tree ih_{pot} and the multiplier Mod, which expresses the increment-reducing effects of competition, vitality and site (Figure 2, top). The potential height increment ih_{pot} in this case is deduced from the potential age-height curve. Based on the actual height of the respective tree, its likely age is read from the x-axis of the potential age-height curve. Thereafter, 5 years are added to the obtained age (period Δt), so that the age at the end of period Δt is then shown on the y-axis of the age-height curve (Figure 2, centre). The potential height increment ih_{pot} is represented as the difference between ultimate height and initial height which can be read off from the potential age-height curve. When determining the potential height increment the dependence of height increment on site will then show as a result of the use of the site-specific potential age-height curves. KAHN (1994) developed and parameterised a system of functions from which the potential age-height curves for any type of site unit may be estimated from the following nine site variables: soil nutrient supply (NUT), NO_X-content of the air (NO_X), atmospheric CO_2 (CO_2), duration of vegetation period (DT_{10}), annual temperature amplitude (T_{VAR}), mean temperature during vegetation period (T_V), aridity index according to DE MARTONNE (M_V), total precipitation in the vegetation period (P_V) and degree of soil moisture (MOIST) (Figure 2, bottom).

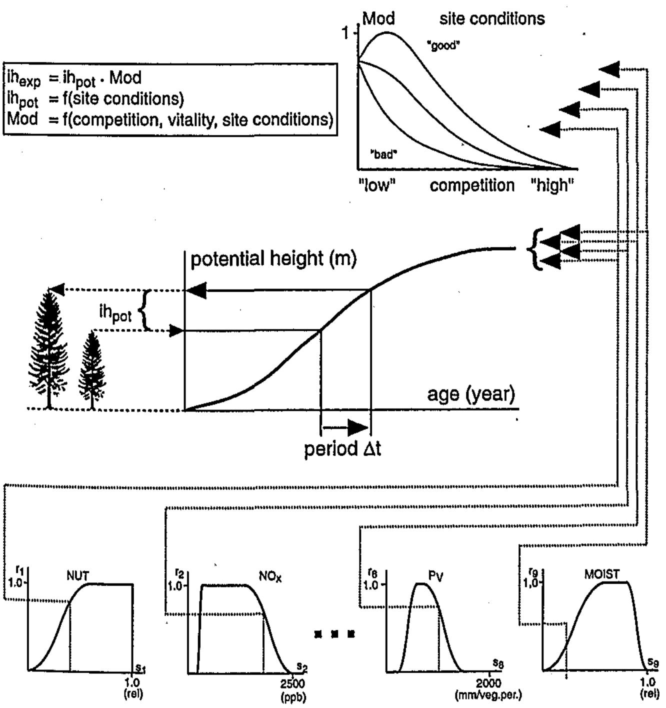

Fig. 2. Deduction of height increment ih_{exp} using the growth model SILVA. Schematic representation of the relationships between the potential age-height curve, which gives us ih_{pot}, the site variables s_1 to s_9 and the multiplier Mod.

Abb. 2. Herleitung des Höhenzuwachses ih_{exp} im Wuchsmodell SILVA. Schematische Darstellung der Abhängigkeiten zwischen der potenziellen Altershöhenkurve, die ih_{pot} erbringt, den Standortvariablen s_1 bis s_9 und dem Multiplikator Mod.

Modelling the potential age-height curve in relation to site

The site-dependent modelling of the age-height curve uses the CHAPMAN-RICHARDS growth-function

$$h_{100} = A \cdot (1 - e^{-k \cdot t})^p \quad (1)$$

where

h_{100} = top stand height in m
A = asymptote in m
k, p = parameters for slope and shape
t = stand age in years

To determine this age-height curve for any given site the height curve A and the time when increment culmination t_{culm} is reached are estimated in relation to nine site variables (formulas 6 and 7). By using A and t_{culm} in auxiliary equations (formulas 8 to 10), the site-specific parameters k and p of the age-height curve may also be calculated. The potential height curve h_{pot} for individual trees is obtained from stand top height h_{100} by multiplying the stand top heights of spruce, fir, pine, beech and pine with the factors 1.138, 1.138, 1.189, 1.132 and 1.184, respectively. These factors have been derived by PRETZSCH and KAHN (1998) from the height-frequency distributions of the long-term experimental plots, scheduled in Table 1. The estimation of the potential height increment ih_{pot} is then done in dependence on site variables as shown in Figure 2. This enables the growth model SILVA 2.2 to simulate stand development for a wide range of site conditions. The problem of determining the site quality (i.e. the site index) of mixed stands is avoided if height and diameter increment potential are considered in relation to site factors. The parameterisation of the relationship between site characteristics and the variables A and t_{culm} (formulas 6 and 7) is based on a total of 330 long-term experimental plots. The measure of certainty ranges from 0.81 to 0.94 for the tree species spruce, fir, pine, beech and pine. These steps are described in detail in the following.

First, the asymptote of the height curve A and the age t_{culm} when increment culmination is reached are modelled in relation to site. Any site is described in terms of n = 1 .... 9 site variables s, with

s_1 = soil nutrient supply (relative values between 0 and 1, i.e. upper and lower boundaries of the ecological amplitude)
s_2 = atmospheric NO_x (ppb)
s_3 = atmospheric CO_2 (ppm)
s_4 = duration of vegetation period (number of days with temperatures over 10 °C)
s_5 = annual temperature amplitude (°C)
s_6 = mean temperature in the vegetation period (°C)
s_7 = aridity index according to DE MARTONNE (mm/°C)
s_8 = total precipitation in the vegetation period (mm/vegetation period)
s_9 = degree of soil moisture (relative values between 0 and 1, i.e. upper and lower boundaries of the ecological amplitude).

The variables s_n express the factors which characterise a site. Soil nutrient supply and degree of soil moisture are given on the ordinal scale. A fuzzy-set theoretical approach for linguistic variables, which follows the approximation system by CHEN and HWANG (1992), converts them into metric scale. The required information on climate can be deduced from the growth region to which a specific site belongs. Atmospheric NO_x and CO_2 are regional and/or global variables. All variables are transformed by unimodal dosis response functions $f(s_n)$ in the interval [0;1]:

$$r_n = f(s_n),\ n = 1 \ldots 9 \text{ und } r_n \in [0;1]. \quad (2)$$

The response factors r_n describe the effect of the factor s_n on potential height growth of a tree species and hence proves context-sensitive for tree species. Figure 3 shows the dosis response functions for spruce and beech and gives an example of the effect of the nine site variables on the potential height increment under the dominating site conditions (the site type with the most frequent occurence) in the growth region 12.8 Oberbayerisches Tertiärhügelland (South Bavarian pre-alpine uplands) (vertical beam). The response factors r_n are aggregated to form complex ecological factors. We start off by aggregating the response factors r_1 to r_3, r_4 to r_6 and r_7 to r_9 into three ecological factors: nutrient supply KF_1, thermal supply KF_2 and water supply KF_3, respectively

$$KF_1 = \left(\prod_{i=1}^{3} r_i\right)^{1-\gamma_3} \cdot \left(1 - \prod_{i=1}^{3} (1 - r_i)\right)^{\gamma_3} \quad (3)$$

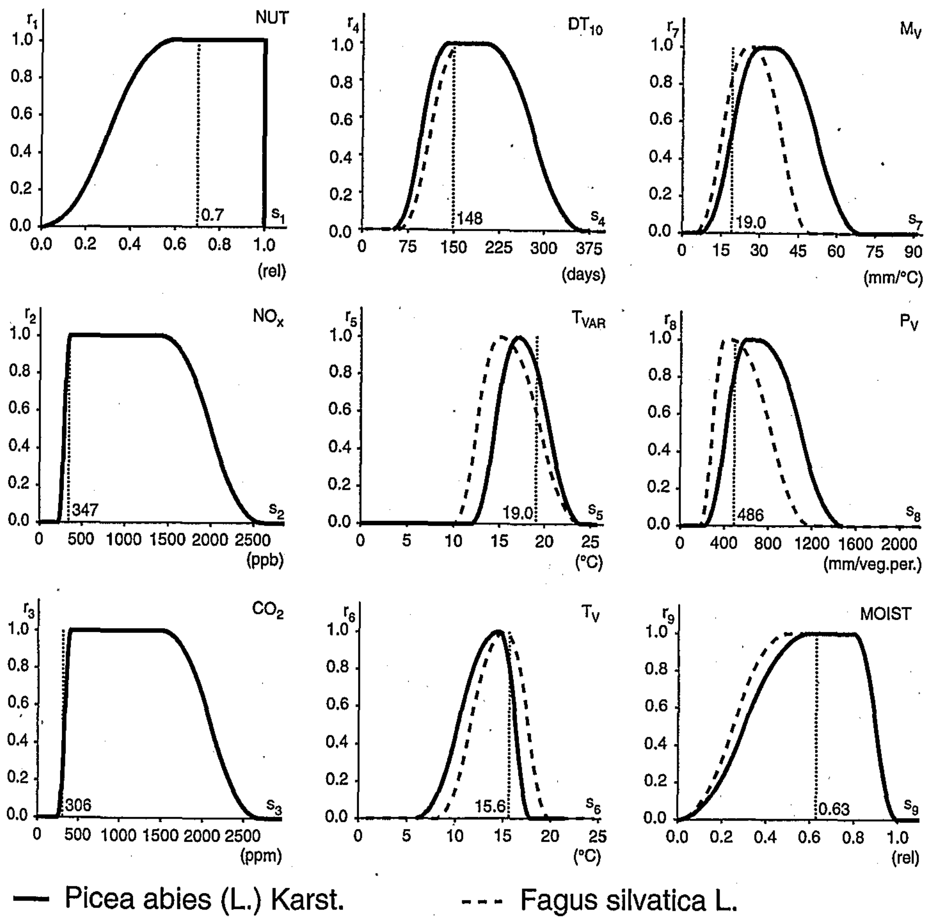

Fig. 3. Values for site variables s_1 to s_9 soil nutrient supply (NUT), atmospheric NO_x (NO_x), atmospheric CO_2 (CO_2), duration of vegetation period (DT_{10}), annual temperature amplitude (T_{VAR}), mean temperature during the vegetation period (T_V), aridity index according to DE MARTONNE (M_V), total precipitation during the vegetation period (P_V) and moisture of soil (MOIST) and their relative response factors r_1 to r_9 on potential height increment of spruce (full line) and beech (dotted line) under representative site conditions in the growth region 12.8 Oberbayerisches Tertiärhügelland (South Bavarian tertiary uplands) (dotted line perpendicular to the x-axis).

Abb. 3. Ausprägung der Standortvariablen s_1 bis s_9: Nährstoffversorgung des Bodens (NUT), NO_x-Gehalt der Luft (NO_X), CO_2-Gehalt der Luft (CO_2), Länge der Vegetationszeit (DT_{10}), Jahrestemperaturamplitude (T_{VAR}), mittlere Temperatur in der Vegetationszeit (T_V), Ariditätsindex nach De MARTONNE (M_V), Niederschlagssumme in der Vegetationsperiode (P_V) und Bodenfrische (MOIST) und ihre relativen Wirkungswerte r_1 bis r_9 auf den potenziellen Höhenzuwachs von Fichte (durchgezogene Linie) und Buche (gestrichelte Linie) auf einem wechselfeuchten Lehmboden aus Löß im Wuchsbezirk 12.8 Oberbayerisches Tertiärhügelland (gestrichelte, senkrecht zur Abszisse stehende Linie).

$$KF_2 = \left(\prod_{i=4}^{6} r_i\right)^{1-\gamma_4} \cdot \left(1 - \prod_{i=4}^{6} (1 - r_i)\right)^{\gamma_4} \quad (4)$$

$$KF_3 = \left(\prod_{i=7}^{9} r_i\right)^{1-\gamma_5} \cdot \left(1 - \prod_{i=7}^{9} (1 - r_i)\right)^{\gamma_5}. \quad (5)$$

As a second step, these three ecological factors are combined and then used to estimate the asymptote of the height curve and the time of culmination

$$A = A_0 + A_1 \cdot \left(\prod_{j=1}^{3} KF_j\right)^{1-\gamma_1} \cdot \left(1 - \prod_{j=1}^{3} (1 - KF_j)\right)^{\gamma_1} \tag{6}$$

and

$$t_{culm} = t_0 + t_1 \cdot \left(\prod_{j=1}^{3} KF_j\right)^{1-\gamma_1} \cdot \left(1 - \prod_{j=1}^{3} (1 - KF_j)\right)^{\gamma_2}. \tag{7}$$

Here, the γ aggregation operator from ZIMMERMANN and ZYSNO (1980) is used so that γ_1 to γ_5 are estimated from the regression analysis of the data of long-term experimental plots. The symbols used above are:

A	=	asymptote in m
A_0	=	minimum asymptote in m
A_1	=	maximum asymptote minus A_0 in m
t_{culm}	=	age of stand at which height increment culmination is reached, in years
t_0	=	minimum value for t_{culm} in years
KF	=	complex ecological factor
$\gamma_1 - \gamma_5$	=	aggregation operators
j	=	index

This gives us parameter A for the CHAPMAN-RICHARDS growth function (formula 1). To determine the parameters k and p of the same function, an auxiliary equation is used. This equation expresses the time at which increment culmination is reached t_{culm} and tree height at the time of increment culmination h_{tculm} as follows:

$$h_{tculm} = B \cdot (1 - e^{c \cdot t_{culm}}). \tag{8}$$

The parameters B and c are estimated using the data from long-term experimental plots. This permits the derivation of the tree height h_{tculm} at the time of increment culmination It is related to the asymptote A and the parameter p as follows:

$$h_{tculm} = A \cdot (1 - \tfrac{1}{p})^{p}. \tag{9}$$

An algorithm is used to solve the equation 9 to give p, which together with t_{culm} helps to determine the slope parameter k

$$k = \frac{-\ln(\frac{1}{p})}{t_{culm}}. \tag{10}$$

Figure 4 shows an example of the height growth potential and the change in competitive conditions in favour of beech if precipitation in the vegetation period were to decrease from 700 to 300 mm and soil moisture from 0.6 to 0.2 (left and centre). The site is located in the Upper Bavarian tertiary uplands

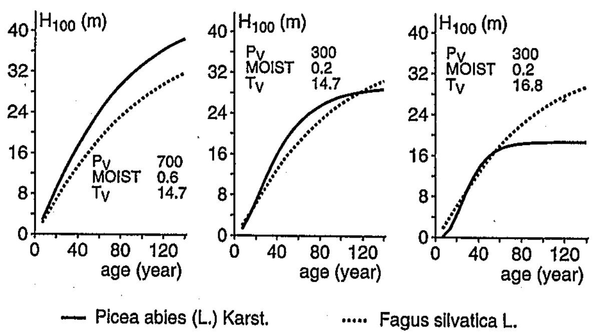

Fig. 4. Depending on the site factors s_1 to s_9 used the site-growth-model provides height growth relationships between spruce and beech which may range from inferior growth of beech, similar growth of beech to superior growth of beech in the mixed spruce-beech stand. P_V is given in mm/year, MOIST in a relative scale from 0 to 1.0 and T_V in degree Celsius.

Abb. 4. Je nach eingesteuerten Standortfaktoren s_1 bis s_9 erbringt das Standort-Leistung-Modell Höhenwachstumsrelationen zwischen Fichte und Buche, die von mattwüchsiger Buche, gleichwüchsiger Buche bis zu überlegener Buche im Fichten-Buchen-Mischbestand reichen können. P_V bezeichnet die Niederschlagssumme in der Vegetationsperiode in mm/Jahr, die Bodenfrische MOIST reicht auf einer relativen Skala von 0 bis 1,0, und die mittlere Temperatur in der Vegetationszeit T_V ist in Grad Celsius angegeben.

(P_V = 700 mm, MOIST = 0.6 and T_V = 14.7) and characterised further in Figure 3. The right hand side of the figure shows which height growth could be expected if the temperature within the vegetation period were also to rise from T_V = 14.7 to 16.8 °C.

5 Generating starting values for simulations

The starting values required for creating distance-dependent individual tree models are diameter, height, height of crown base and stem co-ordinates for all individual trees. Generally, only research experiments and, in this case, only the long-term experimental plots provide sufficiently complete information. Therefore, the model SILVA has been equipped with algorithms which are capable of providing a realistic supplement for missing data on tree dimensions and tree positions (PRETZSCH 1997). If spatial data on stand structure are available, data supplementation may be restricted to filling in the gaps in tree heights and heights of crown bases. Where sampling of concentric circles (figure 5, left) or angle counts (centre) has been used, the structure generator STRUGEN will supplement the missing stand elements (right), and thus create complete sets of diameters, heights, crown base heights and tree positions from which entire stands may be constructed. Diameter distribution can be produced from the diameter range and the basal area of a stand by using an algorithm developed by NAGEL and BIGING (1995). After that, uniform height curves, species-specific crown base functions and crown diameter functions may be used to obtain a height and crown dimensions for each tree. The trees are then arranged on a stand area via a POISSON process in such a manner that realistic distances between the trees and plausible micro-structures are created. An algorithm converts the verbal expression of the mixed structure into a macro structure and makes it conform to reality as closely as possible. Conformity does not mean that e.g. a certain tree needs to occupy identical positions in the real and the generated stand, but rather that the characteristics of real and generated stand are similar and that, among other things, inter-species competition, height structuring and the horizontal distribution patterns of the original and the simulated stand are comparable.

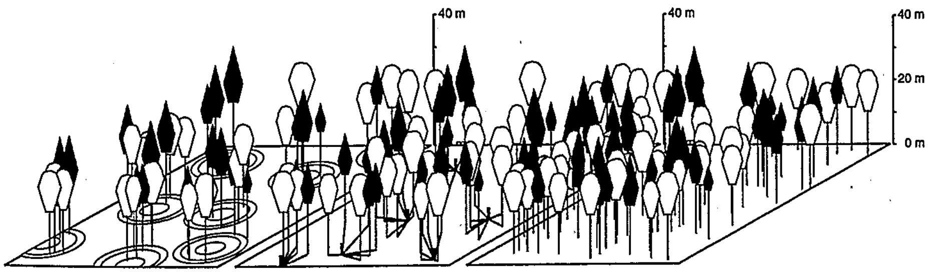

Fig. 5. Where information on individual trees in a stand is limited to random samples from permanent test plots (left) or angle counts (centre), data on the missing stand elements will be supplemented by the structure generator STRUGEN (right).

Abb. 5. Liegen von einem Bestand die Einzelbauminformationen nur stichprobenartig aus konzentrischen Probekreisen (links) oder Winkelzählproben (Mitte) vor, so ergänzt der Strukturgenerator STRUGEN die fehlenden Bestandesglieder (rechts).

6 Examples of application on various scales

Scenario calculations at stand level

To demonstrate the application of the growth model SILVA 2.2 at stand level a pure spruce stand is compared with a mixed spruce-beech stand (PRETZSCH and KAHN 1996). The test site is on a moderately dry to moist site with low nutritient supply from the growth region South Bavarian tertiary uplands. The site index for top height achieved by spruce at age 100 is approx. 34 m (ASSMANN and FRANZ 1963), while beech reaches a site index of II.0 under a moderate thinning regime (SCHOBER 1967). The yield tables applied in South Germany use absolute site indices (20 m to 40 m, index age 100) for spruce and relative site characteristic (I to V) for beech. The original stands consist of 1,400 planted spruce trees per hectare in the pure stand (spruce: 20 years old) and of 1,000 planted spruce plus 600 naturally regenerated beech trees per hectare in the mixed stand. Both stands are subjected to moderate thinning so that the degree of thinning is controlled by species-specific stem number curves.

Simulations cover a period of 145 years and, as an example, the development of basal area and current annual volume increment are shown in Figure 6. Thinning is repeated several times in the first half of the prediction period as a reaction to the great increment performance of spruce at this stage of its life. Basal area increases from 2.8 m^2/hectare in the pure spruce stand and 2.9 m^2/hectare in the mixed spruce-beech stand (35 % beech), achieves the maximum values of 67 and 58 m^2/hectare, respectively, at age 130 and then shows a downward curve with progressive age. Figure 6 (right) shows that the annual volume increment at young stand age rises quicker in the pure (full black line) than in the mixed stand (grey dotted line). Beech mixture causes a slight decrease in culmination height and a retardation in the time required for the culmination of the current volume increment due to the competitive strength of beech. With progressive age beech may even cause the volume increment of the mixed stand to repeatedly exceed that of the pure stand, despite the later culmination age of beech.

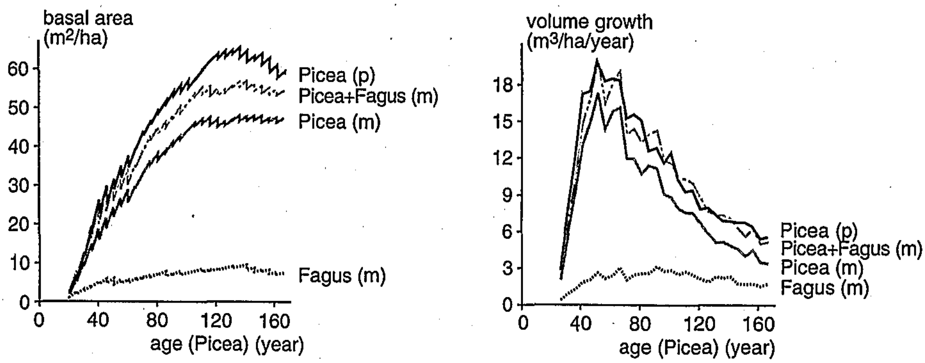

Fig. 6. Results of the variant study on pure spruce stand versus mixed spruce-beech stand. This shows the basal areas of the stands (left) and the current annual volume growth (right) for the 145 year prediction period. Picea (p) = pure spruce stand, Picea (m) = spruce in the mixed stand, Fagus (m) = beech in the mixed stand, Picea + Fagus (m) = spruce and beech, combined, in the mixed stand.

Abb. 6. Ergebnisse der Variantenstudie Fichten-Reinbestand versus Fichten-Buchen-Mischbestand. Dargestellt sind die Bestandesgrundfläche (links) und der laufende jährliche Volumenzuwachs (rechts) in dem 145-jährigen Prognosezeitraum. Picea (p) = Fichten-Reinbestand, Picea (m) = Fichte im Mischbestand, Fagus (m) = Buche im Mischbestand, Picea+Fagus (m) = Fichte und Buche zusammen im Mischbestand.

For the financial evaluation the mean annual value increment is considered as the most appropriate characteristic (i.e. felling value at respective age plus intermediate returns, divided by stand age). By contrast, the current annual value increment corresponds to the difference between the total value achieved in two consecutive periods, divided by the duration of these periods. The pure spruce stand in this example does better than the mixed stand as far as the mean annual value increment is concerned (Figure 7, left). If these results are transferred to corresponding management blocks, the spruce stand at age 120 will sustainably yield 730 DM[2] per hectare and year at the time of value increment culmination and on the basis of given costs and prices, provided rotation time is set for maximum annual value increment, i.e. for 120 years. To simplify matters, prices and costs

[2] In spite of the conversion from DM to EURO, in this paper the financial yield is reported in DM. Thus consistency is kept with related former publications from DEEGEN et al. (2000), DENSBORN (1999), HANEWINKEL et al. (2000), KAHN und PRETZSCH (1997), UTSCHIG (1999). 1 DM = 0.51 EURO = 0.56 US $ (19. Oct. 2001).

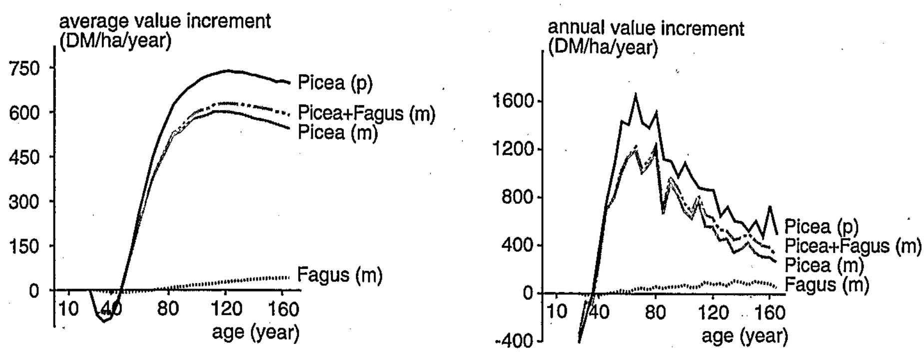

Fig. 7. Results of the variant study on pure spruce stand versus mixed spruce-beech stand. This shows the development of the mean annual value increment (left) and of the annual value increment (right) for the 145-year prediction period. Picea (p) = pure spruce stand, Picea (m) = spruce in the mixed stand, Fagus (m) = beech in the mixed stand, Picea + Fagus (m) = spruce and beech, combined, in the mixed stand.

Abb. 7. Ergebnisse der Variantenstudie Fichten-Reinbestand versus Fichten-Buchen-Mischbestand. Dargestellt sind die Entwicklungen des durchschnittlichen jährlichen Wertzuwachses (links) und des laufenden jährlichen Wertzuwachses (rechts) in dem 145-jährigen Prognosezeitraum. Picea (p) = Fichten-Reinbestand, Picea (m) = Fichte im Mischbestand, Fagus (m) = Buche im Mischbestand, Picea + Fagus (m) = Fichte und Buche zusammen im Mischbestand.

are assumed to be constant and any risks of damage to the stands are ignored. The mean annual value increment in the spruce-beech stand peaks at age 120 with a sustainable net return of 620 DM per hectare and annum (Figure 7, left). The difference to the pure spruce stand is thus characterised by opportunity costs of DM 110 per hectare and annum (= 730 DM − 620 DM). However, if a rotation time of 80 years is envisaged for the pure spruce stand, the net return would be reduced to DM 600 per hectare and year. In practice this could happen for instance due to brown rot, immission damage, storms and hurricanes or insect calamities. In this case a balance of DM 20 per hectare and annum would be shown in favour of the mixed stand. The steep rise in mean annual value increment prior to the culmination point and the fact that it regresses slowly after this point gives the manager a greater latitude in extending rather than reducing the rotation time. This also explains the development of current value increment (Figure 7, right), which achieves peak values of 1,200 to 1,640 DM/hectare and annum at stand ages ranging from 50 to 80 years.

Besides the volume and monetary value related results, it is possible, for any phase of the prediction run, to calculate structural indices which indicate the diversity of habitat and species within the stand (AMMER and SCHUBERT 1999, BEGON et al. 1991, DETSCH 1999). The indices R by CLARK and EVANS (1954) for horizontal tree distribution pattern, A by PRETZSCH (1998) for vertical species profile and S by PIELOU (1975, 1977) for species intermingling demonstrate how the structure in the pure spruce stand and the mixed spruce-beech stand may be modified by age development and specific thinning regimes.

The comparison and weighting between different treatment variants is assisted by a summary of various results (Figure 8). Next to the structure indices S, A and R, the values h_g/d_g[3] as stability indicator, dGWERTZ[4] as the decisive monetary and dGZ_{max}[5] as the

[3] h_g/d_g = mean height/mean diameter serves as indicator for the physical stability of trees against storm and snowdamages.
[4] dGWERTZ = mean annual value increment, i.e. (value of remaining + removal stand)/age.
[5] dGZ_{max} = maximum of the mean annual volume increment, i.e. (volume of remaining + removal stand)/age.

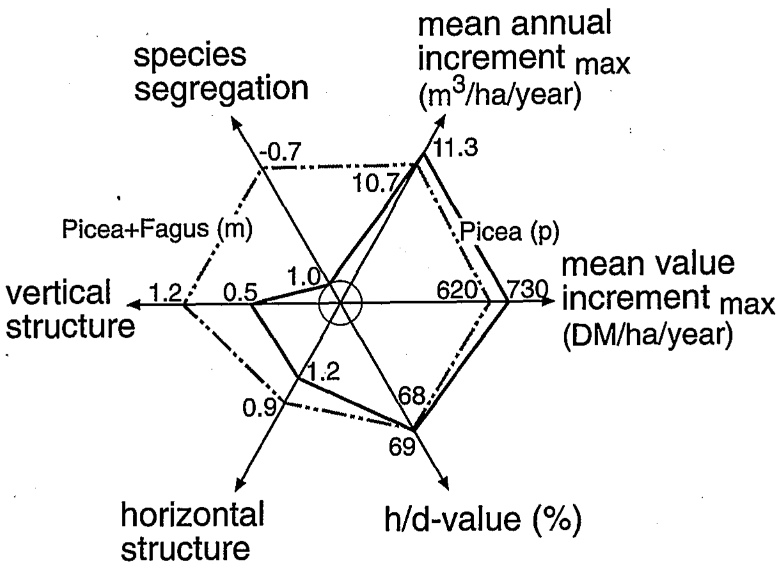

Fig. 8. Profiles of the most important output data for pure and mixed stands (species segregation, vertical structure, horizontal structure, h/d-value, mean value increment, mean anual increment) permit the weighting and optimisation of ecological and/or economic aspects of stand treatment. Picea + Fagus (m) = mixed spruce-beech stand, Picea (p) = pure spruce stand.

Abb. 8. Profile der wichtigsten Ausgabegrößen für Rein- und Mischbestand (Indizes für die Segregation, vertikale und horizontale Strukturierung, h/d-Werte, durchschnittlicher Gesamtzuwachs an Wert und Volumen) erlauben eine Abwägung und Optimierung von ökologischen bzw. ökonomischen Aspekten der Bestandesbehandlung. Picea (p) = Fichten-Reinbestand, Picea+Fagus (m) = Fichte und Buche zusammen im Mischbestand.

yield-related values are presented. The structural indices as well as the h_g/d_g-value refer to a stand structure at a stand height of 30 m; similar profiles may, however, be generated for any point in time. It appears that, on the selected site, given the thinning regime applied here and based on the assumptions regarding wood harvesting costs, wood prices and risks, the pure spruce stand is superior in volume increment and financial characteristics to the mixed spruce-beech stand. Conversely, the pure stand is inferior as regards structure and stability characteristics.

Dynamic planning at forestry enterprise level

At enterprise, regional or national level the simulator is no longer applied interactively via a menu dialogue, but automatically in the batch-mode. The starting values for the prediction runs (inter alia data on stand and strata allocation) go back to the input provided by forest inventory data bases, while the control parameters (inter alia treatment regimes, wood prices, wood harvesting costs) are downloaded in special files so that any number of subsequent forecasts may be performed (ĎURSKÝ 2000). At enterprise, regional or national level the overall consequences of individual forest management decisions – such as liquidity problems or loss of timber grades – become obvious. Thus, undesirable developments may be rectified by re-considering and adjusting treatment programmes at strata or stand level. Simulation at forest enterprise level is here constructed on the base of inventory data and involves the following steps: (1) All inventory sampling points are allocated to certain strata in a cross-classification process; these strata may refer to site/type of stand or to tree species/development stage. (2) A specific silvicultural treatment scenario (e. g. selective or schematic thinning, target diameter or crop tree thinning, thinning from below) is allocated to each stratum. (3) The overall forecasting is performed. This makes it possible to analyse the consequences of stand or strata-related treatment on the long-term development of the enterprise. To prevent undesirable developments at enterprise level the treatment programmes applied to any strata may be modified if required. (4) Analysis of the results. Important results for planning practice include site-related yield tables with gross felling budgets and maps on natural, economic and ecological variables for the selected treatment programmes. The results range from the initial state to the end of the forecasting period and describe the development of indicators on single plots, stands, strata, and within the enterprise as a whole.

In the following, the Traunstein Municipal Forest area of 553 hectares will serve as an application example. These forests are located in the growth region 14.4 Oberbayerische Jungmoräne and Molassevorberge (South Bavaria's alpine foothills). The dominant tree species is spruce on 69 % of the forest area, while beech, hardwood species (e.g. Acer spec., Fraxinus spec., Ulmus spec.) and white fir and other conifers cover 11 %, 10 %, 10 % of the forest area, respectively. The forecast is based on the data of about 600 in a 100 m x 100 m grid permanently established inventory plots and the calculations comprise a period of several decades. The results will provide information on total growth performance, stand stability, value performance and structural diversity. The simulation of several silvicultural treatments helps to demonstrate the consequences of different treatments at enterprise level.

Figure 9 shows an example of the development of increment, standing volume, harvested volume and net return of a removal stand during a 30-year period following inventory. The development under A-degree treatment (slight thinning from below) is used as a reference and contrasted with selection cutting, (starting with 300 selective trees, assessed continuously and released gradually) and future tree thinning (150 future trees, fixed early and released heavily). In comparison to selection cutting, future tree thinning, although

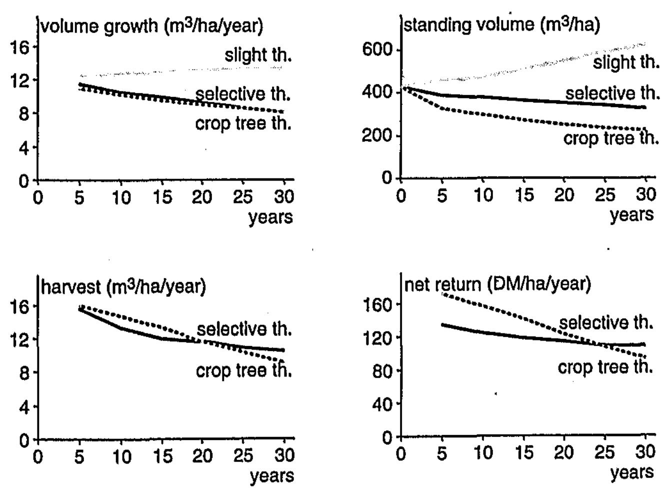

Fig. 9. Development of volume growth, standing volume, harvest volume and net return in the Municipal Forest Traunstein, given development under slight thinning from below, selective thinning and crop tree thinning. Standing volume is being stabilised, increased or depleted depending on the thinning regime.

Abb. 9. Entwicklung von Zuwachs, Vorrat, Nutzungsmenge und holzerntekostenfreien Erlösen im Stadtwald Traunstein bei Einsteuerung einer schwachen Niederdurchforstung (slight th.), Auslesedurchforstung (selective th.) und Z-Baum-Durchforstung (crop tree th.). Je nach unterstelltem Pflegeprogramm wird der Vorrat stabilisiert, auf- oder abgebaut.

superior as regards intermediate and net returns, would lead to a distinct decrease in volume from the current 426 cubic meters/hectare (harvested volume in bark) down to about half that amount in the 30 year period. This is not compensated by growth acceleration and may therefore jeopardise the sustainability of net returns. Selection cutting would cause a slight decrease in standing volume and thus tend to stabilise the net returns.

The evaluation of different treatments may be based on any combination or all of the economical and ecological variables presented in Figure 8. This kind of forecasting will reveal the varying and potentially contradictory long-term consequences of the selected treatments on the forestry enterprise. For instance, the aims of maximising structural diversity and net return may be difficult to fulfil at the same time. By taking multiple factors into consideration, the forester is able to select the treatments appropriately – so that both the structural diversity and net return remain at an acceptable level. Thus, the knowledge gained through the simulations assists the adjustment of treatment programmes at strata or enterprise level to fulfil the overall goals of the forestry enterprise.

Application on a large regional scale for research on the effects of climate change

The site-growth module of the growth model SILVA 2.2 permits the input of altered climatic and site conditions and therefore also the estimation of the effects of climate change on forest growth (Figure 4). As an example, the growth of spruce is projected under present and altering climatic conditions in Bavarian growth regions (see PRETZSCH and UTSCHIG 2000). The analysis is based on the site type that occurs most frequently in any given growth region. The data of this site type are used in the site-growth-model. Each forecast comprises the development of spruce stands from age 30 up to age 120. Therefore, as a first step, representative 30 year-old forest stands, which are located on the most frequent site type of each growth region, are identified from the forest inventory data base of the Bavarian State Forestry Administration. The sample plot data (points in a 200 m × 200 m grid) is used to determine the start, control and site parameters for the simulations.

The yield-related parameters of the selected forest stands (mean height, mean diameter and basal area of the stand per hectare at age 30) were calculated. These serve to reproduce the missing data on detailed stand structures for the growth simulations (NAGEL and BIGING 1995, PRETZSCH 2001). The scenario calculations are based on thinning from above at the young stage and, from age 50 onwards, on thinning from below. Thinning structure (e.g. thinning from above, below, schematic, selective thinning) are defined according to general thinning rules (PRETZSCH and KAHN 1998), and the degree of thinning (e.g. slight, moderate, heavy) is controlled by basal area curves, which are typical for each respective region. In total, the simulations describe the development of the representative stands based on the generated structure and according to the input provided on the site conditions and silvicultural treatments up to 120 years of age.

The simulation under altered climatic conditions is performed in the same manner as the forecast above. Only the climate parameters were changed. Growth reactions to the following climate scenario were tested: a 2 °C rise in temperature and a 10 % decrease in the precipitation during the vegetation period together with a prolongation of the vegetation period by 10 days (BAYERISCHER KLIMAFORSCHUNGSVERBUND 1999, FABIAN 1991, FABIAN and MENZEL 1998). Thus, based on present and assumed future climatic conditions the characteristic values for natural production, economy and ecology were calculated for each growth region and the results of these scenario calculations compared with one another. Before proceeding to the calculation results we should bring to mind that the climate-growth relationship within SILVA 2.2 is static in the following sense. It does not reflect the effect of gradually changing climate conditions, but prognosticates how growth would be under other climate conditions.

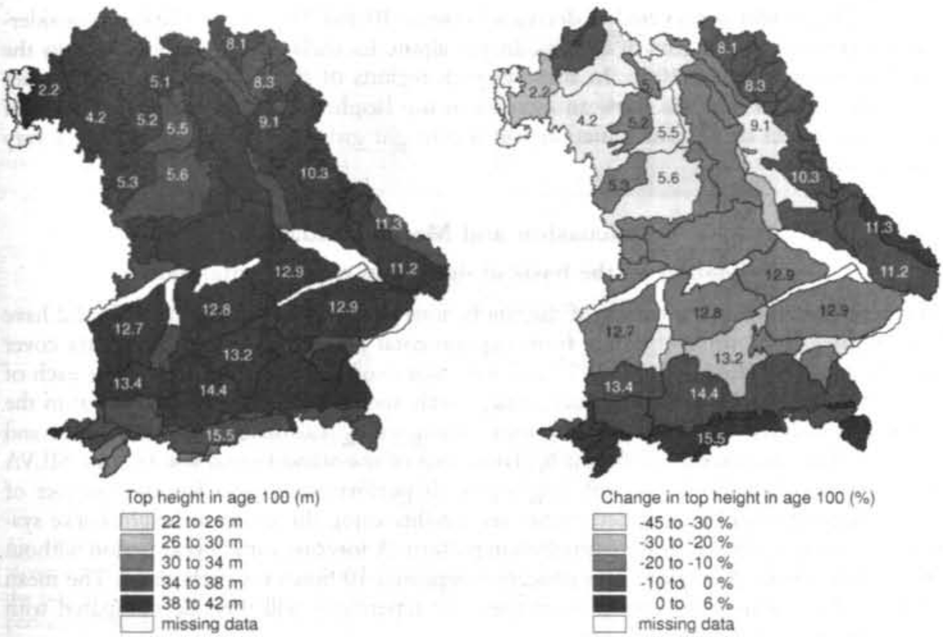

Fig. 10. Top height h_{100} of representative spruce stands in Bavarian growth regions at age 100 years under present climatic conditions (left) and reactions of top height to climate change (right), assuming the following: Increase in temperature within the vegetation period of 2 °C, decrease in precipitation in the vegetation period by 10 % and prolongation of the vegetation period by 10 days.

Abb. 10. Oberhöhe h_{100} repräsentativer Fichtenbestände in den bayerischen Wuchsbezirken im Alter von 100 Jahren unter gegenwärtigen Klimabedingungen (links) und Reaktion der Oberhöhe auf Klimaveränderungen (rechts). Unterstellt wurde ein Anstieg der Temperatur in der Vegetationszeit um 2 °C, ein Rückgang des Niederschlages in der Vegetationszeit um 10 % und eine Verlängerung der Vegetationszeit um 10 Tage.

Figure 10 (left) shows top heights at age 100 of the representative stands in the growth regions covered. These values may be directly used to determine site quality (= site index). The greatest top heights were achieved in the growth regions 13.4, 14.4, 12.9, 5.3, 5.2, 5.1 and 2.2. Growth region 2.2. has been included in this peak group because in the Buntsandsteinspessart (variegated sandstone hills of the Spessart) spruce will very frequently grow only on exceptionally favourable sites. Spruce is shown to be capable of reaching top heights of 35 to 40 m in many growth regions. The bottom end on this scale shows spruce stands in montane areas and on sites in lowlands with limited supplies of water and nutrients, in particular in growth regions where pine is the dominant tree species.

Under the selected climate scenario the top heights of the study sites did not exceed 40 m at age 100. In areas with limited water supply, e.g. in growth region 13.2 Münchener Schotterebene (Munich gravel plateau) there is a distinct decrease in top height. At age 100 the top heights to be expected will merely amount to between 22 and 25 m in the growth regions 4.1, 4.2, 5.5 and 5.6. Here, growth conditions for spruce have clearly deteriorated. In some regions of north and east Bavaria the assumed changes in climate will cause optimum developments in top height. In the alpine foothills, too, spruce is expected to continue to show good height growth performance. Figure 10 (right) shows the expected change in top height at age 100 in relative terms. Areas shaded in the lightest colour tone show a 30 to 40 % decrease in top height at age 100 compared with present growth. Top height is expected to decrease between 10 and 20 % at age 100 for a considerable proportion of the growth regions. In the alpine foothills and the montane areas the decrease remains below 10 %. In some growth regions of the Alps and the Bayerischer Wald the scenario analyses show an increase in top height of 6 %. However, this kind of supportive effect of climatic variations on top height growth has been noted for a very few sites only.

7 Discussion and Model Validation

Validation on the basis of data from experimental plots

The bias, precision and accuracy of the predictions of the growth model SILVA 2.2 have been estimated by using the data from experimental plot inventories. These data cover the observation period 1870 to 1995 and were not used in the model fitting. For each of the pure and mixed stands of spruce, pine, beech and oak considered here, input in the growth model SILVA consists of the mean diameter d_g (calculated from basal area and number of stems), mean tree height h_g, basal area of the stand G and site factors. SILVA will then calculate site-dependent height-growth performance, establish the number of stems-diameter distributions, determine tree heights using the uniform height curve system and create a horizontal tree distribution pattern. A forecast for a 5 year period without any kind of thinning is done. This process is repeated 10 times for each stand. The mean of the annual volume increment from these 10 repetitions will then be compared with the actual mean volume increment.

If we compare for i = 1....n stands the prediction results ($x_{i,\ i = 1...n}$) with the real developments ($X_{i,\ i = 1....n}$), the differences $e_i = x_i - X_i$ are obtained. The means $\bar{e}$

$$\bar{e} = \frac{\sum_{i=1}^{n} e_i}{n} = \frac{\sum_{i=1}^{n} (x_i - X_i)}{n} \qquad (11)$$

and $\bar{e}\,\% = \bar{e}/\bar{X} \cdot 100$ give the absolute and percentual bias, respectively. Figure 11 shows the distribution of the relative differences $e_i\,\%$ between estimated and real volume increment in spruce, beech, oak and pine stands ($x_i = iv_{prog}$ and $X_i = iv_{real}$). The standard deviation m_x

$$m_x = \sqrt{\frac{\sum_{i=1}^{n} (x_i - X_i)^2}{n-1}} \qquad (12)$$

will show the absolute accuracy, $m_x\,\% = m_x/\bar{X} \cdot 100$ the relative accuracy of the model with respect to relative volume increment.

The data base for this evaluation relies for the species spruce, beech, oak and pine on data from 220, 194, 86, 115 observation periods, respectively. The distribution of the relative deviations from reality iv % reveals a bias in the increment estimate between −1,9 and 4.8 percent for the tree species spruce, beech, oak and pine. The values for accuracy obtained with equation 12 are $m_x\,\% = 18.54$ to 38.62 percent. This result implies that, given normal distribution, 68 percent of the increment estimates will not deviate more than ±18.54 % (oak) and ±38.62 % (pine), respectively, from the real volume increment. Compared with the bias of 3.5 % to 119.1 % and the accuracy of 54.5 % to 175.6 % found, according to Reimeier (2000), when estimating the volume increment on the basis of the yield tables commonly used for spruce, beech, oak and pine stands in south Germany, the simulator SILVA 2.2 is considerably more accurate (Pretzsch and Ďurský 2001).

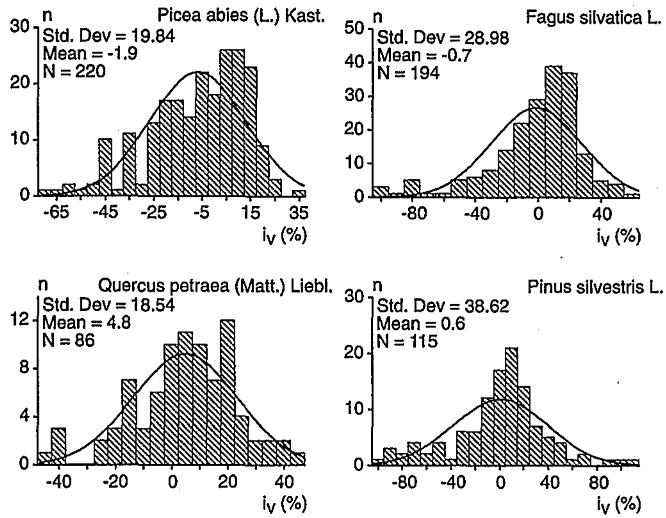

Fig. 11. Frequency distribution and values for the percent differences between real and forecast volume increment for the species spruce, beech, oak and pine. The mean of the distributions (Mean) reveals the bias and the standard deviation (Std. Dev) the accuracy in the estimates of volume increment as performed by the growth simulator SILVA 2.2.

Abb. 11. Häufigkeitsverteilung und Maßzahlen der prozentischen Differenzen zwischen wirklichem und prognostiziertem Volumenzuwachs für die Baumarten Fichte, Buche, Eiche und Kiefer. Der Mittelwert der Verteilungen (Mean) lässt den Bias und die Standardabweichung (Std. Dev) die Treffgenauigkeit bei der Schätzung des Volumenzuwachs mit dem Waldwachstumssimulator SILVA 2.2 erkennen.

Precision is calculated from the deviations of the predicted values $x_{i,\, i\, =\, 1...n}$ from the observed values $X_{i,\, i\, =\, 1...n}$, after having eliminated the bias from the predicted values. By substituting the difference $x_i - X_i$ in formula 11 by e_i, precision is represented as the standard deviation of the bias

$$s_e = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{e} - X_i)^2}{n-1}} = \sqrt{\frac{\sum_{i=1}^{n} (e_i - \bar{e})^2}{n-1}}. \quad (13)$$

Precision is frequently expressed in relation to the mean observed value

$$s_e\,\% = \frac{s_e \cdot 100}{\bar{X}}. \quad (14)$$

At stand level, the precision s_e % of the simulators prognosis varies between 5 and 40 % according to which yield elements and treatment regimes are considered. Here, precision s_e % for the estimates of diameter and mean height was found to be between 5 and 10 %, for values immediately affected by thinning and mortality such as number of stems, basal area and standing volume between 10 and 20 % and for annual increment between 20 and 40 %.

ĎURSKÝ (2000) has tested bias and accuracy of the diameter increment model SILVA on the basis of 2,254 trees on a total of 30 experimental plots monitored by the Forest Research Stations. The validity test for spruce is based on experimental plots not included in the model fitting process, which cover a wide spectrum of stand structures and treatment regimes. For all these stands Figure 12 represents the mean bias (left) and accuracy (right) achieved in forecasting diameter increment within a five-year period. For individual stands and surveys deviations of the forecast from reality may amount to between −30 and +70 percent and were found to be predominantly weather-related. On average, however, there is no significant systematic bias in diameter increment values. The accuracy for predicting diameter increment of individual trees ranges between 16.8 percent in homogeneous structured stands and 48.9 percent in heterogeneous structured and very dense stands. For the majority of the stands accuracy was shown to lie between 30 and 35 percent (Figure 12, right).

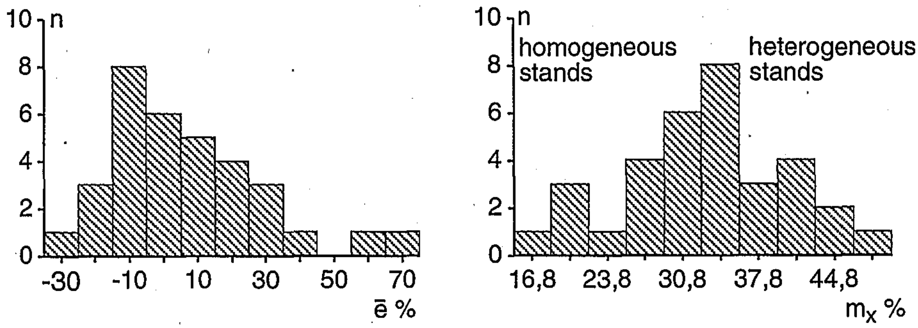

Fig. 12. Bias $\bar{e}$ % and accuracy m_x % of the forecast diameter increment of individual trees in spruce stands. This shows how frequently a bias of between −30 and 40 percent (left) occurs and an accuracy between 16.8 and 48.3 percent (right) is achieved in the poorly to well-structured spruce stands under investigation.

Abb. 12. Verzerrung $\bar{e}$ % und Treffgenauigkeit m_x % der Vorhersage des Durchmesserzuwachses von Einzelbäumen in Fichtenbeständen. Dargestellt ist die Häufigkeit, mit der in den untersuchten strukturarmen bis strukturreichen Fichtenbeständen Verzerrungen zwischen −30 und 70 Prozent (links) bzw. Treffgenauigkeiten zwischen 16,8 und 48,3 Prozent (rechts) auftreten.

Data from experimental plots may also be used for the validation of the simulator at tree level. Figure 13 shows a comparison between real and predicted diameter increments (periods 1987 to 1996 and 1992 to 1996, respectively) from the experimental spruce areas Weißenburg 613/2 and Fürstenfeldbruck 612/12. There is good coincidence between real and predicted diameter increments on the experimental plot Weißenburg 613/2 (left), with a bias of merely $\bar{e} = -0.13$ cm within a five-year increment period. Additional the accuracy of ±27 % is given; this means that for 68 percent of the prediction runs diameter increment values were measured that do not deviate from reality by more than ±27 %.

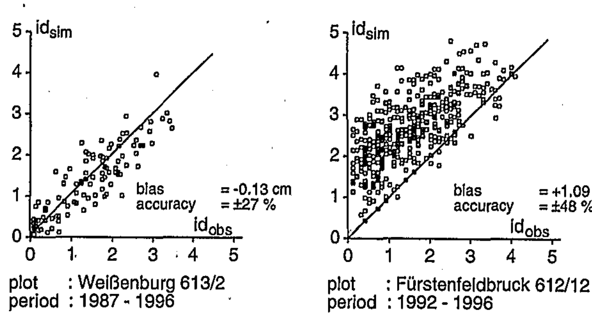

Fig. 13. Model validation using the diameter increment of individual trees on the long-term spruce trial plots at Weißenburg 613/2 (left) and Fürstenfeldbruck 612/12 (right).

Abb. 13. Modellvalidierung mit den Durchmesserzuwächsen von Einzelbäumen auf den langfristigen Fichten-Versuchsflächen Weißenburg 613/2 (links) und Fürstenfeldbruck 612/12 (rechts).

The situation is entirely different for the experimental area in Fürstenfeldbruck (right). Here, diameter increments are, on average, over-estimated by $\bar{e}$ = 1.09 cm and accuracy reaches $m_{\bar{x}}$ = ±48 % of the real diameter increment. This inaccuracy in the estimates is due to the fact that a short and climatically not representative growth period had been chosen for the validation process. Long-term growth processes are, among other things, superimposed by both periodically occurring climatic effects and disturbance events which makes it difficult to compare forecasts with reality. Whenever the growth conditions happen to alter in the increment period used in the model validation process, some bias in the prediction results is bound to become manifest if the model fails to take these variations in growth conditions into account. The problem of variations in growth conditions during a period used for model validation can be obviated by basing the validation process on longer periods of time with average climatic conditions. Short-term weather-related events will then recede into the background. For long-term validation runs known variations in climate or growth conditions should form part of the data input used in site-sensitive models.

Validation on the basis of inventory data

Validation of the growth model at regional level may be based, among other approaches, on data from forest inventories. For this study we used the data from permanent inventory plots on forest estate level, located at 200 m × 200 m grid points and remeasured each 10 years. In the validation of the height growth model we rely on height data of forest inventories from growth regions 11.03 Bayerischer Wald (Bavarian Forest), 15.05 Mittlere Bayerische Kalkalpen (central Bavarian Calciferous Alps), 12.08 Oberbayerisches Tertiär-

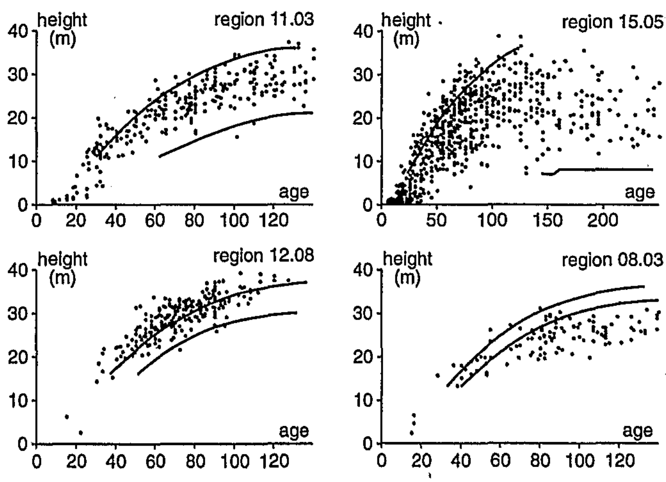

Fig. 14. Validation of the SILVA 2.2 height growth model by comparison of forecast height growth curves in selected growth regions with the random sample data from forest inventories. For the growth regions 11.03 Bayerischer Wald, 15.05 Mittlere Bayerische Kalkalpen (top) and 12.08 Oberbayerisches Tertiäres Hügelland as well as 8.03 Fichtelgebirge (below) the mean height development for each representative stand was carried out for both the upper and lower performance spectra (top and bottom lines respectively).

Abb. 14. Validierung des Höhenwachstumsmodells des Simulators SILVA 2.2 durch Vergleich der prognostizierten Höhenwachstumsverläufe in ausgewählten Wuchsbezirken mit den in diesen erhobenen Stichprobendaten der Forsteinrichtung. Für die Wuchsbezirke 11.03 Bayerischer Wald, 15.05 Mittlere Bayerische Kalkalpen (oben) und 12.08 Oberbayerisches Tertiärhügelland sowie 8.03 Fichtelgebirge (unten) wurde die Entwicklung der Mittelhöhe für jeweils einen repräsentativen Bestand im oberen Leistungsspektrum (obere Linie) und unteren Spektrum (untere Linie) ausgeführt.

hügelland (South Bavarian tertiary uplands) and 8.03 Fichtelgebirge (Fichtel Mountains). For these growth regions thousands of height measurements from forest inventories are available. For the validation, sites from both the upper and lower performance spectrum of the growth region are selected. Representative stands with yield-related inventory results at age 30 are identified for each site. Under the assumption of intense selective thinning a forecast is then performed for a period of 100 years. For the majority of the growth regions, the results show that close correlations exist between the simulated and real heights and diameters – an encouraging result considering that data from less representative experimental plots rather than from inventory data had been used to fit the growth model.

Figure 14, top, shows good correspondence between the forecast and reality in the growth regions 11.03 Bayerischer Wald (Bavarian Forest) and 15.05 Mittlere Bayerische Kalkalpen (Central Bavarian Calciferous Alps). The good correspondence is evident from the position of the inventory result between the height growth curves for the upper and lower performance spectra, represented by the upper and the lower boundary lines of the clusters. The systematic deviation between prognosis and reality in the growth region 12.08 Oberbayerisches Tertiärhügelland (South Bavarian tertiary uplands) and 8.03 Fichtelgebirge (Fichtel Mountains) (bottom) are probably attributable to the particularly high nitrogen immissions in the alpine foothills and the pronounced damage to tree crowns in the Fichtelgebirge (Fichtel Mountains) (PRETZSCH and UTSCHIG 2000). In this manner region-specific information on the accuracy of the model may be deduced for the most important yield elements.

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